CONTROL OF HYBRID AC-DC MICROGRID USING VARIABLE WEIGHING FACTOR ALGORITHM

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List of Publications

A.1. Journal Publication

i) Ali, Syed Umaid, et al. "Model predictive control—Based distributed control algorithm for bidirectional interlinking converter in hybrid AC-DC microgrids." International Transactions on Electrical Energy Systems (2021): e12817. [Impact Factor: 2.860] (cited as ref [62])

ii) Ali, Syed Umaid, et al. "Model predictive control of consensus-based energy management system for DC microgrid." PloS one 18.1 (2023): e0278110. [Impact Factor: 3.752] (cited as ref [61])

A.2. Conference Publications

i) Ali, Syed Umaid, et al. "Model Predictive Control for three phase rectifier with grid connected and standalone mode of operation." 2021 31st Australasian Universities Power Engineering Conference (AUPEC). IEEE, 2021 (cited as ref [63])

Dedicated to my dear parents, who are inspiration to me throughout my life.

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ABSTRACT

The electricity system is facing a structural transformation due to initiatives such as an increasing penetration of renewable distributed generation (RDG) units, widespread use of different converter topologies for storage, generation & loads, increased utilization of DC generation & load, led to inception of hybrid AC-DC network. This posted significant challenge in terms of its control and optimization. Moreover, Bidirectional Interlinking Converters (BICs) are used for flexible power interaction between AC and DC networks in hybrid AC-DC; both of them thus form a hybrid AC-DC network. Control of the network, especially the control of BIC, must ensure the vital coordination between AC and DC networks to achieve the key objective of appropriate power allocation amongst all the converters. Researchers have shown considerable interest in this promising area due to the non-triviality of the control design. Researchers are using multiple BICs with coordinated control or single BIC with multiple layer Proportional Integral Derivative (PID) control schemes for BIC to act as grid supporting grid forming (GSGFM) or grid supporting grid feeding (GSGFE) unit. Moreover, fixed roles has been assigned to RDG and BESS based bidirectional DC-DC converter (BDDC). In this thesis, there are two major contributions related to the control of hybrid network: first being is to present Model Predictive Control (MPC) based control for hybrid network. A simple model for the BIC has been used through which it can act as grid supporting GSGFM unit to regulate either AC-DC voltage or GSGFE unit to regulate AC-DC power sharing. The efficacy of proposed controller is simulated with realistic considerations and show improved steady state and transient performance with more accurate power allocation amongst all the converters along with detailed comparison with traditional PI based dual-droop control. The second part of our work considers converter-based DC microgrids comprising of RDG and battery energy storage systems (BESS), which are being integrated into power systems infrastructure at rapid pace. For better performance and reliable operations, it is envisioned that RDG, BESS along with loads will form microgrids which can strengthen grid resilience, operate autonomously while the main grid is down, help mitigate grid disturbances as well as function as a grid resource for faster system response and recovery. For autonomous operation power converters will be assigned the role of Grid Supporting Grid Forming (GSGFM) units for voltage regulation and Grid Supporting Grid Feeding (GSGFE) units for current regulation. The architecture of a consensus-based energy management system (EMS) is presented with MPC based variable weighing factor algorithm for power converters of RDG and BESS to act as GSGFM DG or GSGFE DG for both islanded and grid connected mode. Taking existing control schemes, their voltage regulation capability (GSGFM), current regulation capability (GSGFE) and mode changing capability is discussed to maximize the usage and improve the performance of power converters. The basic design principal of our proposed EMS is to maximize the usage of controllers of all the DG units of microgrid by assigning them the role of GSGFM DG or GSGFE DG as per their power handling capacity and grid loading conditions; thus, achieving the good steady-state performance with THD less than 1.1% and quick dynamic response with settling time less than 0.06 sec. These results will help in achieving the reliable and autonomous operation of hybrid MG with multiple DGs. Pakistan is the sixth largest nation in the world with around 51 million people (20% of the population) living off grid with no access to electricity. The proposed algorithm will aid in offering the off-grid solution to those areas, which are not connected to the grid.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BIC	Bidirectional interlinking Converter
BESS	Battery Energy Storage System
DG	Distributed Generation
FCS-MPC	Finite Control Set Model Predictive Control
GSGFM	Grid Supporting Grid Forming
GSGFM DG	GSGFM Distributed Generation Unit
GSGFE	Grid Supporting Grid Feeding
GSGFE DG	GSGFE Distributed Generation Unit
GSGFMI	Grid Supporting Grid Forming Inverter
GSGFMR	Grid Supporting Grid Forming Rectifier
GSGFMD	Grid Supporting Grid Forming DC/DC converter
GSGFEI	Grid Supporting Grid Feeding Inverter
GSGFER	Grid Supporting Grid Feeding Rectifier
GSGFED	Grid Supporting Grid Feeding DC/DC converter
HESS	Hybrid Energy Storage System
MG	Microgrid
MPC	Model Predictive Control
PV	Photovoltaic
PID	Proportional integral Derivative
RDG	Renewable Distributed Generation
SMC	Sliding Mode Control
2L-VSC	Two-Level Voltage Source Converter

Chapter 1

Introduction

Today power grids are predominately AC due to historical development and practical advantages, the increasing efficiency of DC technology and its suitability for modern energy systems are driving a gradual shift. In the past, AC grid concept was predominantly adopted because transformers were available for easy and efficient change in voltage levels needed for distribution and transmission. Transformers were used to increase the voltage levels required for power transmission and then reduce to voltage levels suitable for distribution and utilization [1]. The advancements in solid-state devices, power converter topologies, and control techniques have significantly contributed to the increased deployment of HVDC transmission lines. This development will increase the need for an integration of DC system with conventional AC system in foreseeable future. Not only HVDC but these advancements have also generated great interest in medium-voltage DC system (MVDC) and low-voltage DC system (LVDC) [2]. Efforts to mitigate CO_2 emissions and climate change are also encouraging the use of DC power systems in AC distribution & transmission networks. Moreover, RDG units such as solar, biomass etc. and BESS provide DC power as their interface with DC grid and DC transmission lines is relatively easy with plug & play capability. Keeping in view the increasing penetration of DC systems, it is imperative to transform conventional power grid into a hybrid network [3]. In hybrid network, both AC and DC sub-grids are connected through large & highly efficient power converters known as bidirectional interlinking converter (BIC). Adding to previously mentioned advantage of DC transmission line with AC supply, it can be concluded that usage of BIC allows to reduce the number of stages required for AC to DC conversion in a hybrid network as compared to conventional power systems which there is an inverter or rectifier for each DC source & load.

Above description clearly shows that there is still much work needs to be done about implementation of hybrid AC-DC networks. Most of the industrial and home appliances are designed for AC power supply however they internally operate on DC power and AC is converted into DC by rectifier. Some of those appliances may work with DC supply as well but large number of devices will have compatibility issues with DC supply. Similar issues arise while developing infrastructure for hybrid AC-DC network since AC and DC supply cannot be provided to every point of the network. In this thesis our primary focus is on the control of hybrid AC-DC networks, with special emphasis on control of BIC and DC/DC converters. A detailed background on existing control topologies is presented along with the proposed control algorithm. Two major contributions related to the control of hybrid AC-DC network are presented: first being is to present Model Predictive Control (MPC) based distributed control for bidirectional interlinking converter (BIC) in hybrid AC-DC network. A simple model for the BIC has been used, through which it can act as GSGFM unit to regulate either AC-DC voltage or GSGFE unit to regulate AC-DC power sharing. The second part of this work considers converter-based DC microgrids comprising of RDG and battery energy storage systems (BESS), which are being integrated into power systems infrastructure at rapid pace. Both of these contributions will help in achieving the reliable and stable operation of hybrid microgrid with multiple DGs.

1.1 Background

United Nations General Assembly (UNGA) devised 17 Sustainable Development Goals (SDG) out of which SDG # 7 is to "Ensure access to affordable, reliable, sustainable and modern energy for all" [4]. Basic purpose of SDG is to increase coordinated efforts to decrease the proportion of world population without access to electricity. As a result, the global population without access to electricity decreased to about 840 million in 2017 from 1.2 billion in 2010 [5]. Progress in expanding access to electricity was made in several countries, notably India, Bangladesh, and Kenya. According to the World Bank, 90 percent of the world's population had access to electricity as of 2018 [6]. One of the major efforts to achieve SDG is to implement microgrids all over the world with 8,203 microgrids providing 36,700 MW of power [7]. Around 60% deployment of microgrids have been in the regions of North America and Asia Pacific. These two regions accounted for 40% and 20% of total deployments. Asia Pacific has large deployments due to small scale remote microgrids under rural electrification program while North America has much higher levels of deployment in the commercial and industrial space. Projects like Bright Indonesia [8], Power Africa - Beyond the Grid [9], Smart Power India [10] are leading the way for remote microgrid deployment. Approximately 96.6% of the population without access to electricity lives in developing countries, and 79% lives in rural areas [11]. Microgrids are a small group of generating units and loads operating independently or connect to main grid. As compared to centralized generation, Microgrids favors distributed generation thus reducing transmission losses. Microgrid can be categorized as shorter version of electricity grid, which operates in lower medium voltage networks. It consists of renewable distributed generation (RDG) units i.e., solar, wind etc. and energy storage systems i.e., batteries, super capacitors etc.

and controllable loads (e.g., air conditioners) [12].

Microgrid operate in both modes grid connected as well as islanded mode [13]. It can separate themselves from central grid, thus operating in islanded mode [14]. Microgrids are most suitable for off-grid electrification programs in rural areas and islands where the traditional grid cannot reach in the near future as shown in figure 1.1. Also, microgrids can supply electric power to isolated systems like far-off telecom infrastructure, electric vehicles, space crafts, data centers [15–18].

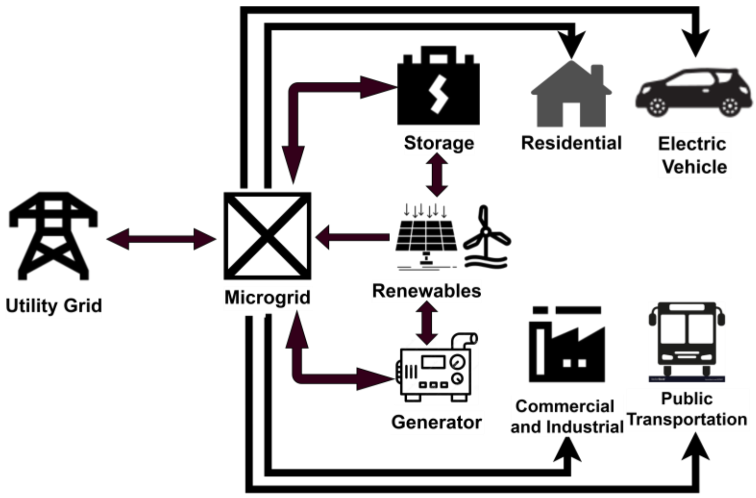


Figure 1.1 Typical Microgrid with multiple RDG and consumers [30]

Traditional electrical networks consisting of unidirectional power flow from generation side to distribution side to the consumer side is experiencing a major transition to a diverse transmission & distribution network with bidirectional power flow capability [19].

The salient features of microgrid are as follows: [20-22]:

- Operation in both modes i.e., grid connected mode and islanded mode.
- Provide low-cost and clean energy.
- Reduce CO_2 carbon emissions-based generation units.
- Incorporate power generation from variety of sources.
- Help mitigating transmission losses.
- Provide net metering option by selling electricity to the utility.
- Quickly deployed as compared to the traditional power plants.
- Provide distributed generation as compared to the traditional centralized generation.
- Microgrid presence strengthens the utility as well.
- Microgrid in combination with regional power grid can incur less capital cost, high reliability, less operational cost and cheap electricity for customers.

In microgrid all the local sources including RDG, BESS etc. are responsible for regulating the voltage and power, rather than relying on voltage and current regulation from main grid [23]. In recent years, industrial development and the increase in population have led to the rise in the industrialization of the whole world [24]. As industrialization increases, energy demand has increased for those industries. An increase in energy demand gives rise to the energy crisis, which is considered a significant problem globally [25]. Imbalances in electrical generation and demand, along with system faults, are significant challenges that lead to power outages and blackouts, impacting the economy and social life [26]. Conventional power sources such as fuel-based power plants or generating units cannot fulfil the rising energy demands. With the rising cost of fuel and the environmental impact of fuel-based plants, conventional power plants are discouraged [27]. So, it led to increased use of a clean form of energy to generate electricity, and the biggest source is renewable distributed generation (RDG) based power plants integrated with the conventional grid. RDG consisting of solar, wind, wave, tidal, biogas, biomass, etc., is used for electricity generation. Amongst these, solar and wind are the most abundantly available and used worldwide as the most primary and reliable sources of electricity [28]. So traditional power generation with depleting fossil fuel resources is now replaced with an increasing RDG penetration along with technological development of efficient wind power plants & solar panels, making microgrid a viable and prominent solution. RDG’s are a possible replacement or solution to the problems posed by conventional fossil fuels. They also can meet load demand and produce clean energy with no direct CO_2 emission, thus reducing the effects of pollution, climate change and providing the other environmental & human health benefits [29].

1.1.1 Operating modes of Microgrid

There are two modes of operation for microgrid:

i. **Grid Connected Mode**

In this mode, utility is supplying power to the microgrid through the Point of Common Coupling (PCC). Power flow from the grid takes place to keep the power balance. Following points state the operating modes for microgrid:

1. When the microgrid is operating in grid-connected mode, voltage regulation will be done by the utility and current regulation will be done by the local controllers [31].

ii. **Islanded Mode of Operation**

Microgrids have the capability to provide electricity in case of any grid fault or scheduled maintenance by isolating themselves from utility. This mode is called as islanded mode. All the functions performed by utility in grid connected mode are performed by converters in islanded mode. When the microgrid is operating in islanded mode, voltage regulation and current regulation will be done by the local controllers [32]. Microgrid work independently with all RESs, BESS and load with all having their respective controllers [33]. Load prioritization is sometimes needed in this mode as electricity generation in this mode is all dependent on local RDG or BESS sources which might not be able to fulfill load all the time. So, load shedding strategy is employed in case of inadequate supply of electricity [34].

1.1.2 AC, DC & Hybrid MG System

The importance of microgrids based on their supply to the load is explained below:

1. **DC Microgrid**

DC microgrid with RDG such as wind, PV etc., BESS and load are shown in Fig. 1.2(a). All sources are connected to the DC bus through their converters. DC bus is connected to the utility grid through the bidirectional interlinking converter (BIC) for power-sharing between utility and DC loads. DC microgrids can offer higher efficiency and lower conversion losses compared to AC microgrid systems when supplying DC loads directly [35]. Nowadays, DC electronic loads are growing in popularity as more electronic devices convert and store energy. Modern devices such as laptops, phones, desktop computers, tablets, electric ovens, printers, TVs, batteries and super capacitors require DC power. DC power is now needed in major residential and industrial applications such as renewable energy park, Electrical Vehicles, hybrid energy storage systems, telecom stations, data centers, DC powered community homes and electric ships [36-38]. Modern day loads are AC based loads so DC supply is converted to AC through the inverters, having conversion losses being the disadvantage. Also, voltage drops are a major problem in DC based distribution system. The voltage level is low at the far end of the network, requiring an voltage booster in DC microgrid distribution network.

2. **AC Microgrid**

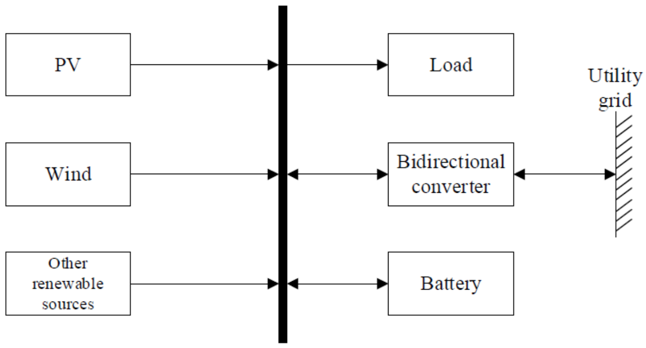
AC microgrids are easily connected with the utility as they supply AC power [39]. Figure 1.2 (b) shows the AC MG having RDG such as solar, wind, battery and load. All the modern loads are AC based so AC MG is more preferable and major R & D has been done on AC MGs [40]. The advantage of the AC microgrid as compared to DC microgrid is that it connects with the grid directly [41]. The disadvantage is that its operation, control & management is complex [42].

3. **Hybrid microgrid**

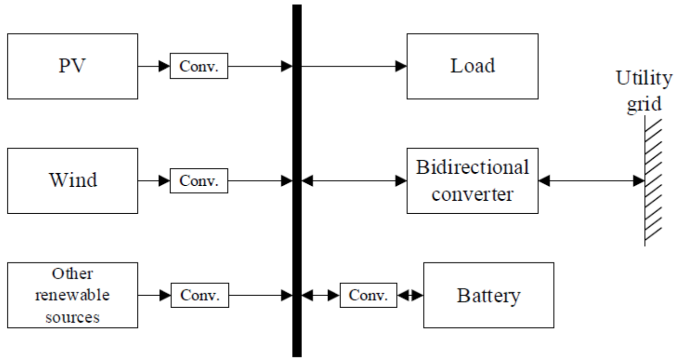
The microgrids consisting of both AC and DC microgrids are known as Hybrid microgrids. In a hybrid microgrid, both AC and DC grids are connected through a bidirectional interlinking Converter (BIC) [43], as shown in Figure 1.2 (c). Both AC and DC buses are connected through BIC. All the AC loads and utility supply directly connects to the AC bus. DC-based RDG such as wind, PV etc., battery and load directly connects to the DC bus. A major advantage of the hybrid AC-DC microgrid is that it provides flexibility for integration of BESS with the grid to store electricity that can provide support for advanced grid functions i.e. grid voltage support, ancillary support, etc. [44]. Thus, hybrid AC-DC microgrid contains both the advantage of DC microgrid and AC microgrid [45].

The second target of SDG # 7 is to substantially increase the share of renewable energy in the global energy mix. Power generation from conventional fuels including furnace oil (FO), gas, LNG, etc., has serious environmental issues as well as they have got low energy efficiency. The addition of over 300 GW of renewable energy in 2023 has elevated the penetration level of renewables in the global electricity mix to around 30% [46]. These advantages of incorporating renewable energy are:

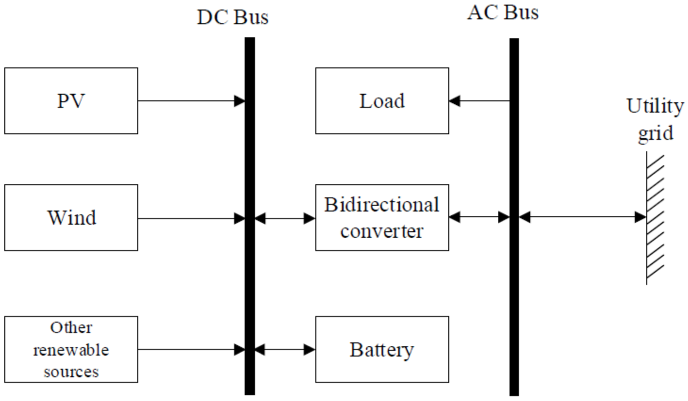
- High efficiency as compared to traditional power plants.
- Cheap electricity as compared to fuel-based power plants.
- Less transmission losses as local RDG units will be near to loads.
- More reliable as microgrid can operate in islanded mode in case of utility grid black out.
- Can be used as off-grid source to provide electricity to far-off rural areas where utility grid can't be provided due to high cost of laying transmission line infrastructure.



(a) DC microgrid



(b) AC microgrid



(c) Hybrid AC-DC microgrid.

Figure 1.2 Microgrid classification

Microgrids with multiple RDGs generate electricity for residential and industrial consumers [47]. Due to the low power generation capacity of RDG, a combination of one or more RDG has led to the concept of a more sustainable microgrid. Also, one RDG cannot guarantee the stability and security of a microgrid. A microgrid has the advantage of multi-sources power generation capacity & reliability with efficient supply to local loads and possible integration with the conventional grid [48]. So multiple RDG are used as distributed generation (DG) units to ensure an uninterrupted supply of electricity to all the residential and industrial consumers. Battery Energy Storage Systems (BESS) can be used to increase the penetration of RDG in a power system, but there is equally essential to optimize their capacity as well as location as per requirement. The primary objective of using BESS in combination with RDG is not to eliminate conventional and polluting generation units, but rather to decrease the no. of units required to stabilize RDG in the hybrid microgrid [49]. Such no. of units required to complement RDG in the hybrid microgrid are typically the not efficient rather they are very expensive, such as gas turbines or diesel generators. By reducing the use of these units through the use of BESS, costs and greenhouse gas emissions can be eliminated. As the costs of RDG & BESS are decreasing rapidly with continuously maturing underlying technology, RDG and BESS plants are now economically viable to both consumers as well as independent power producers [50]. So that leads to give high cost benefit ratio for PV and BESS plants as compared to standalone solar plants [51]. Moreover, the number of deployments of PV and BESS projects are increasing with power production of 36 GW in 2018 as compared to 19 GW in 2017 [52].

With RDG units supplying power, bidirectional power flow is the need of an hour for an electrical network [53]. More emphasis should be given to developing a sustainable electrical distribution network in developing nations to encourage this huge transition in the distribution network [54]. In contrast, developed countries should address this transition's technical and economic challenges. It requires integrating intelligent supervisory control based smart system which should be flexible as well [55]. An active intelligent distribution network utilizes future technologies to harvest clean, renewable energy to adopt the concept of smart-grid/microgrid. Factors such as reduction of carbon emissions by 50% till 2050, increase in demand for highly reliable power supply distribution, more contribution of RDG in the power mix, better utilization of network assets and their management by network operators etc. are also favoring the deployment of an active, intelligent distribution network [56]. Microgrids plays an essential role in transforming the centralized power system toward the decentralized & distributed power system. For this, microgrid requires superior energy management system (EMS) to achieve stable, sustainable, economical and continuously running operation [57]. In this thesis, EMS with suitable control hierarchy has been discussed in great detail in Chapter 3 and 4.

An important question is as per convention going on in the world for last century, grids should remain AC or not. AC grid concept was adopted due to the fact that transformers were available for easy and efficient change in voltage levels needed for transmission and distribution. Recent efforts in increasing the efficiency of power converters led to production of comparable efficient DC/DC converters which can perform same adjustments in DC power system [58-63]. DC power system has its own advantages:

- It does not need utility grid to regulate voltage and power.
- It has high transmission efficiency; since no reactive power is involved here as compared to AC power system.
- Power transfer ratio for a given conductor is high.
- Better voltage regulation and transfer of power over long distances is possible since no reactive power is involved.

- Quickly deployed as compared to the AC grid.
- Provide distributed generation as compared to the traditional centralized generation.
- RDG units such as solar, biomass etc. and BESS provide DC power so their interface with DC grid is relatively easy with plug & play capability.
- Microgrid in combination with regional power grid can incur less capital cost, high reliability, less operational cost and cheap electricity for customers.

Above mentioned advantages lead us to the hybrid network paradigm with both DC & AC grids connected to each other via BIC. This configuration has substantial advantages; although it also requires an efficient control for BIC as well as AC and DC sources [64]. In hybrid microgrid, both AC & DC sub-grids are connected through BIC as shown in Figure 1.3. BIC is responsible for integration of all DGs, BESS and load in both microgrids. Moreover, GFM operations and GFE operations for voltage & current regulation in both microgrids is ensured.

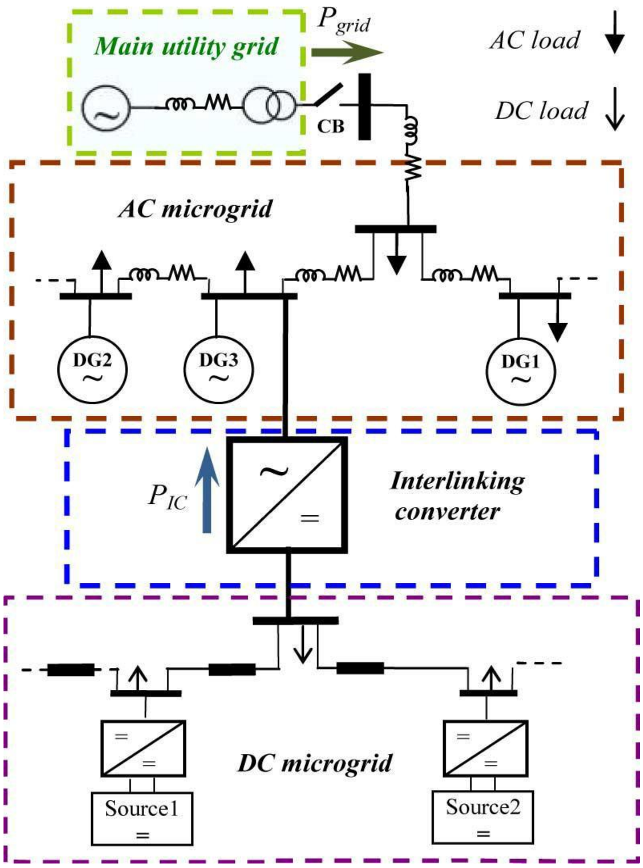


Figure 1.3: BIC in hybrid microgrid [67]

In hybrid AC-DC networks, voltage regulation is ensured by Grid Supporting Grid Forming (GSGFM) converter and current regulation is ensured by Grid Supporting Grid Feeding (GSGFE) converter [65]. GSGFM converters provide voltage regulation that can be represented as an ideal DC voltage while GSGFE converters provide current regulation that can be represented as an ideal current source connected to the grid in parallel with high impedance [66]. The major difference between Grid Forming (GFM)/Grid Feeding (GFE) and GSGFM/GSGFE is that latter type of converters can regulate voltage and current in both grid connected and islanded mode [67]. In this thesis MPC is being implemented on BIC and bidirectional DC/DC converter to act as GSGFM/GSGFE to regulate voltage and current without changing their configuration.

1.2 Research Gap

Following research gaps have been addressed in this thesis:

1. Single BIC with single loop control configuration capability to act as GSGFM inverter (GSGFMI) or GSGFM rectifier (GSGFMR) unit for regulating voltage (AC voltage or DC voltage) or as GSGFE (GSGFEI or GSGFER) unit for power sharing (AC power sharing or DC power sharing) is not yet achieved. BICs can only act as GSGFM (GSGFMI or GSGFMR) unit to regulate either AC voltage or DC voltage or GSGFE (GSGFEI or GSGFER) unit to regulate AC-DC power sharing using single layer Proportional Integral Derivative (PID) control scheme [68]. Then by using either multiple BICs with coordination control or multiple layer PID control schemes, BICs are able to achieve multiple roles of GSGFM and GSGFE units to control multiple variables such as AC voltage, DC voltage and power sharing of AC & DC microgrids. There are some inherent issues associated with PI such as Pulse Width Modulation (PWM), PID parameter tuning, cascading scheme delayed response issue, complex coordinate transformation, complex architecture in case of multiple BICs etc. While PI control is a widely used control technique in power systems, it has limitations when it comes to handling the non-linear complexities of the grid such as those caused by renewable energy sources, energy storage systems, and other distributed energy resources.
2. RDG are only used as GSGFE DG because of their intermittent nature i.e. their output is subject to changes due to weather conditions, cloud cover, and other factors [69]. So, RDG is used to regulate power only. But RDG at their rated power can be used as GSGFM DG. RDG based DC-DC converter with single loop control configuration capability to act as GSGFMD for regulating DC voltage or as GSGFED for DC power sharing is yet to be explored [70].
3. The primary objective of using BESS in combination with RDG is not to eliminate conventional and polluting generation units, but rather to decrease the no. of units required to stabilize RDG in the hybrid microgrid [49]. Such no. of units required to complement RDG in the hybrid microgrid

are typically the not efficient rather they are very expensive. Offsetting the consumption of those units can bring average unit cost down and greenhouse gas emissions. Using RDG as GSGFM DG can help to diminish the use of BESS.

4. In islanded mode, BESS are operated as GSGFM units to regulate voltage. Charging of BESS is done in two stages. In first stage, charging is done on the basis of difference between generated and load power. So, charging current is limited and BESS operate as GSGFM unit. In second stage, as BESS achieve threshold voltage (almost fully charged), its voltage must be kept constant and for that BESS should operate as GSGFE unit, so that its current begins to taper approaching asymptotically to zero, while charging continues. The authors have adopted and refined this idea based on [71].
5. MPC is used to operate PV & BESS in GSGFE modes [72-73]. MPC can be used to operate PV in both GSGFM and GSGFE modes but it will need to devise multiple control objective in MPC cost function. MPC provides a framework for multiple control objectives in a cost function by associating weighing factor with each objective. It is worth pointing out that, the performance of MPC is deeply influenced by the weighing factors, the tuning of which is still a challenge to be undertaken [74-75].

1.3 Problem Statement

This thesis discusses two major issues related to control of hybrid AC-DC network. These issues are as follows:

1. The first challenge is that BIC has been used to transfer power from AC Microgrid to DC Microgrid and vice versa in hybrid AC-DC microgrids. BICs can only act as GSGFM unit to regulate either AC voltage or DC voltage or GSGFE unit to regulate AC-DC power sharing. Then by using either multiple BICs with coordination control or multiple layer Proportional Integral Derivative (PID) control schemes enabling BICs to achieve multiple roles of GSGFM and GSGFE units to control multiple variables such as AC voltage, DC voltage and power sharing of AC & DC microgrids. There are some inherent issues associated with this approach such as Pulse Width Modulation (PWM), PID parameters tuning, cascading scheme delayed response issue, complex coordinate transformation, complex architecture in case of multiple BICs etc. While Proportional-Integral (PI) control is a widely used control technique in power systems, it has limitations when it comes to handling the non-linear complexities of the grid such as those caused by renewable energy sources, energy storage systems, and other distributed energy resources.
2. The second challenge is the regulation of voltage (GSGFM) and power (GSGFE) in both

AC and DC networks with RDG and BESS. For stable operation, there should be one GSGFM DG to regulate voltage and other units available as GSGFE DG. So, in case of hybrid RDG plus BESS networks, at least one of the two networks should act as GSGFM while other can act as GSGFE. While in case of dual PID control loop approach, roles are fixed for BESS acting as GSGFM and RDG with intermittent nature acting as GSGFE, respectively. Moreover, in comparison to RDG, BESS units are much expensive and inefficient in performance. Therefore, the overall cost of electricity is increased due to excessive use of BESS DG that can be reduced through RDG acting as GSGFM.

1.4 Research Objectives

So, main objectives of this research are as follows:

(1) To propose multi-variable controlled MPC algorithm of BIC in hybrid microgrid.

(2) To propose multi-variable controlled MPC algorithm of bidirectional DC/DC converter in hybrid microgrid.

(3) To implement coordinated control of MPC based BIC and DC/DC converters in hybrid microgrid.

1.5 Contributions

In order to achieve mentioned objectives, following contributions are made in this research:

1. A consensus-based Energy Management System (EMS) with MPC based variable weighing factor algorithm is proposed for all the DGs to operate in either GSGFM or GSGFE mode in all non-linear conditions by performing multi-variable control using auto-tuned weighing factors in the hybrid cost function. Only one hybrid cost function is used for all the DGs, so transients related to sudden change of cost function do not occur. By incorporating auto-tuning weighing factors into the MPC cost function, every DG will have capability to switch between GSGFM & GSGFE. This method directly affects the robustness and overall performance of the proposed MPC controller in abnormal or fault conditions. In this method, calculations to select optimal weighing factors are performed in every sampling interval. The weighing factors are calculated dynamically, such that highest priority is assigned to a given objective which has large error that should be corrected. So, weighing factor represents the urgency of correcting the largest error.

2. MPC based variable weighing factor algorithm is proposed for BIC to regulate the highest deviated parameter (AC-DC voltage or power) in all non-linear conditions by performing multi-variable control using variable weighing factor algorithm. The proposed algorithm enables BIC to act as a GSGFM DG (GSGFMI or GSGFMR) or GSGFE DG (GSGFEI or GSGFER). The

control objectives are to regulate voltages & power (both AC and DC) to their reference values in steady state.

3. MPC based variable weighing factor-based algorithm is proposed for RDG to operate in either GSGFM or GSGFE mode in all non-linear conditions by performing multi-variable control using auto-tuned weighing factors in the hybrid cost function. Traditionally RDG are being used as GSGFE in standalone mode but proposed variable weighing factor based MPC framework allows RDG DGs to act as GSGFM DG to regulate voltage and GSGFE DG to regulate power.

4. MPC based variable weighing factor-based algorithm is proposed for BESS to operate in either GSGFM or GSGFE mode in all non-linear conditions by performing multi-variable control using auto-tuned weighing factors in the hybrid cost function. Traditionally BESS is being used as GSGFM in standalone mode. Proposed variable weighing factor based MPC framework allows BESS to act as GSGFE DG to regulate power with RDG acting as GSGFM DG regulating the voltage. BESS act as GSGFM DG only when RDG is unable to act as GSGFM DG.

1.6 Structure of Thesis

The organization of the thesis is as follows:

Chapter 2 consists of the introduction of the hybrid AC-DC microgrid with literature review on hybrid Microgrid control and MPC application on it.

Chapter 3 consists of notable contributions to control of BIC in hybrid AC-DC microgrids followed by the technical details and results of our proposed methodology.

Chapter 4 consists of notable contributions to control of bidirectional DC-DC converter in hybrid AC-DC microgrids followed by the technical details and results of our proposed methodology.

Chapter 5 consists of notable contributions to control of hybrid AC-DC microgrids using MPC followed by the technical details and results of our proposed methodology.

Finally, thesis is concluded in Chapter 6 with a summary of key findings of our research followed by a discussion on the open research problems/future works in this domain.

Chapter 2

Introduction to Hybrid AC-DC microgrid

2.1 Introduction

A transition from conventional electrical power systems to hybrid AC-DC network is discussed in detail in chapter 1. In this chapter, a detailed and comprehensive literature review of applications being considered in relevant areas is laid out i.e. BIC & hybrid AC-DC networks, DC/DC converters based microgrids and role of model predictive control. In each application the literature review is discussed followed by summarizing the gaps to which our proposed methodology provides a solution. For conciseness and readability, the summary of existing literature is explained at the end of each application followed by explaining that how our proposed methodology differs from existing literature.

The work in the thesis is best understood with some background in power system modelling and control of BIC and DC/DC converters in hybrid AC-DC microgrid. For this reason, an overview of the operation modes of the microgrid and types of microgrids has already been discussed in first chapter. The detailed literature review on control of single/multiple BIC's using dual loop PID control method in hybrid microgrids is first discussed. Then present application of MPC on control of BIC in hybrid AC-DC microgrid will be discussed. After that, literature review on PI & MPC based control of DC/DC converters is presented.

2.2 Literature Review

This section describes the recent work on control of hybrid Microgrid control and MPC application on it. Then it describes the recent work on control of DC/DC converter and MPC application on it.

2.2.1 Hybrid AC-DC microgrid

2.2.1.1 Single BIC topology

A centralized primary power control of a hybrid AC-DC MG with PV, wind, diesel and BESS were proposed [76]. MPPT technique has been used to regulate the pitch angle of wind turbine to regulate dc bus voltage at constant value as shown in figure 2.1. Solar panels are being used to regulate dc bus voltage using MPPT technique as well. Battery storage system also regulates the dc bus voltage by charging or discharging keeping in view the dc grid voltage situation. Diesel generator is being used to stabilize AC grid frequency in case of power mismatch between load and source. All the above-mentioned sources do not achieve power sharing once there are unbalanced and nonlinear loads in Microgrid.

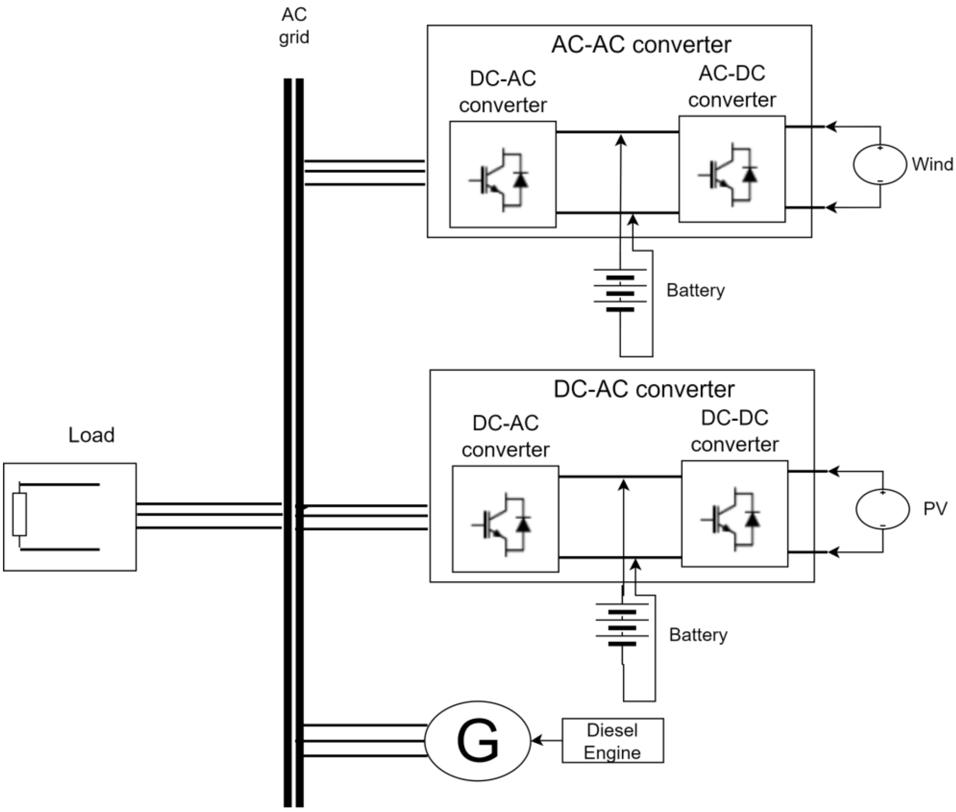


Figure 2.1 Centralized primary power control of a hybrid Microgrid [76]

A new control design methodology for BIC in hybrid microgrid was proposed to control dc microgrid voltage thus regulating the power flow between DC microgrid and AC microgrid was proposed [77]. Hybrid microgrid consisted of one AC DG and load, one DC DG and load and one bidirectional interlinking converter. By using proposed control design strategy, voltage reference tracking was improved and voltage disturbance rejection had been achieved. But the proposed strategy couldnot do global power sharing between both the microgrids. Also, it acted as voltage slack only for DC microgrid. It did not regulate voltage on AC microgrid.

A two-layer control topology for optimal economic hybrid MG was proposed [78]. One layer ensured economic power dispatch for AC and DC microgrids while other layer ensured smooth power flow management by implementing three levels i.e., primary, secondary and tertiary control for BICs as shown in figure 2.2. Hybrid microgrid consisted of three DGs and three loads in DC and AC microgrid respectively. Slack terminals had been implemented in both the microgrids which are responsible for maintaining DC voltage and AC frequency and their economic dispatch as well. Controller of bidirectional interlinking converter would optimize power flow between the microgrids. But the performance of proposed two-layer control scheme was not reported under islanded conditions or conditions where slack terminals were not being able to control voltage or frequency and addition of new load as well as non-linear load.

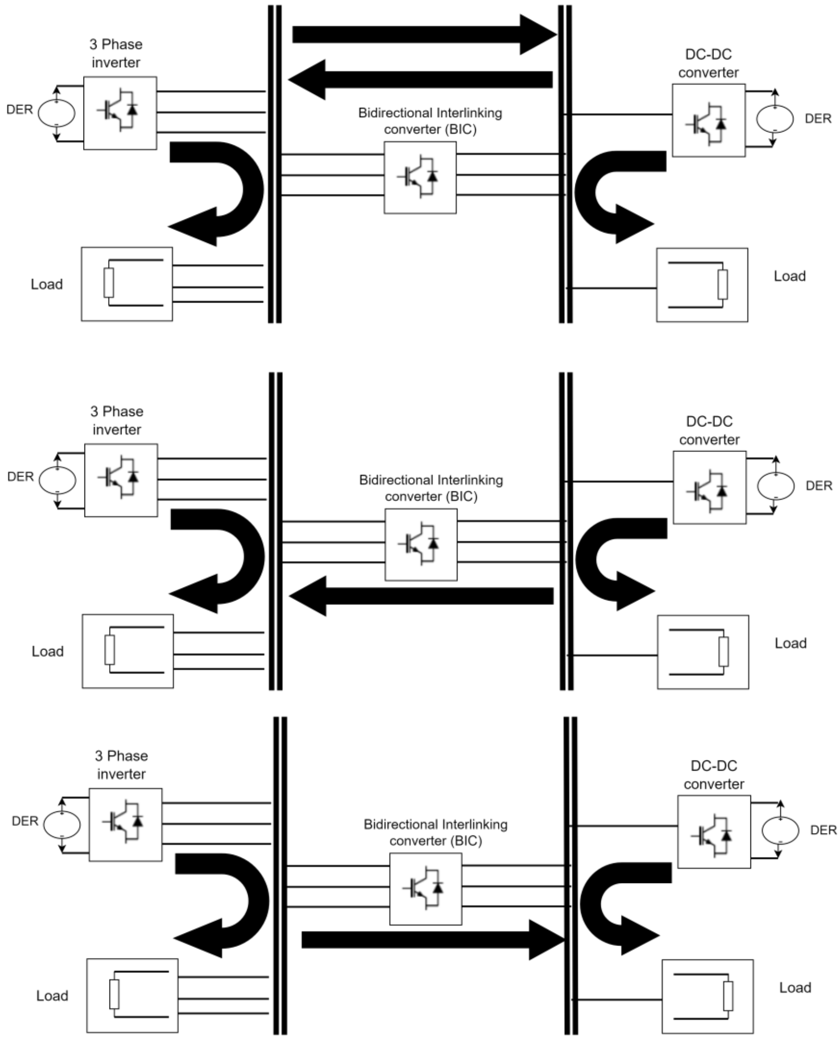


Figure 2.2 Two-layer control scheme for Hybrid AC-DC Microgrid [78]

A modified unified interphase power controller (UIPC) to optimize power flow in hybrid microgrids was proposed [79]. Hybrid microgrid consisted of one AC & DC Microgrid. In contrast to conventional UIPC, the modified UIPC had two controllers, one as line power converter (LPC) to control power flow and other one as bus power control (BPC) to regulate the DC bus voltage. But the proposed UIPC would not regulate AC voltage in islanded mode. Also, performance of UIPC against non-linear and additional load had not been reported.

A distributed coordination control among bidirectional interlinking converter and secondary controllers of hybrid microgrid was proposed [80]. The control architecture optimized power flow as well as control DC Microgrid voltage and AC Microgrid frequency. Hybrid AC-DC microgrid consisted of three DGs and one load each in DC and AC Microgrid. The proposed control architecture worked well under increased load in DC or AC Microgrid. However proposed control architecture involved PI controllers which are not robust and gives slow response to disturbances. Also, those controllers had to be reprogrammed with PI parameter tuning in case of addition or loss of DG in either AC or DC Microgrids.

A modified line impedance compensation-based droop control strategy was proposed [81] for bidirectional interlinking converter in hybrid microgrid. The control architecture solved the problem of power deviation caused by voltage drop in droop control. It regulated power sharing and AC microgrid voltage as shown in figure 2.3. Hybrid microgrid consisted of one energy storage system, solar panel & load in DC microgrid as well as one wind turbine, energy storage system & load in AC microgrid. The proposed control architecture worked well under different operating modes as compared to traditional droop control. Droop control had been used to control voltage and power sharing of AC microgrid, which would require equivalent pid gains. Moreover, addition of new DG or load would require the change in pid gain, thus making this technique not realistic to implement for non-linear load. Also, traditional droop controllers limited the ability of a microgrid system to support bidirectional power flow (AC to DC or DC to AC) or to accommodate changes in the system configuration thus acting as a barrier for the expansion of microgrid systems. Moreover, it did not discuss the regulation of DC voltage.

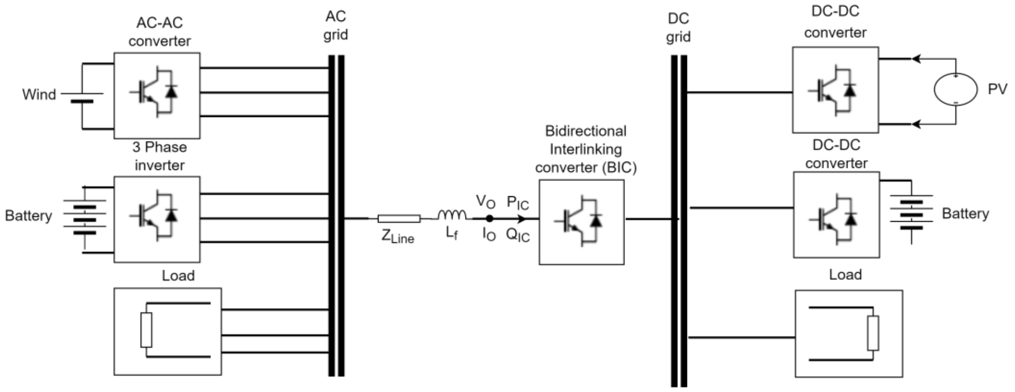


Figure 2.3 Structure of Hybrid Microgrid with modified line impedance compensation-based droop control strategy [81]

A bidirectional droop control strategy based on PI control was proposed [82] for BIC in hybrid microgrid. The control architecture solved the problem of power sharing thus achieving power balance of isolated hybrid microgrid. It regulated current, DC microgrid voltage and AC microgrid frequency. Hybrid microgrid consisted of one ESS, solar panel & load in DC microgrid as well as one wind turbine, energy storage system & load in AC microgrid. The proposed control architecture worked well under different operating modes when compared with conventional droop control. The proposed control strategy allowed more power flow into the microgrid that has greater load demand resulting in balanced power source sharing between AC microgrid power source and DC microgrid power source regardless of the load fluctuations in DC microgrid or AC microgrid. Droop control had been used to control voltage and power sharing of AC Microgrid which would require equivalent pid gains. Moreover, addition of new DG or load would require the change in pid gain, thus making this technique not realistic to implement for non-linear load. Moreover, it did not discuss the regulation of DC voltage.

A three staged droop control strategy based on PI control was proposed [83] for bidirectional interlinking converter in hybrid microgrid. The control architecture solved the problem of power sharing regulation between AC & DC microgrids by regulating power inside individual microgrids. It regulated power sharing in both microgrids. Hybrid microgrid consisted of two sources & one load each in DC microgrid and AC microgrid. The proposed control architecture worked well under different operating modes as compared to traditional droop control. Droop control had been used to regulate power sharing of AC Microgrid which would require equivalent pid gains. Moreover, addition of new DG or load would require the change in pid gain, thus making this technique not realistic to implement for non-linear load. Moreover, it did not discuss the GFM operations of DC and AC microgrid.

A costing based droop control strategy was proposed [84] for bidirectional interlinking converter in hybrid microgrid. The control architecture reduced the cost of power transfer through bidirectional interlinking converter compared with traditional droop control method thus achieving low-cost power balance of isolated hybrid microgrid. It regulated current and DC microgrid voltage. Hybrid AC-DC microgrid consisted of two energy storage systems, two solar panels & load in DC microgrid as well as two wind turbines in AC microgrid. The proposed control architecture worked well under different operating modes when compared with conventional droop control. The proposed control strategy maintained stable operation for wide range of pid gains used for bidirectional interlinking converter, thus working without losing the generality of traditional droop control. But, adaptive droop control strategy to provide response in case of load or DG addition was not discussed which means that addition of new DG or load would require the change in pid gain, thus making this technique not realistic to implement for non-linear load. Moreover, it did not discuss the regulation of AC microgrid voltage in islanded mode.

A control strategy based on two stages control technique for bidirectional interlinking converter connected to energy storage system was proposed for hybrid microgrid [85]. The control architecture improved the quality of power supplied through bidirectional interlinking converter to utility grid as compared with traditional droop control method thus improving the overall flexibility of the hybrid microgrid and providing ancillary services to the utility grid by reducing the harmonics and improving the power factor at PCC. It regulated power sharing and DC microgrid voltage. Hybrid microgrid consisted of one source & load each in DC and AC microgrid. The proposed control architecture worked well under different operating modes when compared with conventional droop control. It was proven that the proposed control strategy had the capability for proposed modified bidirectional interlinking converters to manage the power flow at all operating conditions of hybrid microgrid. However, the presence of multiple BICs made the overall control architecture more complex. Also droop control strategy to provide response in case of DG addition was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not realistic to implement for expandable microgrids. Moreover, it did not discuss the regulation of AC microgrid voltage in islanded mode.

A decentralized control strategy was proposed [86] for BIC in hybrid microgrid. The proposed control architecture did not depend on measurement of variation in frequency and instead used a voltage-controlled method in the control loop. Therefore, the power quality of AC microgrid was improved as well as uniform control property is achieved due to which frequency deviation is reduced. In addition, the proposed control architecture did not use PLL. The proposed control architecture supported plug and play operation for sources in AC or DC microgrid thus providing the uniform control property. It regulated power sharing and DC microgrid voltage. Hybrid AC-DC microgrid consisted of one source & load each in DC and AC microgrid. The proposed control architecture worked well under different operating modes when compared to conventional droop control. The proposed control strategy exhibited excellent dynamic response. Also, stability related issues were resolved by eliminating the delay associated with the PLL dynamics. The proposed control architecture exhibited excellent transient response in case of load changes or unbalanced loads by reducing transient voltage drop significantly. The improvements were much evident in power sharing characteristics of AC microgrid but the proposed control did not discuss the regulation of DC microgrid voltage in grid connected mode.

A distributed power management strategy based on the concept of coordination factors was proposed [87] for hybrid AC-DC microgrid. The proposed control architecture achieved reactive power sharing between all AC distributed energy resources, current regulation between AC and DC distributed energy resources (DERs). It regulated power sharing only in primary layer. Hybrid microgrid consisted of one source & load each in DC and AC microgrid. The proposed control architecture worked well under different operating modes when compared to conventional droop control. The proposed control strategy selected the coordination factor as a tool to overcome the differences among AC and DC distributed energy resources and unified the multi-objective control. Then, bidirectional interlinking converter established a dynamic connection among all distributed energy resources only by extracting the maximum coordination factor of each microgrid, so the communication burden can be significantly reduced and stability & expandability of hybrid AC-DC microgrid can be enhanced. However proposed control architecture involved communication between bidirectional interlinking converter and distributed energy resources. But this strategy could fail during lack of communication or communication delays.

An adaptive droop control algorithm along with a unified power management strategy was proposed [88] for hybrid AC-DC microgrid. The proposed control algorithm dynamically changed droop coefficients of the voltage source converter to ensure maximum utilization of available resources in each microgrid under different operating modes as shown in figure 2.4. So better power sharing for intra and inter microgrid in a hybrid microgrid was achieved as compared to traditional droop control method thus improving the overall flexibility of the hybrid microgrid. It regulated current and DC microgrid voltage. Hybrid AC-DC microgrid consisted of one solar panel, battery & load each in DC and AC microgrid. The proposed control algorithm worked well under different operating modes when compared to conventional droop control. The proposed control strategy showed that the frequency isolation of the systems is possible to ensure power sharing regulation in all operating conditions for hybrid AC-DC microgrid. Thus, better utilization of resources within each microgrid was achieved due to which less amount of power had to be imported from utility grid and within microgrid as well. However, droop control strategy to provide response in case of DG addition was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not realistic to implement for expandable microgrids. Moreover, it did not discuss the regulation of AC microgrid voltage in islanded mode.

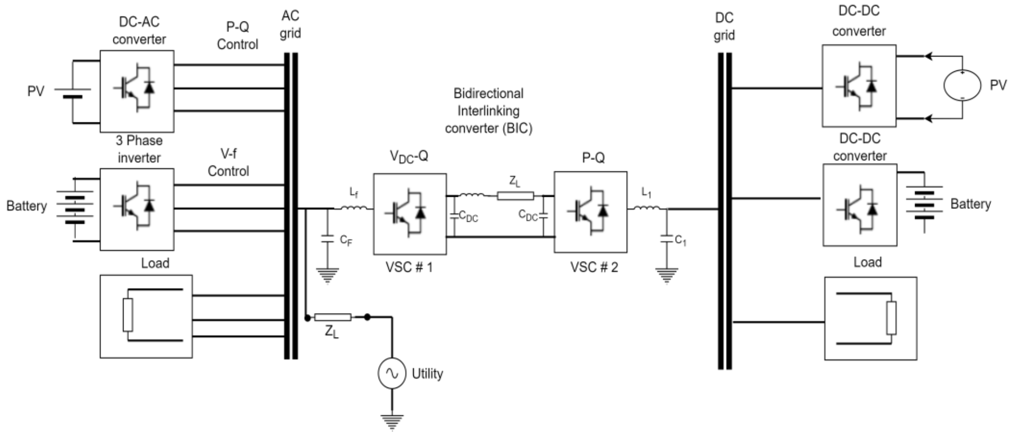


Figure 2.4 Hybrid AC-DC Microgrid with novel adaptive droop control algorithm [88]

An improved coordination control strategy for hybrid microgrid consisting of a bidirectional interlinking converter with energy storage system (ESS) was proposed as shown in figure 2.5 [89]. The proposed control algorithm was designed for hybrid AC-DC microgrids, where distributed ESS's with different state of charges (SOCs) were used along with bidirectional interlinking converters to regulate AC microgrid frequency and GFM operation of DC MG. The above mentioned control method solved issues of power flow burden on bidirectional interlinking converter by supporting DC microgrid voltage and AC microgrid frequency through adaptive SOC based droop control for bidirectional DC/DC converter and bidirectional interlinking converter. The proposed control strategy ensured control structure simplicity, stable operation and easy power interaction between microgrids. Hybrid microgrid consisted of one wind turbine, diesel generator & load in AC microgrid as well as one solar panel, micro turbine and load in DC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. The proposed control strategy showed that by adapting proposed distributed coordinated power control, plug and play capability of multiple bidirectional interlinking converters could be achieved. Thus, if newly enabled or disable bidirectional interlinking converter was modified, then there would be no impact on hybrid microgrid operation. Moreover, control method could operate hybrid microgrid efficiently in case of communication link failures and communication time delay. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, it did not discuss the regulation of AC microgrid voltage and DC microgrid voltage in islanded mode.

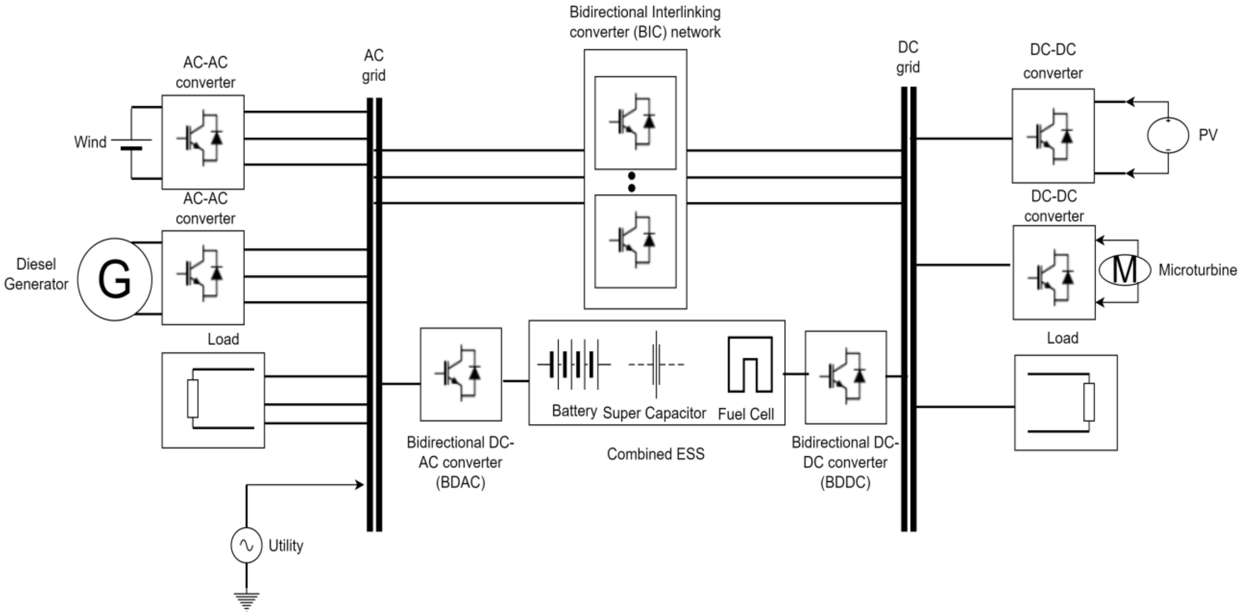


Figure 2.5 Hybrid AC-DC Microgrid with improved coordination control method [89]

A frequency-voltage droop control strategy for BIC linking ESS to AC MG was proposed [90] for hybrid microgrid. A control algorithm was designed for coupling foe DC microgrid voltage with AC microgrid frequency in outer control loop through scaling factor which ultimately gives the droop coefficient. The above mentioned control method solved issues of operating hybrid AC-DC microgrid in a more economical and flexible manner by adapting SOC based droop control strategy through which a battery with high SOC would supply more power as compared to battery with low SOC. So, the proposed control strategy allowed power sharing based on the SOC of the individual battery. Hybrid AC-DC microgrid consisted of two batteries in DC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. The proposed control strategy showed that by reducing switching between different control modes through selection of frequency-voltage droop coefficients, energy losses could be reduced and efficiency could also be improved. Also, in microgrids with different power generation capacity units, it would be critically important to incorporate the relative strength of individual energy storage system. However, droop control strategy to provide response in case of DG addition was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not realistic to implement for expandable microgrids. Moreover, it did not discuss the regulation of AC microgrid voltage in islanded mode.

A novel control method was proposed for AC and DC microgrid [91] in hybrid microgrid. The above mentioned control algorithm was designed for distributed cooperative secondary control of hybrid AC-DC microgrid to restore the AC microgrid frequency & voltage and DC microgrid voltage. The above mentioned control method solved the issues of restoring active and reactive power to their respective reference values thus resulting in better maintenance and more robust operation. Hybrid AC-DC microgrid consisted of one source & load each in AC and DC microgrid. The proposed control algorithm worked well under different operating modes with traditional droop control on primary layer and proposed distributed cooperative secondary control on secondary layer. The proposed control strategy showed that by restoring frequency and voltage accurately, appropriate power sharing amongst AC and DC microgrid could be achieved. Also, in case of communication failures such as communication disconnection or reconnection problem etc. or plug & play occurred, less transient peak was achieved as compared to traditional droop control method. However, droop control strategy to provide response in case of DG addition was not discussed which means that addition of new DG would require the change in PID gain, thus making this technique not realistic to implement for expandable microgrids. Moreover, it did not discuss the regulation of AC microgrid and power sharing in grid connected mode.

A coordinated control strategy was proposed for BIC with ESS [92] in hybrid microgrid. The proposed control algorithm considered a novel hybrid microgrid structure with one central ESS rather than placing energy storage system each at AC and DC MG. The above mentioned control method solved issues of employing multiple bidirectional interlinking converters for a large power transfer. Hybrid microgrid consisted of one source & load each in AC and DC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. The proposed control strategy showed that by using single energy storage system, overall system stability could be improved as well as control complexity could be reduced. Also, issues such as circulating current between multiple interlinking converters, over reliance on bidirectional interlinking converter for power sharing amongst AC microgrid & DC microgrid, unequal state of charge (SOC) between multiple energy storage systems etc. were eliminated using the proposed control strategy. However, droop control strategy to provide response in case of DG or load addition was not discussed which meant that addition of new DG or load would require the change in PID gain, thus making this technique not realistic to implement for expandable microgrids. Moreover, it did not discuss the regulation of AC microgrid voltage and power sharing in islanded mode.

A coordinated AC frequency/DC voltage control (CFVC) strategy was proposed for hybrid microgrid with RDG in AC and DC microgrids [93]. The proposed control strategy was implemented using fractional order proportional integral derivative (FOPID) controllers. Design parameters calculation with respect to set point and controller gains was achieved using bacterial foraging optimization (BFO) algorithm. The proposed control strategy solved the issues of power fluctuations in AC and DC microgrid. Both AC and DC microgrid support each other with respect to changes in DC voltage and AC frequency thus improving the power interactions between AC and DC microgrids. Hybrid AC-DC microgrid consisted of solar panels, wind turbine & load in AC microgrid as well as solar panel, wind turbine, energy storage system & load in DC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. The proposed control strategy showed that by using CFVC droop control, different type and sizes of load in both microgrid could be provided power using optimal current regulation between both microgrids. Also, issues such as poor dynamic response of Proportional Integral, Proportional Integral Derivative controllers etc. have been avoided using the proposed control strategy. However, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation would make this technique not realistic to implement for expandable microgrids. Moreover, it did not discuss the regulation of AC microgrid voltage and power sharing in islanded mode.

A generalized droop control method was proposed for BIC in hybrid microgrid [94]. The proposed control strategy was implemented using 3-dimensional place with each axis responding to change in AC microgrid frequency, DC microgrid voltage and power sharing capability of the bidirectional interlinking converter. Frequency droop control for AC MG and GFM operations for DC MG was implemented for bidirectional interlinking converter to respond to fluctuation in AC MG frequency and DC MG GFM operation. The proposed control strategy solved the issues of both under loading and overloading of both AC and DC microgrid. Both AC and DC microgrid support each other with respect to load changes on DC microgrid voltage and AC microgrid frequency thus improving the power interactions between AC and DC microgrids as well as providing autonomous power transfer without any dependency on any form of communication. Hybrid AC-DC microgrid consisted of power sources & load in both AC and DC microgrids. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. The control strategy inducted three quantities of AC microgrid frequency, DC microgrid voltage and power sharing into the outer control loop along with scaling factor which define the bidirectional interlinking converter voltage and frequency droop. Also, issues such as impact of load changes on DC voltage and AC frequency, transient time, frequency deviations etc. have been solved using the proposed control strategy. However, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation would make this technique not realistic to implement for expandable microgrids. Moreover, it did not discuss the regulation of DC microgrid voltage and power sharing in grid connected mode.

A unified control strategy was proposed for bidirectional interlinking converter in hybrid microgrid [95]. The above mentioned control method removed the various redundant triggering mechanism in order to make the process of mode transition for bidirectional interlinking converter easy as shown in figure 2.6. Mode transition was required for bidirectional interlinking converter to regulate DC microgrid voltage, AC microgrid voltage, AC microgrid power sharing and DC microgrid power sharing. Hierarchical control for hybrid AC-DC microgrid was implemented which consists of both centralized and decentralized control levels in primary, secondary and tertiary level. The proposed control strategy solved the issues of unnecessary triggering mechanisms, not being able to recover from communication failure and to have communication fault ride through capability in bidirectional interlinking converter. Hybrid AC-DC microgrid consisted of solar panel, 1st energy storage system (battery), 2nd energy storage system (fuel cells) & load in DC microgrid as well as micro turbine, wind turbine & load in AC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. The proposed control strategy unified the different control structures of bidirectional interlinking converter with the objective of elimination of mode switching mechanism. Moreover, resilience and reliability of hybrid AC-DC microgrid was enhanced by elimination of inaccurate mode switching as well. However, droop control strategy to provide response in case of DG addition was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not realistic to implement for expandable microgrids. Also, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation would make this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of DC microgrid voltage and power sharing in grid connected mode.

A decentralized bidirectional voltage supporting control strategy was proposed for hybrid microgrid [96]. The above mentioned control method was able to regulate AC microgrid voltage and DC microgrid voltage in case of unintentional islanding event. Droop control based on AC phase angles vs DC voltage along with virtual impedance was proposed for bidirectional interlinking converters to regulate AC microgrid voltage and DC microgrid voltage with seamless mode transition mechanism without additional voltage sources. Also, the proposed control strategy enabled bidirectional interlinking converters to regulate current between AC and DC microgrids without reduction in frequency of AC microgrid during islanded mode as well as operational life of energy storage system could also be prolonged. Hybrid AC-DC microgrid consisted of solar panel, energy storage system (battery) & load in DC microgrid as well as energy storage system (battery), wind turbine & load in AC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. By adopting proposed control strategy, power sharing was done amongst multiple bidirectional interlinking converters as per their power handling capability. Furthermore, in case of power fluctuation in any microgrid, other microgrid would coordinately bear the fluctuation load as per its power handling capability thus ensuring the resilience and reliability of hybrid AC-DC microgrid. However, droop control strategy to provide response in case of DG addition was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not realistic to implement for expandable microgrids. Also, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation would make this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of DC microgrid voltage and power sharing in grid connected mode.

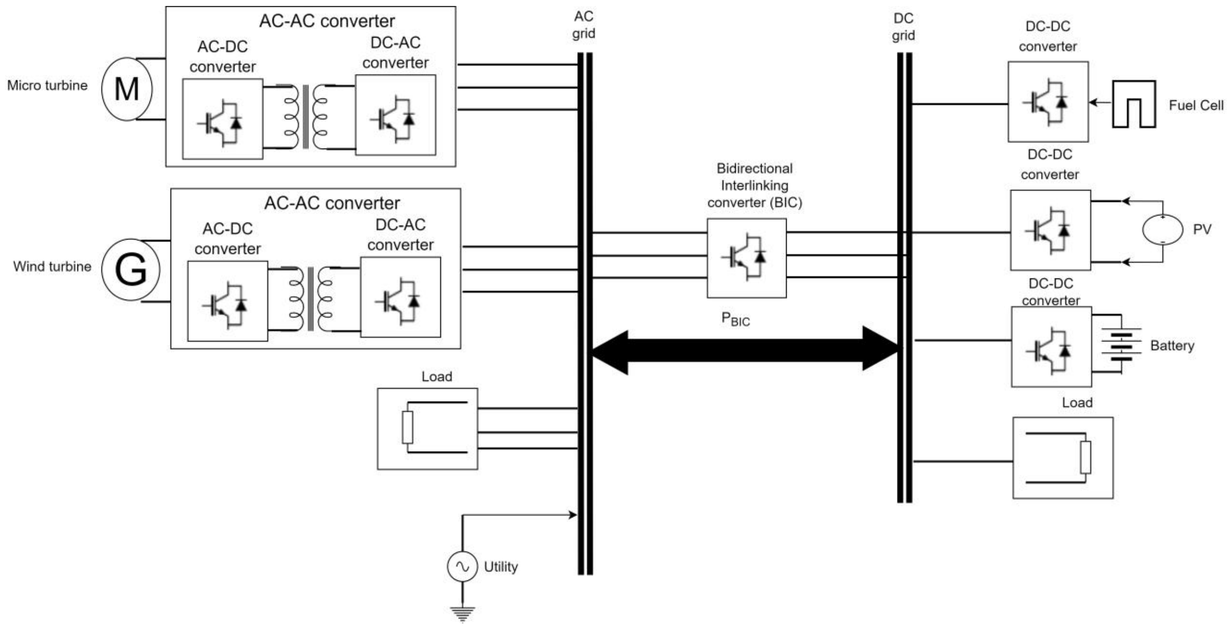


Figure 2.6 Structure of Hybrid AC-DC Microgrid [95]

A new variant of bidirectional interlinking converter coupled with static VAR compensator (SVC) called as hybrid coupled interlinking converter (HCIC) was proposed for hybrid AC-DC microgrid [97]. Moreover, improved droop control was also developed for the proposed HCIC. Droop control based on Active power and power angle (P-δ) and Reactive power, Active power and voltage (Q-P-V) was developed for converter part of HCIC. Droop control based on Active power, Reactive Power and Power angle (P-Q-α) was developed for SVC part of HCIC. Main purpose of droop control was to control reactive and active power flow in hybrid microgrid. Also, the above mentioned droop control method for HCIC ensured excellent power quality compensation and good power flow. Hybrid AC-DC microgrid consisted of solar panel, energy storage system (battery) & load in DC microgrid as well as energy storage system (battery), wind turbine & load in AC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. By adopting proposed control strategy, power flow requirements were met with low cost/rating system as well as it greatly promoted the development of more robust hybrid AC-DC microgrids. Moreover, proposed control strategy enhanced filtering characteristics of SVC part of HCIC to suppress the harmonic power and inject active power. However, droop control strategy to provide response in case of DG addition was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not realistic to implement for expandable microgrids. Also, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation would make this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of DC microgrid voltage and power sharing in grid connected mode.

An active power distributed control method for bidirectional interlining converter (BIC) in islanded hybrid AC-DC microgrid was proposed [98]. A mathematical expression was derived to give active power reference for each BIC to fulfil the active power sharing control objective. Consequently, no additional Proportional Integral (PI) controllers were required. Moreover, modified dynamic consensus algorithm (MDCA) was also developed for the BIC. MDCA was used to estimate the data required to calculate the references for active power sharing. MDCA prevented instability from the cyber physical interactions. Main purpose of active power distributed control along with MDCA was to enable autonomous power sharing between AC and DC microgrids by the equalization of the common dc bus voltage and normalized frequency. Hybrid microgrid consisted of three DGs & load in each DC & AC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. By adopting proposed control strategy, autonomous power sharing between multiple BICs was achieved as well as it greatly promoted the development of more robust hybrid AC-DC microgrids. Moreover, proposed control strategy provided a new method to design the corresponding estimator parameters. However proposed control architecture involves communication between bidirectional interlinking converter and distributed generation units. But this strategy can fail during lack of communication or communication delays. Also, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation would make this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of GFM (voltage regulation) and GFE (power sharing) operations of DC microgrid in grid connected mode.

An adaptive autonomous control method for hybrid AC-DC network comprising on continuous mix P-norm algorithm is proposed [99]. Hybrid AC-DC microgrid consists of utility, wind turbine & load in AC microgrid while solar panel, fuel cells & load are connected in DC microgrid along with single bidirectional interlinking converter. The proposed novel strategy is aimed at regulating the AC microgrid frequency and DC microgrid voltage within permissible limit under various conditions. Measurements of DC voltage from DC microgrid and AC frequency from AC microgrid are fed to the controller which then calculate the value of amount of power from AC microgrid to DC microgrid vice versa. After determination of direction of power flow, adaptive tuning of the gains of the PI controller of droop controller of bidirectional interlinking converter is done by continuous mix P-norm algorithm. Fast response to the disturbances on both AC and DC microgrid is being ensured by utilizing variable step size of Continuous mix P-norm algorithm. This ensures the robust response against impulsive noise as compared to other PI tuning techniques. Moreover, less settling time, fast response and tight regulations has been achieved using continuous mix P-norm algorithm. The proposed control algorithm worked well under different operating modes as compared to traditional dual droop approach. However, authors did not discuss the power sharing in both AC and DC microgrids by bidirectional interlinking converter. Instead, power sharing is being done by RDG of AC & DC MG, the intermittent nature of RDG brings the complexity in it. Also droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well.

A control strategy based on line impedance estimation for hybrid microgrid was proposed [100]. Hybrid microgrid consisted of solar panels, wind turbine, batteries & load in AC microgrid while solar panel, wind turbine, energy storage & load are connected in DC microgrid along with single bidirectional interlinking converter. The proposed novel strategy is aimed at improving the hybrid AC-DC microgrid reliability and efficiency by ensuring correct estimation of line impedance of bidirectional interlinking converter and accurate voltage regulation in islanded mode. This was achieved by first injecting small signal into the bidirectional interlinking converter through one of the distributed generation units connected from the AC side. The small signal is then recovered by LC filter and phase locked loop (PLL) without any communication mechanism thus correctly calculating its exact line impedance. With correct calculation of exact line impedance, voltage regulation was achieved by compensating any voltage drop on the line with bidirectional interlinking converter local information. Moreover, accurate power transfer through bidirectional interlinking converter was achieved using proposed novel approach. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral control method. However, the droop control strategy to provide response in case of DG addition, PWM modulation and complex coordinate transformation was not discussed which meant that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid power sharing in islanded mode.

A control strategy based on frequency and voltage regulation of hybrid AC-DC microgrid through bidirectional virtual inertia method was proposed [101]. Hybrid AC-DC microgrid consists of wind turbine, utility & load in AC microgrid while solar panel, energy storage & load were connected in DC microgrid along with single bidirectional interlinking converter. The proposed novel strategy was aimed at improving the microgrid stability. This was achieved by introduction of virtual inertia support to bidirectional interlinking converter so that changes in DC voltage and AC frequency is slowed down thus enhancing stability of hybrid microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral derivative control method. The proposed control strategy demonstrated the dynamic performance of bidirectional interlinking converter to ensure voltage regulation in all hybrid microgrid operational scenarios. However, the droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of DC microgrid voltage and current in both modes.

A control strategy based on ten switch bidirectional interlinking converter in hybrid microgrid was proposed [102]. Hybrid microgrid consists of wind turbine, utility, diesel generator & load in AC microgrid while solar PV, fuel cell, battery, super capacitor & load were connected in DC microgrid along with bidirectional interlinking converter. The proposed novel strategy was aimed at improving the DC voltage regulation and total harmonic distortion in an effective manner by improving the grid architecture. Moreover, instead of pulse width modulation (PWM), space vector modulation (SVM) technique is used for ten switch bidirectional interlinking converter. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral derivative control method. The proposed control strategy demonstrated the dynamic performance of bidirectional interlinking converter to ensure voltage regulation in all hybrid microgrid operational scenarios. However, the droop control method to provide response in case of DG addition, tuning of parameters for PID controllers and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC MG power sharing.

A control strategy based on low-cost bidirectional interlinking converter in hybrid microgrid was proposed [103]. Hybrid microgrid consists of wind turbine, utility & load in AC microgrid while solar panel, battery & load were connected in DC microgrid along with bidirectional interlinking converter. The proposed novel strategy was aimed at improving the load management strategy and reducing the repeated conversions in DC and AC microgrids. This was achieved by using low-cost bidirectional interlinking converter that reduces the need of battery charge and recharge cycles to cover renewable distribution generation sources intermittencies. Cost effective operation of hybrid microgrid was achieved with low-cost BIC power sharing. Moreover, AC microgrid comprises of permanent magnet synchronous generator (PMSG) based wind turbine while DC microgrid comprises of MPPT based solar PV unit. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral control method. The proposed control strategy demonstrated the dynamic performance of proposed modified bidirectional interlinking converter to ensure power regulation in all hybrid microgrid operational scenarios. However, the presence of multiple BICs made the overall control architecture more complex. Also droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC MG power sharing.

A control strategy based on optimal power flow paradigm method for hybrid microgrid was proposed [104]. Hybrid microgrid consists of single DG & load each in both microgrid along with single BIC. Moreover, hybrid microgrid was connected to the IEEE 5 bus and 14 bus system. The proposed novel strategy was aimed at improving the computational burden caused by optimal flow paradigm method. First of all, state space model of bidirectional interlinking converter was converted into optimal power flow problem. Solution of optimal power flow problem would ultimately ensure optimal flow of power in of both microgrids. This would require to include status of breakers connected to both AC and DC microgrid, into the constraints of bidirectional interlinking converter. Voltages of both AC and DC microgrids were segregated into their individual matrices so that there are no large numerical values of resistances in the matrices. So, the solution of this updated optimal power flow problem was achieved through parabolic relaxation technique which has got low computational burden as compared to its rival technique such as conic relaxation etc. Use of parabolic relaxation technique enabled authors to convert optimal power flow model of bidirectional interlinking converter from non-convex model into convex quadratic programming form so that technique such as sequential penalization method can be applied to achieve realistic solutions. The proposed control strategy demonstrated the dynamic performance of proposed modified bidirectional interlinking converter to ensure voltage regulation in all hybrid AC-DC microgrid operational scenarios. However, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of currents in grid connected & islanded mode.

A power management strategy based on modified bidirectional interlinking converter consisting of battery management system integrated with conventional topology of bidirectional interlinking converter for hybrid microgrid was proposed [105]. Hybrid microgrid consisted of single DG & load each in both AC and DC microgrid along with two bidirectional interlinking converters (one is the conventional bidirectional interlinking converter and other one is the modified bidirectional interlinking converter). The proposed novel strategy was aimed at improving the voltage regulation, power sharing regulation and power quality in both grid connected and islanded mode. In grid connected mode, regulation of DC microgrid voltage was performed by bidirectional interlinking converter while modified bidirectional interlinking converter is used for regulation of power sharing. Power sharing is being done by master follow droop control which divides the power between grid and battery. Battery regulates power sharing subject to the condition that SOC of the battery should be greater than the minimum SOC. In islanded mode, regulation of AC microgrid voltage was performed by bidirectional interlinking converter while modified bidirectional interlinking converter is used for regulation of DC microgrid voltage as well as supporting the AC microgrid. Also, techniques such as load shedding, source shedding is also being adopted according to SOC of battery. The control strategy demonstrated the dynamic performance of multiple networked bidirectional interlinking converters to ensure voltage regulation in all hybrid microgrid operational scenarios. However, the presence of many BICs made the overall control architecture more complex. Also droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of both microgrids power sharing in islanded mode.

A single stage interlinking converter based in bipolar hybrid AC-DC microgrid was proposed for voltage balancing function [106]. Hybrid AC-DC microgrid consisted of utility, wind turbine, AC generator & load connected to AC microgrid while PV panels, energy storage & load is connected to DC microgrid along with bidirectional interlinking converter as shown in figure 2.7. The proposed novel strategy was aimed at improving the voltage regulation by providing efficient control system based on PID controllers for balancing DC link voltage in both grid connected and islanded mode. In grid connected mode, regulation of DC microgrid voltage was performed by bidirectional interlinking converter. Power sharing was being done by other DGs. In islanded mode, regulation of AC microgrid voltage was performed by bidirectional interlinking converter while other DGs is used for regulation of DC microgrid voltage as well as supporting the AC microgrid. The proposed control strategy demonstrated the dynamic performance of bidirectional interlinking converter to ensure voltage regulation in all hybrid AC-DC microgrid operational scenarios. However, the presence of PID controllers, PWM modulation and complex coordinate transformation make this architecture not suitable for different operational requirements. Also it meant that addition of new DG would require the change in PID gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid power sharing by bidirectional interlinking converter.

A control strategy based on robust back stepping control scheme for BIC in hybrid microgrid was proposed [107]. Hybrid AC-DC microgrid consisted of utility & load in AC microgrid and PV, battery energy storage system & load in DC microgrid along with single bidirectional interlinking converter. The proposed control strategy for the BIC in a hybrid microgrid with distributed sources and loads, which aimed to regulate both the dc-bus voltage and AC BIC currents, even in the presence of unmeasurable disturbance signals and unmodeled dynamics. The proposed method used a robust controller based on the feedback linearization method that can handle parametric uncertainties, unmodeled dynamics, and disturbances and it did not require remote measurements with communication links and guarantees large signal stability. The proposed control method considered the power imposed on the BIC's DC-link as an unmeasurable disturbance and effectively rejects its impact on system performance without requiring additional sensors, which increases system reliability and decreases sensitivity to failures. The proposed control scheme demonstrated smoother transient responses with lower levels of current distortion, while being robust to various uncertainties and disturbances, including parametric uncertainties, unmodeled dynamics, and power regulation between the AC & DC microgrids. The controller also offered a plug-and-play feature that enables the addition or removal of distributed sources and loads without distorting the microgrid stability. The simulation results validated the effectiveness of the proposed method in regulating the dc-bus voltage and AC BIC currents, maintaining robust performance, and enhancing system reliability and simplicity. However, it did not discuss the regulation of AC microgrid voltage in islanded mode and AC & DC microgrid power sharing in grid connected mode.

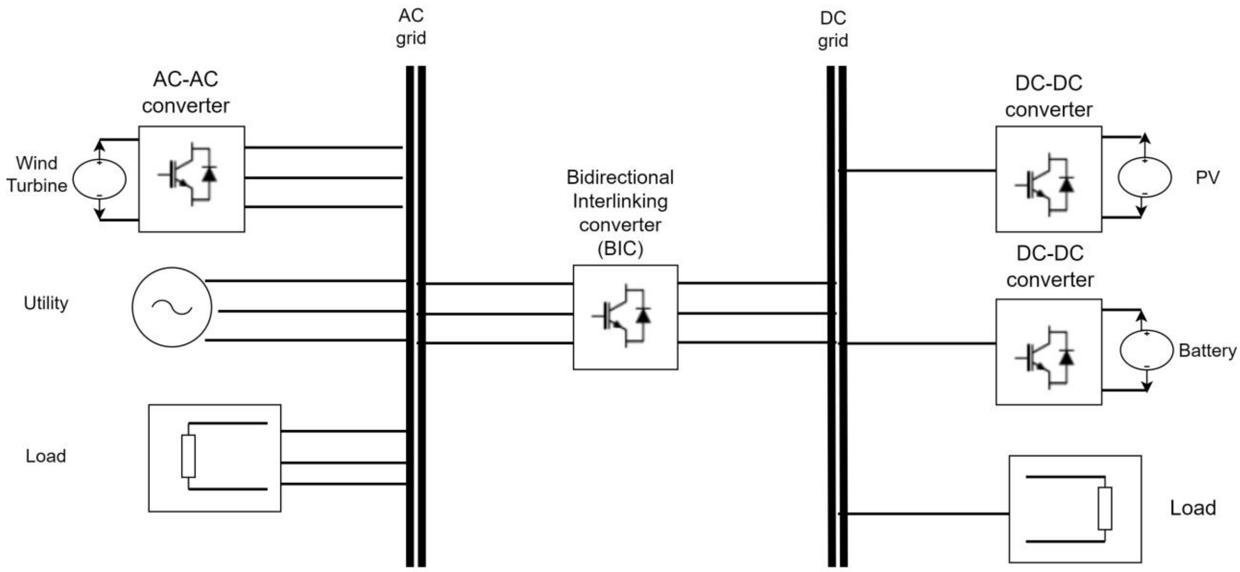


Figure 2.7 Hybrid AC-DC Microgrid with single stage interlinking converter [106]

A control strategy based on multiresonant controllers for bidirectional interlinking converter in hybrid microgrid was proposed [108]. Hybrid microgrid consisted of distributed generation (DG) units, battery energy storage system & load in both AC & DC microgrid along with single bidirectional interlinking converter as shown in figure 2.8. The aim of the propose control strategy was to maintain a sinusoidal PCC voltage under nonlinear load conditions. The proposed control scheme used multiresonant and repetitive controllers to deal with high-order harmonics and determines the desired IC harmonic current by detecting the PCC voltage instead of the load current. This allowed for the compensation of the harmonic currents caused by nonlinear loads to keep the PCC voltage sinusoidal, while also providing exact active power sharing between the DC microgrid and AC microgrid. One of the main advantages of the proposed control scheme was that it could be implemented easily without requiring communication links, central controller, transformer, or support from different power circuits. This reduced the total system cost, size, and power loss, and allowed the bidirectional interlinking converter to independently operate in hybrid MG. Furthermore, bidirectional interlinking converter could play as a shunt active power filter (APF) in addition to its inherent role in hybrid MG. Overall, the above mentioned control method improved the power quality in hybrid AC-DC microgrid under nonlinear load conditions and allowed for bidirectional fundamental power sharing between the AC & DC MG. Controller design was implement such that that each power converter in the hybrid MG could be controlled independently without a communication link. However, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid voltage and power sharing in islanded mode.

2.2.1.2 Multiple BIC topology

Multiple parallel bidirectional interlinking converters are used to connect the AC and DC systems, enabling power flow between the different systems and ensuring efficient operation of the microgrid. However, coordinating the operation of multiple bidirectional interlinking converters can be challenging, as they must work together to regulate the power flow. In the proposed method [109], each bidirectional interlinking converter uses a distributed control algorithm to communicate with its neighboring converters and exchange information about its operating conditions and power flow. Hybrid AC-DC microgrid consisted of AC grid having local loads and energy storage system and DC grids having DC loads and P.V system as shown in figure 2.9. Two bidirectional interlinking converters connected DC and AC grids. Bidirectional interlinking converters only regulated the DC grid voltage through DC grid droop controls. So, it meant that bidirectional interlinking converters only transfer power from AC grid to DC grid which is against the basic concept of bidirectional power flow by placing interlinking converter between AC and DC grids. Also, multiple bidirectional converters had been connected between AC and DC grid thus making the overall control architecture more complex.

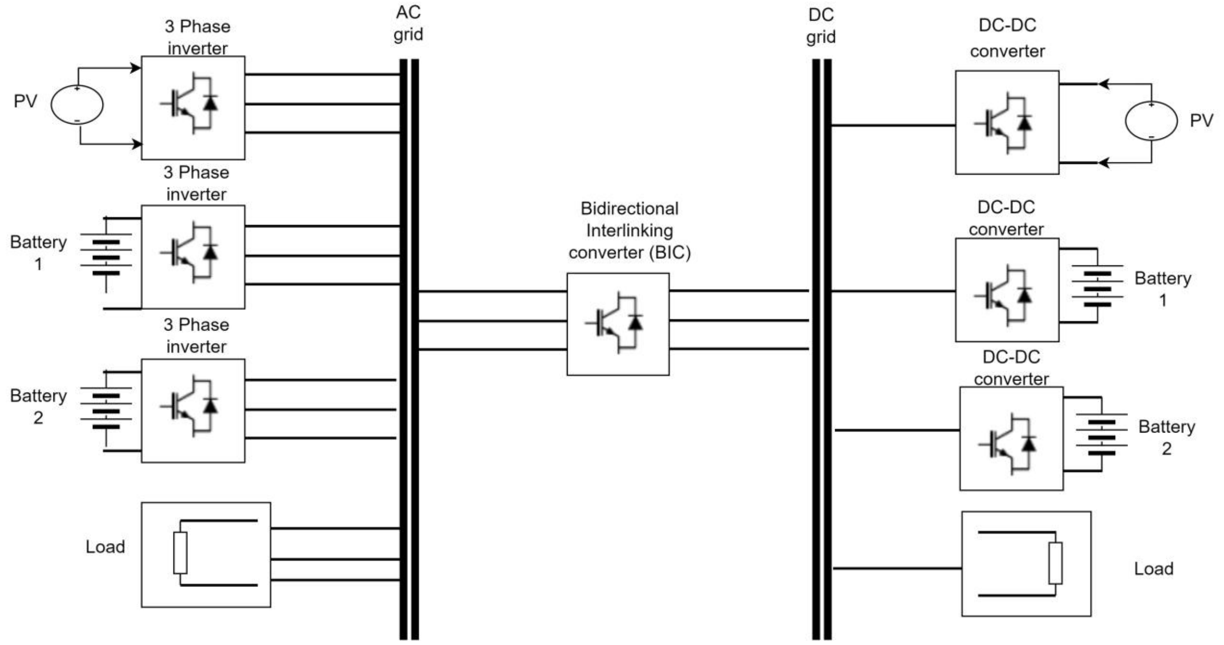


Figure 2.8 Hybrid AC-DC Microgrid with multiresonant controllers [108]

Moreover, in another paper, a coordination control for multiple parallel bidirectional interlinking converters was proposed for regulating voltage in dc microgrid. Hybrid AC-DC microgrid consisted of dc loads and one DG (PV) in the dc microgrid was proposed [110]. The dc microgrid was connected to the utility by three parallel bidirectional interlinking converters. Critical issues i.e., circulating currents among interleaving converters, degraded performance in constant power load (CPL) and slower response of voltage restorations were addressed by the proposed strategy as shown in figure 2.10. Again, bidirectional interlinking converters were only controlling unidirectional power flow and the presence of multiple bidirectional interlinking converters making the overall control architecture more complex.

A unified control for multiple BICs in hybrid microgrid was proposed [111]. Hybrid microgrid consists of two slack terminals, one in each microgrid and two bidirectional interlinking converters as shown in figure 2.11. Slack terminals were being used to control voltage and frequency in DC and AC microgrid. When slack terminals were available, all the bidirectional interlinking converters worked in power management mode The control variable fulfiled various power control objectives i.e., proportional power sharing, power dispatch and other objectives provide a required compatibility. When slack terminals were not available, then all the bidirectional interlinking converters seamlessly transfer to voltage or frequency control mode of relevant microgrid. Here, droop control had been used to control voltage and frequency of AC and DC microgrids which would require equivalent pid gains for both microgrids. In this approach, multiple bidirectional interlinking converters had been used. Moreover, addition of

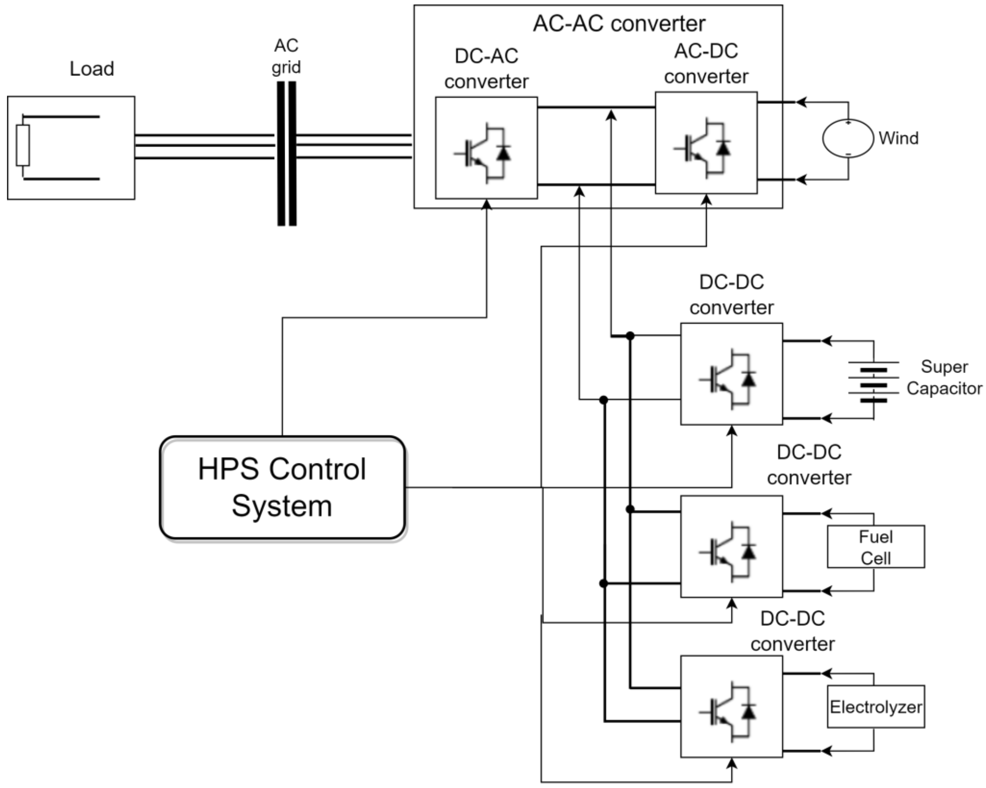


Figure 2.9 Control of a DC coupled hybrid AC-DC Microgrid [109]

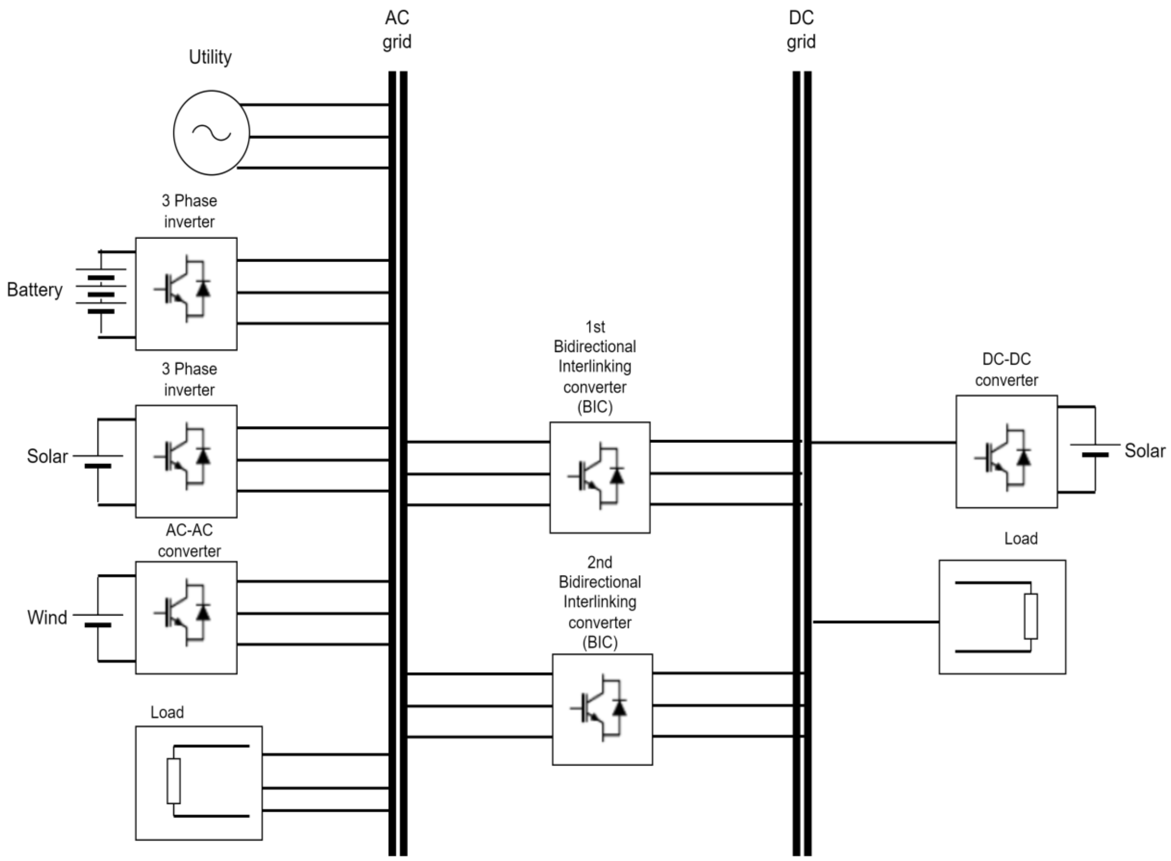


Figure 2.10 Coordination control for Hybrid AC-DC microgrid [110]

new DG or load would require the change in pid gain, thus making this technique not realistic to implement for non-linear load. In addition, accurate global power sharing would not be achieved due to mismatched impedances between DC microgrid and bidirectional interlinking converter.

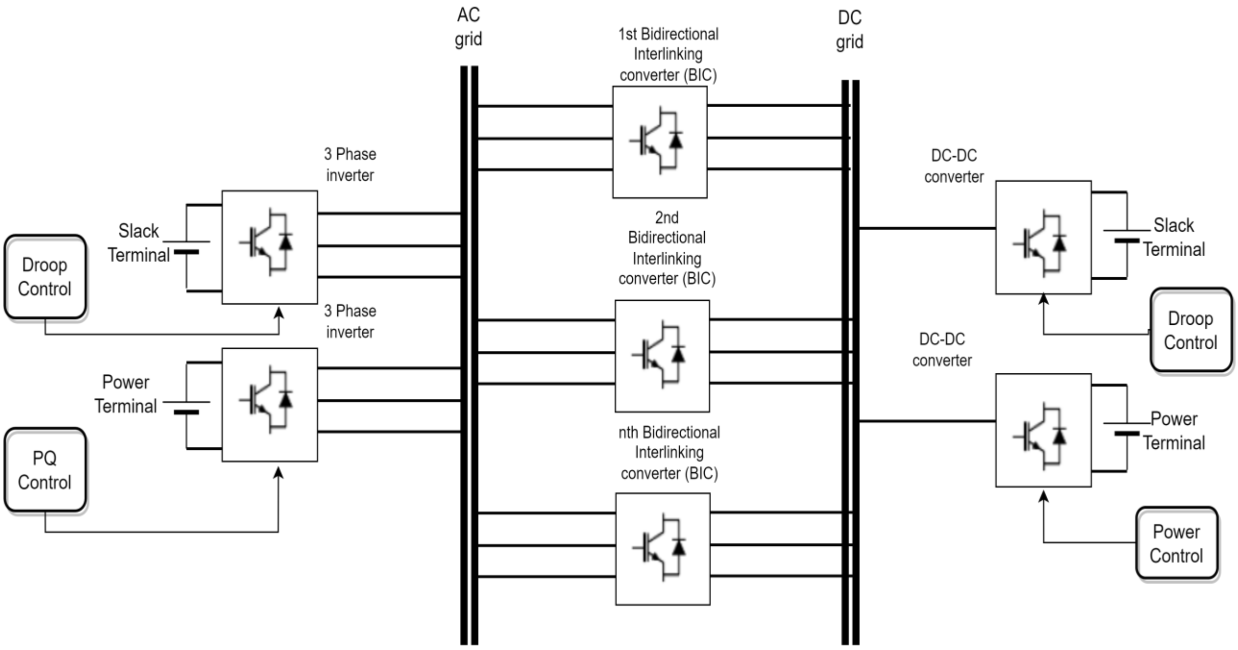


Figure 2.11 Unified control for Hybrid AC-DC Microgrid [111]

An autonomous power sharing control for hybrid AC-DC microgrid having multiple bidirectional interlinking converters was proposed [112]. Hybrid AC-DC microgrid consisted of one DC source, one AC source and three bidirectional interlinking converters. Frequency based droop control had been used to achieve power sharing among DC microgrid, AC microgrid and bidirectional interlinking converter. In the proposed approach, bidirectional interlinking converters and the dc sources were coordinated by the frequency of an injected ac ripple in the dc microgrid. This control fulfils various objectives such as distribution of power sharing as per power handling capacity, removal of circulating power, preventing overstressing bidirectional interlinking converter and DC voltage regulation. In this approach, multiple bidirectional interlinking converters had been used. Also, global power sharing among DC and AC sources would not be achieved due to different loading situations in both microgrids under steady state.

Multiple bidirectional interlinking converters would be different from each other in aspects such as manufacturer, components size, components power rating etc. Also, far distances between bidirectional interlinking converters were another issue to be addressed while designing control architecture for them. Normally more focus was being extended on the equal power sharing among bidirectional interlinking converters but the issue of different power ratings of bidirectional interlinking converters should be considered as well. Moreover, if a new bidirectional interlinking converter had to be installed then centralized bidirectional interlinking controller had to be programmed again, thus losing the feature of plug and play characteristic. In addition, as in [113-114], traditional droop controllers limited the ability of a microgrid system to support bidirectional power flow (AC to DC or DC to AC) or to accommodate changes in the system configuration thus acting as a barrier for the expansion of microgrid systems.

A distributed power sharing control strategy for multiple BICs in hybrid microgrid was proposed [115]. Hybrid microgrid consists of one DC DG, one AC DG and three bidirectional interlinking converters. Each bidirectional interlinking converter had its own local controller which generates respective power reference. Local controllers exchange information with one another thus allowing a proportional power allocation to each bidirectional interlinking converter based on its power rating as shown in figure 2.12. Overall system reliability and scalability was ensured by this strategy. But this strategy could fail during lack of communication or communication delays. Also, multiple bidirectional interlinking converters had been used.

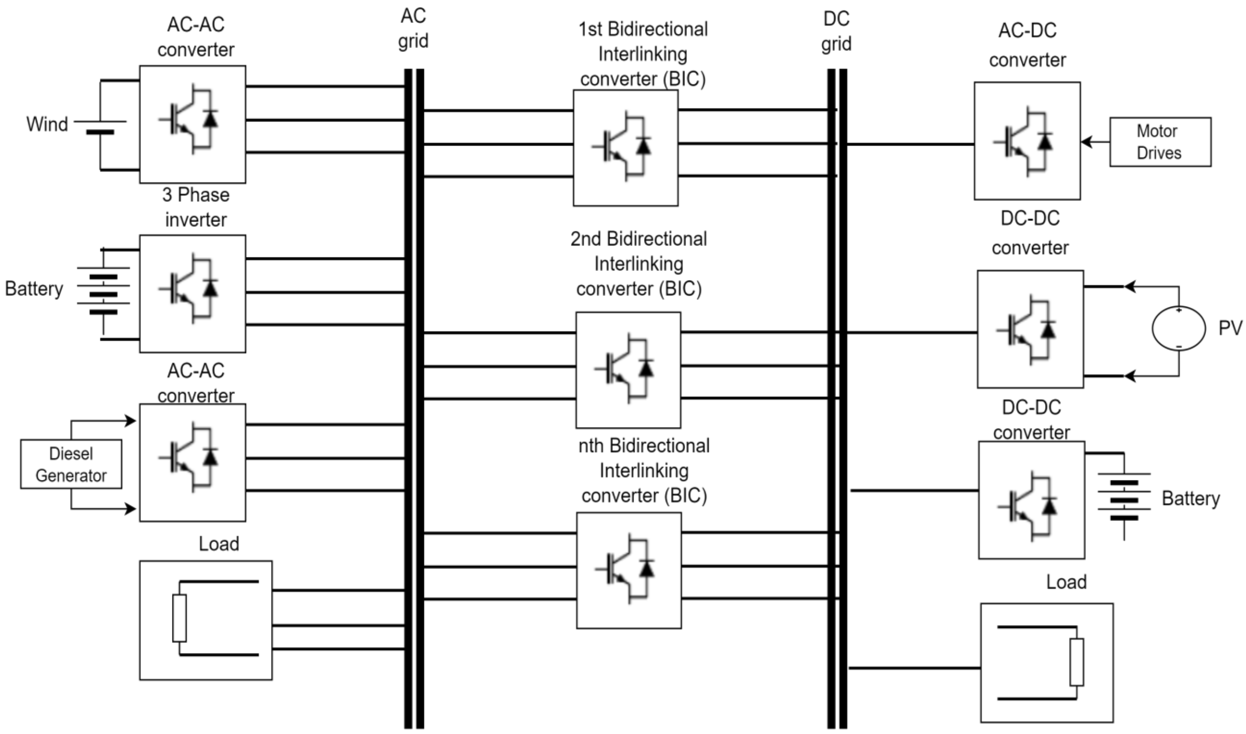


Figure 2.12 Distributed power sharing control for Hybrid AC-DC microgrid [115]

A nonlinear robust fractional-order control was proposed [116] for parallel bidirectional interlinking converters in hybrid microgrid. The above mentioned control method optimized power flow between AC & DC MG. Hybrid AC-DC microgrid consisted of solar panels in DC microgrid and DFIG in AC microgrid along with respective loads. The proposed control architecture worked well under increased load in DC or AC Microgrid. However proposed control architecture involved high gain observer PI controllers which works well when the system parameters changes. Moreover, multiple bidirectional interlinking converters were only controlling unidirectional power flow and the presence of multiple bidirectional interlinking converters made the overall control architecture more complex.

An optimal robust input output feedback linearization-based sliding mode control was proposed [117] for parallel bidirectional interlinking converters in hybrid microgrid in all modes. The proposed control architecture optimized power flow as well as control DC microgrid voltage. Hybrid AC-DC microgrid consisted of solar panels & batteries in DC microgrid and wind turbine & solar panels in AC microgrid along with respective loads. The proposed control architecture worked well under variations of both loads and parameters. However, multiple bidirectional interlinking converters were only controlling unidirectional power flow and DC voltage and the presence of multiple bidirectional interlinking converters made the overall control architecture more complex.

A distributed uniform control strategy was proposed [118] for parallel bidirectional interlinking converters in hybrid AC-DC microgrid. The proposed control architecture optimized power flow by proportionally allocating load to each DG as well as proportionally power sharing among parallel bidirectional interlinking converters. It can also regulate power sharing, DC microgrid voltage and AC microgrid voltage. Hybrid AC-DC microgrid consisted of one fuel cell, battery, solar panel & load in DC microgrid as well as one diesel generator, micro turbine, wind turbine & load in AC microgrid. The proposed control architecture worked well under different operating modes with no controller mode transition required. However proposed control architecture involved communication between all the bidirectional interlinking converters. But this strategy can fail during lack of communication or communication delays. Also, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Droop control had been used to control voltage and power sharing of AC and DC Microgrids which would require equivalent pid gains for both microgrids. Moreover, addition of new DG or load would require the change in pid gain, thus making this technique not realistic to implement for non-linear load.

A bidirectional virtual inertia control strategy was proposed [119] for parallel bidirectional interlinking converters in hybrid AC-DC microgrid. The proposed control architecture optimizes power flow as well as the offset between the GFM operation of DC MG and the AC MG frequency by using bidirectional virtual inertia control strategy for interconnected converters by analogy to virtual synchronous generator control. It could also regulate power sharing, DC microgrid voltage and AC microgrid frequency. It can also respond to changes in the DC bus voltage and AC frequency in the transient process. Hybrid microgrid consisted of one ESS, solar panel & load in DC microgrid as well as one micro gas generator, wind turbine & load in AC microgrid. The proposed control architecture worked well under different operating modes as compared to traditional droop control. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, it did not discuss the regulation of AC voltage in case of islanded microgrid.

A two-stage based decision making strategy for selection of optimum number of bidirectional interlinking converters was proposed [120] for hybrid microgrid consisting of AC microgrid & DC microgrid. The proposed control architecture improved the power flow and power quality in hybrid microgrid. It regulated GFE operation by finding the optimum number of parallel bidirectional interlinking converters. Hybrid AC-DC microgrid consisted of one energy storage system, solar panel & load in DC microgrid as well as one wind turbine, energy storage system & load in AC microgrid. The proposed control strategy ensured the reliability enhancement and power quality improvement at the lowest investment cost. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, it did not discuss the regulation of DC and AC voltage.

A modified virtual synchronous machine along with a dual droop control strategy was proposed [121] for parallel bidirectional interlinking converters in hybrid microgrid. The above mentioned control method solved the issues of resynchronization of bidirectional interlinking converter after disturbance, circulating current among parallel bidirectional interlinking converters and non-linear load behavior of bidirectional interlinking converter. So dynamic behavior of multiple bidirectional interlinking converters as a synchronous machine in case of variation of GFM operation of DC microgrid and AC microgrid frequency was achieved as compared to traditional droop control method thus improving the overall flexibility of the hybrid MG. Hybrid MG consisted of one source & load each in DC and AC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. Also, better performance of bidirectional interlinking converter after reconnection is achieved by using virtual synchronous machine along with a dual droop strategy. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Also droop control strategy to provide response in case of DG addition was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not realistic to implement for expandable microgrids. Moreover, it did not discuss the regulation of AC microgrid voltage in islanded mode.

A distributed control strategy along with a LEC and GEC was proposed [122] for parallel bidirectional interlinking converters in hybrid MG. The above mentioned control method solved the issues of economic power allocation demand and AC & DC microgrid voltage bus restoration. Hybrid microgrid consisted of one ESS, solar panel, micro turbine & load in DC microgrid as well as one diesel generator, wind turbine, energy storage system & load in AC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. The proposed control strategy showed that by sharing load information with neighboring DGs within the individual microgrid, LEC strategy could be used to achieve economic power dispatch along with individual microgrid voltage deviation. GEC strategy was used to regulate power sharing amongst AC and DC microgrid using bidirectional interlinking converters. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. In addition, droop control strategy to provide response in case of DG addition was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not realistic to implement for expandable microgrids. Moreover, it did not discuss the regulation of AC microgrid voltage in islanded mode.

A multi-dimensional droop control strategy for parallel two-stage bidirectional interlinking converters along with a novel harmonic-based control strategy for bidirectional DC/DC converters was proposed [123] for hybrid MG. The above mentioned control method was designed for emerging hybrid AC-DC microgrids, where bidirectional DC/DC converters are used to connect multiple DC microgrid to a common dc bus and bidirectional interlinking converters are used to exchange power between the DC and AC microgrids. The proposed control strategy solved the issues of operation of hybrid MG in a more economical and flexible manner as well as overstressing and loading problems of DGs thus resulting in better maintenance and more robust operation. Hybrid AC-DC microgrid consists of one solar panel, fuel cell & load each in AC and DC microgrid. The proposed control algorithm worked well under different operating modes as compared to traditional droop control. The proposed control strategy showed that by selecting frequency of harmonics and DC microgrid bus voltage as global variable, a droop control strategy would be employed for accurate power sharing amongst bidirectional DC/DC converters. For bidirectional interlinking converters, 3-D droop strategy was employed as an integrated control strategy for accurate power sharing between AC and DC microgrid as well as power of energy storage system connected to bidirectional interlinking converter. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Also droop control strategy to provide response in case of DG addition was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not realistic to implement for expandable microgrids. Moreover, it did not discuss the regulation of AC microgrid voltage in islanded mode.

A control strategy for multiple BICs in hybrid microgrid was proposed [124]. Hybrid microgrid consists of solar panel, wind turbine & load in AC microgrid while solar panel, wind turbine, battery & load are connected in DC microgrid along with multiple bidirectional interlinking converters. The proposed novel strategy was aimed at improving the power quality in an effective manner. One of the bidirectional interlinking converters with the largest power handling capacity was selected as the master interlinking converter while other acts as slave interlinking converters. Master interlinking converter regulates AC voltage while slave interlinking converter regulate DC voltage. The novel strategy makes use of virtual impedance method for master and slave interlinking converters to achieve AC and DC voltage regulation. Since both AC and DC voltages were regulated thus there are no harmonics in AC voltage and no ripples in DC voltage. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral control method. The control strategy demonstrated the dynamic performance of multiple networked bidirectional interlinking converters to ensure voltage regulation in all hybrid microgrid operational scenarios. However, the presence of multiple BICs made the overall control architecture more complex. Also droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid power sharing in islanded mode.

A control strategy based on event triggered power management control for multiple BICs in hybrid microgrid was proposed [125]. Hybrid microgrid consists of energy storage, diesel generator, wind turbine & load in AC microgrid while solar panel, energy storage, micro turbine & load are connected in DC microgrid along with multiple bidirectional interlinking converters. The proposed novel strategy was aimed at improving the hybrid AC-DC microgrid reliability and scalability in an effective manner by avoiding over stress of multiple bidirectional interlinking converters. Over stressing of bidirectional interlinking converters was avoided by ensuring proportional power sharing between multiple bidirectional interlinking converters. For proportional power sharing, economic power sharing was achieved by droop controllers. Event triggered control consists of continuous time domain and discrete time domain. Continuous time domain ensured economic power interaction between neighboring sub-grids while discrete time domain ensures proportional power sharing between bidirectional interlinking converters. Only data from neighboring bidirectional interlinking converters was used for event triggered control thus achieving less communication burden and economic power operation amongst bidirectional interlinking converter. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral control method. The control strategy demonstrated the dynamic performance of multiple networked bidirectional interlinking converters to ensure power regulation in all hybrid microgrid operational scenarios. However, the presence of multiple BICs made the overall control architecture more complex. Also droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC MG voltage.

A control strategy based on distributed control method for integrated hybrid microgrid was proposed [126]. Hybrid microgrid consisted of fuel cell, micro turbine & load in AC microgrid while solar panel, wind turbine, energy storage, micro turbine & load are connected in DC microgrid along with multiple BICs. The proposed novel strategy was aimed at improving the hybrid AC-DC microgrid reliability and efficiency by reducing the communication lines amongst multiple bidirectional interlinking converters. This is achieved by achieving power sharing at two levels i.e., at distributed generation level and bidirectional interlinking converter level. Cost effective integrated hybrid microgrid was achieved with efficient BIC power sharing. Optimal bidirectional interlinking converter power sharing ratio was achieved using convex optimization theory. Moreover, optimal bidirectional interlinking converter power sharing was achieved using modified dynamic consensus algorithm. The benefit of this strategy is that there is no need for communication between distributed generation units. Only communication between bidirectional interlinking converters is required which required less bandwidth. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral control method. The control strategy demonstrated the dynamic performance of multiple networked bidirectional interlinking converters to ensure power regulation in all hybrid microgrid operational scenarios. However, the presence of multiple BICs made the overall control architecture more complex. Also droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid voltage in islanded mode.

A control strategy based on dynamic master slave control strategy spread across multiple levels for network of integrated hybrid AC-DC microgrids was proposed [127]. Networked Hybrid AC-DC microgrid consists of four microgrids with four bidirectional interlinking converters having communication lines between them. The proposed novel strategy was aimed at improving the resilience of networked hybrid AC-DC microgrid by adopting master slave configuration amongst multiple bidirectional interlinking converters. This was achieved by selecting one bidirectional interlinking converter as a master unit achieving first power management within its own microgrid and then other bidirectional interlining converters are selected as slave units. Then signal was sent among slave bidirectional interlinking converters for power management within other microgrids. Moreover, local weight assigning method was adopted to dynamically select master unit amongst bidirectional interlinking converters. Since communication signal was generated through leader unit only so communication burden and failure related unreliability issues are already eliminated. The benefit of this strategy is that there is no need for high bandwidth communication line between distributed generation units. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral control method. The control strategy demonstrated the dynamic performance of multiple networked bidirectional interlinking converters to ensure power regulation in all hybrid microgrid operational scenarios. However, the presence of multiple BICs made the overall control architecture more complex. Also droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of voltage of AC & DC microgrid.

A control strategy based on output feedback based decentralized management control for multiple BICs in hybrid microgrid was proposed [128]. Hybrid microgrid consisted of 2 DG units connected in AC microgrid while 6 DGs are connected in DC microgrid along with 2 bidirectional interlinking converters. The proposed novel strategy was aimed at improving the hybrid MG stability and reliability in an effective manner by ensuring voltage regulation of both microgrids. Various issues such as plug n play capability for distributed generation units and bidirectional interlinking converter units, variation of load, change in microgrid configuration and mismatch in filter parameters are solved by the proposed control technique. These issues were treated as optimization problem being fed into output feedback based decentralized management control. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral control method. The above mentioned control method demonstrated the dynamic performance of the proposed modified bidirectional interlinking converter to ensure power regulation in all hybrid microgrid operational scenarios. However, the presence of multiple BICs made the overall control architecture more complex. Moreover, it did not discuss the regulation of AC & DC microgrid power sharing.

A control strategy for multiple BICs in hybrid microgrid was proposed [129]. Hybrid microgrid consisted of utility, PV, energy storage system & load in AC microgrid and energy storage system, PV & load in DC microgrid along with multiple bidirectional interlinking converters as shown in figure 2.13. The above mentioned control method takes into account the state-of-charge (SOC) of energy storage systems (ESSs) on both the AC & DC MG. The proposed control strategy aimed to ensure reliable and stable operation of the microgrid, especially during islanded mode operation. By considering ESSs on both the AC and DC sides, the proposed control strategy could balance the power flow between the two sub grids and ensure that the ESSs were used efficiently. The SOC of each ESS was also taken into account to prevent overcharging or over-discharging, which can damage the ESS and reduce its lifespan. The distributed coordination control strategy proposed in this paper used a consensus-based approach, which allows each BPC to communicate with its neighboring BPCs and reach an agreement on the power flow distribution. The control strategy also included a droop-based power sharing mechanism that ensured that the power flow is distributed fairly among the BPCs. Overall, the proposed control strategy offered a solution to the problem of managing ESSs in a hybrid AC-DC microgrid while ensuring reliable and stable operation. However, the increased complexity of the control strategy could pose challenges in terms of implementation and maintenance. The control strategy demonstrated the dynamic performance of multiple networked bidirectional interlinking converters to ensure voltage regulation at all hybrid microgrid operating conditions. However, the presence of multiple BICs made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC current in islanded & grid connected mode.

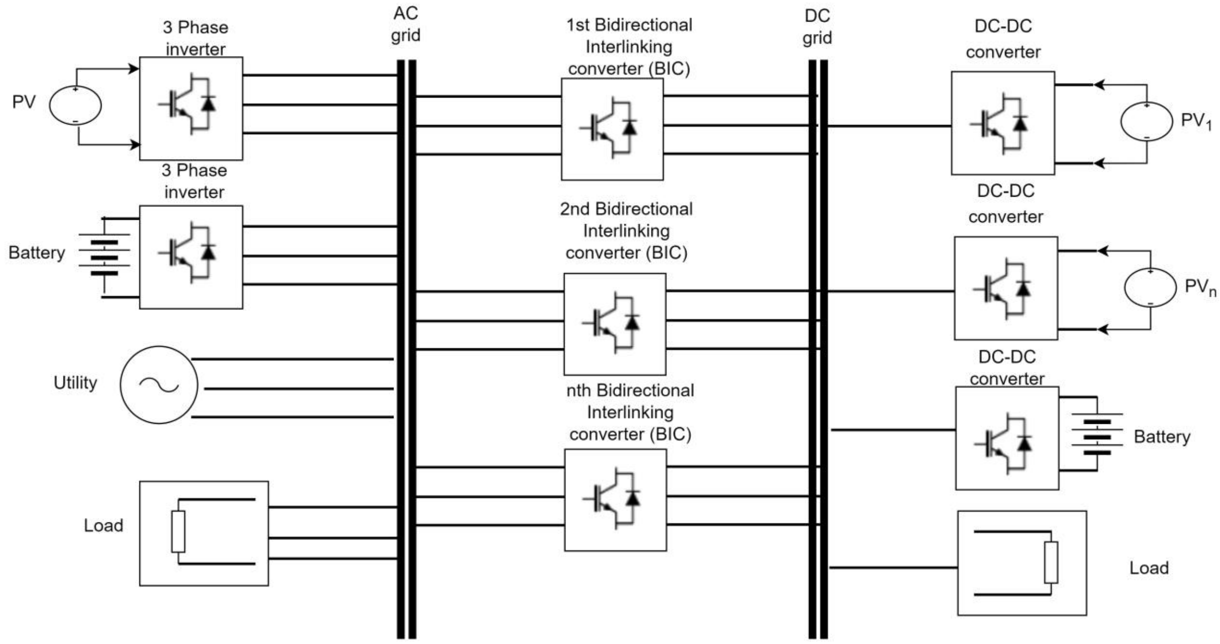


Figure 2.13 Hybrid Microgrid with distributed coordination control [129]

A control method based on flexible control strategy spread across multiple levels for network of integrated hybrid AC-DC microgrids was proposed [130]. Networked hybrid AC-DC microgrid consists of three microgrids with three bidirectional interlinking converters having communication lines between them. The proposed novel strategy was aimed at improving the resilience of networked hybrid AC-DC microgrid by adopting distributed and fixed-time properties amongst multiple bidirectional interlinking converters. This was achieved by adopting distributed structure with networked microgrids connected in a mesh network. This enabled microgrids to perform power regulation by selecting one bidirectional interlinking converter as a master unit achieving first power management within its own microgrid and then other bidirectional interlining converters were selected as slave units. Then signal was sent among slave bidirectional interlinking converters for power management within other microgrids. This enabled microgrids to perform power regulation in case of extreme events. This was achieved by defining two modes of operations i.e. unification mode and division mode. Moreover, all microgrids are operated in division mode where selection of master bidirectional interlinking converter enabled microgrid to operate independently i.e. in islanded mode as well as resynchronized to main grid so that there is no major effect of that microgrid in the main grid. If any extreme fluctuation occurred in any networked microgrid then all microgrids start to operate in unification mode which meant that all microgrids start cooperating with each other and use all available resources to perform voltage and power regulation even for any extreme fluctuation. The benefit of this strategy is that there is no need for high bandwidth communication line between distributed generation units. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral control method. The proposed control strategy demonstrated the dynamic performance of multiple networked bidirectional interlinking converters to ensure power regulation in all hybrid AC-DC microgrid operational scenarios conditions. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Also droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid voltage in islanded mode.

A control strategy based on hierarchical control for multiple BICs in hybrid microgrid was proposed [131]. Hybrid microgrid consisted of utility, PV, battery energy storage system & load in AC microgrid and battery energy storage system, PV & load in DC MG along with multiple BICs. An extended version of a hierarchical control for a hybrid AC-DC microgrid was proposed, with special focus on control of bidirectional interlinking converters between AC and DC microgrids. The hierarchical control system consisted of three layers of control with primary control, secondary control and tertiary control. In the primary control, voltage regulation is achieved using proportional integral (PI) voltage controller and current regulation is achieved using proportional resonant (PR) current controller. Droop control was also employed for DC current sharing. In the secondary control, deviation produced in DC voltage was eliminated by droop control and a PI controller was used to restore DC voltage to its reference value thus achieving accuracy in current sharing. In the tertiary control, a PI controller was used to regulate the frequency of exchange of power between DC bus and DC microgrid. Different operation modes of the hybrid AC-DC MG were discussed, including standalone and grid-connected DC operation modes. In the decentralized primary control level, AC current and DC voltage control were achieved, and droop control was used for DC output load current sharing. The secondary control level involved a common PI controller to restore DC bus voltage deviation caused by droop control in the primary control level. In the grid-connected operation mode, a common tertiary control level was involved to control the grid-connected current in the DC side. In the proposed technique, the emphasis is placed on maintaining a certain level of independence and decoupling between the control levels within the hybrid microgrid. This means that each control level operates autonomously without significant interference from the other levels, and their dynamics are decoupled to a certain extent. Overall, authors discussed a comprehensive study of a hierarchical control system for a hybrid microgrid, particularly for the BICs between AC and DC buses. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well.

A control strategy based on a distributed coordination control to ensure power regulation through multiple BICs in hybrid microgrid was proposed [132]. Hybrid microgrid consisted of utility in AC microgrid and Wind, PV, battery storage system & load in DC microgrid along with multiple bidirectional interlinking converters. A distributed coordination control for both types of bidirectional converters i.e. bidirectional interlinking converters and bidirectional interfacing converters used in coupled hybrid AC-DC microgrids (HMGs) was proposed. The controllers in the proposed technique were specifically designed to address droop power flow issues that can occur in multiple networked bidirectional interlinking converters-based hybrid AC-DC microgrids. The controllers were able to operate in both Grid Supporting Grid Forming mode and Grid Supporting Grid Feeding mode thus ensuring voltage regulation and power regulation for AC & DC microgrids in AC-DC hybrid microgrid. The proposed controllers in this technique aimed to minimize the frequency of parameter tuning and offer improved robustness compared to conventional controllers used for hybrid microgrid systems. Additionally, the above mentioned control method enabled the integration of a centralized battery energy storage system through bidirectional dual active bridge DC/DC converters to achieve good power regulation by ensuring maximum power transfer and isolation capability between medium voltage & low voltage DC microgrid. The study investigated the controller on systems side of hybrid microgrid and then proposed the flexible elementary controller for bidirectional interlinking converters that offers good transient response during different fault modes or scenarios and overcomes circulating current & power issues as well as synchronization issues of multiple networked bidirectional interlinking converters for fault resilient hybrid AC-DC microgrids. The controllers were tested against different operational modes and control scenarios of hybrid AC-DC microgrids, including operational transitions resulting from power variations in distribution generators (DGs), load fluctuations, faults, utility grid status and other aspects. The test results demonstrated the efficacy of the proposed controller algorithms in maintaining smooth operation under different operating states for the paralleled bidirectional interlinking converters incorporated hybrid AC-DC microgrids. Overall, the proposed controllers offered a novel & simple controller with improved transient response for single or networked bidirectional interlinking converters operating within the hybrid microgrid. However, the presence of multiple BICs made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid voltage in islanded mode and AC & DC microgrid power sharing in grid connected mode.

A control strategy based on comprehensive control scheme for voltage regulation and power sharing through multiple BICs in hybrid microgrid was proposed [133]. Hybrid microgrid consists of utility, energy storage system, distributed generation (DG) units & load in both AC & DC microgrid along with single bidirectional interlinking converter. The control scheme consisted of an outer loop flexible power sharing control and an improved robust inner loop control. The outer loop control was designed to achieve flexible power sharing of distributed generations (DGs) in the microgrid based on different power management objectives. The control was realized through the deduced balance state equation and by regulating the frequency and DC voltage. The inner loop control was designed to suppress external disturbance and system model uncertainties while improving dynamic response. It included a disturbance observer link that filters converter currents to suppress high-frequency measurement noise. The proposed control scheme was novel and different from existing literature in that it allows for proportional power sharing and economic power dispatch objectives to be achieved through the regulation parameter. Additionally, the proposed disturbance observer link was a first-order filter that improves system dynamic performance under the influence of external disturbance and model uncertainties. The proposed control scheme was validated through simulations using PSCAD/EMTDC, which demonstrate its effectiveness in achieving independent power balance and sharing, as well as enhancing the working of proposed MG. Overall, the comprehensive control strategy presented an important contribution to the field of hybrid MG control, providing a comprehensive scheme that can effectively address the challenges of power sharing and disturbance suppression. However, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC microgrid voltage in islanded mode and DC microgrid power sharing in grid connected mode.

A control strategy based on non-linear coordinated control scheme for power sharing through multiple BICs in hybrid microgrid was proposed [134]. Hybrid microgrid consisted of various AC & DC sub grids having combination of either energy storage system, wind turbine & load or energy storage system, PV & load in both AC & DC microgrid along with multiple bidirectional interlinking converters. A nonlinear coordinated control strategy for parallel BICs was proposed for a hybrid microgrid to operate in grid-connected mode. The objective of the proposed strategy was to minimize the power losses of the bidirectional interlinking converters while ensuring high dynamic voltage quality. To achieve this objective, the proposed approach involved optimizing the allocation of power flow to these converters in order to maximize the overall efficiency and minimize costs for power distribution among parallel bidirectional interlinking converter. The control strategy consisted of three main parts. First, the efficiency curves of the bidirectional interlinking converters were used to obtain an economically viable optimized power regulation strategy for networked parallel bidirectional interlinking converters. This main aim of distribution scheme was to minimize the cumulative power losses of all the bidirectional interlinking converters. Second, instead of distributing power equally among the parallel bidirectional interlinking converters, the power flow was distributed according to the allocated power flow corresponding to capacity of each bidirectional interlinking converter. This approach reduced the cumulative power losses of all the bidirectional interlinking converters and increases the available power margin for the bidirectional interlinking converter to perform dc voltage regulation in better way. Third, a state dynamic feedback linearization method was proposed for the bidirectional interlinking converter to perform dc voltage regulation. This method quickly perform dc voltage regulation in the event of a power disturbance and ensures high dynamic voltage quality. The simulation results demonstrated that the proposed strategy can effectively maintain the dynamic power balance in the hybrid MG and improve the overall efficiency of the BPCs while maintaining high dynamic voltage quality. The strategy improved the efficiency of the BPCs, increased the power margin of the BPC used to control the dc bus voltage, and maintained high dynamic voltage quality in the hybrid MG. Overall, the above mentioned control method could help to maintain the dynamic power balance in an AC-DC hybrid

AC-DC microgrid and ensure the stable and efficient operation of the microgrid in grid-connected mode. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC and DC microgrid voltage in islanded mode.

A control strategy based on consensus based secondary control scheme for voltage regulation and power sharing through multiple BICs in hybrid microgrid was proposed [135]. Hybrid microgrid consisted of multiple distributed generation (DG) units & load in both AC & DC microgrid along with bidirectional interlinking converters. A novel distributed control scheme focused on secondary layer was proposed for hybrid microgrids, which coordinated the simultaneous control scheme for the AC & DC microgrids, including the bidirectional interlinking converters, by regulating the AC voltage and frequency, with the extra advantage of regulating DC voltage using distributed control. The proposed strategy achieved seamless restoration of the variables modified by the primary control at both sides of the hybrid AC-DC microgrid and avoided circulating currents generated in the hybrid microgrid due to presence of multiple BICs. Moreover, the proposed methodology achieved plug-and-play capability, robustness, and accurate power-sharing capability between the bidirectional interlinking converters and distributed generators, even if they are connected or disconnected. The strategy also considered active powers transferred through the bidirectional interlinking converters, which helped to achieve accurate power sharing between the converters and maintain the current regulation capability of the distributed generators. The analytical model of the closed-loop system for the hybrid AC-DC microgrid was considered with the proposed consensus-based secondary control strategy, which permitted small signal stability analysis and parameter tuning. Furthermore, the performance of proposed control topology was validated through a combination of simulation and experimental testing such as load impacts and plug & play capability. Overall, the proposed control strategy had significant advantages over conventional independently designed secondary level control methods for hybrid microgrids due to the fact that the conventional control strategies neglected the power interaction between the AC & DC microgrids as power flows in and out from multiple bidirectional interlinking converters. The proposed methodology improved power regulation by accurately sharing the required power flow between AC & DC microgrids as well as restoration of the variables and avoided circulating currents, achieving plug-and-play capability and robustness. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well.

A control strategy based on resilient control strategy for unbalanced faults through multiple BICs in hybrid microgrid was proposed [136]. Hybrid microgrid consisted of utility, PV & load in AC microgrid and battery energy storage system, electric vehicle (EV) charging station & load in DC microgrid along with multiple BICs. An enhanced control strategy was proposed for bidirectional interlinking converters in hybrid MG. The proposed method was aimed at improving the resiliency of hybrid AC-DC microgrids against faults, power oscillations etc. generated due to use of renewable distributed generation units having intermittent power output, establishing accurate transient power sharing, and enhancing the frequency stability of HMGs. The proposed control strategy involved a modified harmonic-based control structure for DC/DC converters to make them resilient against disturbances, including grid faults. The strategy also suggested a new control strategy based on 3-D droops to simultaneously suppress active and reactive power fluctuations, establish accurate transient power sharing, and restrain the peak current of ICs during disturbances. An adaptive virtual inertia was also proposed for bidirectional interlinking converters to make them act as synchronverters, thereby enhancing the frequency stability of HMGs in case of faults or volatile renewable generations. Overall, the proposed control strategy was expected to improve the performance of hybrid MGs in the face of faults and renewable intermittency. The strategy was expected to improve the stability of HMGs by removing power oscillations and improving the frequency stability of hybrid microgrids. However, the presence of multiple BICs made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid voltage in islanded mode and AC & DC microgrid power sharing in grid connected mode.

A control strategy comprising of flatness based decentralized control for multiple bidirectional interlinking converters based on adaptive high gain proportional integral (PI) observer in hybrid MG was proposed [137]. Hybrid MG consisted of multiple distributed generation (DG) units & load connected to each microgrid along with multiple BICs. In hybrid MGs, the proposed control method aimed to provide robust voltage and power output robustness against un-modeled dynamics. The proposed technique first determined the state space models for single bidirectional interlinking converter and parallel connected bidirectional interlinking converters. Then, an observer based proportional integral controller with inherent properties of adaptively using high gain values is proposed to do voltage regulation using multiple bidirectional interlinking converters. Values of the high gain of proportional integral controllers changed dynamically due to incoming voltage errors so that best dynamic response is achieved. Finally, the approximated parameters were used to design decentralized controllers based on sliding mode control technique for multiple bidirectional interlinking converters. The strategy is based on the flatness property of differential equations of bidirectional interlinking converter and observer-based control theory. The flatness-based control strategy has the advantage of knowing the dynamic response of state variables in steady-state and transient states, making the design process straightforward. To implement the flatness-based controllers, an observer based proportional integral controller with inherent properties of adaptively using high gain values was designed to approximate unknown inputs, disturbances, and unmeasured states. The high gains of the observer changed dynamically during the estimation process to achieve the best approximation results. With the flat model of bidirectional interlinking converter and the approximation of essential parameters, the system model was input-output (I/O) linearized, and sliding mode control (SMC)-based feedback controllers are designed based on the desired trajectories. The major merit of the flatness-based control strategy was that the dynamic response of state variables in steady state as well as transient state is known, which made the design process straightforward and easy to follow. The proposed approach was demonstrated on a typical hybrid MG comprising of multiple DGs in both AC & DC microgrid to show its effectiveness. Overall, the control technique provided a comprehensive control method for BICs in hybrid microgrids and contributed to the development of efficient and robust power system control methods. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid voltage in islanded mode and AC & DC microgrid power sharing in grid connected mode.

A control strategy comprising of improvised control method for parallel BICs in hybrid MG was proposed [138]. Hybrid MG consisted of multiple distributed generation units & load in both microgrids along with multiple bidirectional interlinking converters. The improvised control strategy enabled BICs in a hybrid MG to operate in islanded mode with the aim to reduce circulating current and power-sharing deviation among converters, which could enhance the security of parallel converters. The proposed method included a unified detection method comprising of a modified droop control for automatic power regulation and an improved controller to estimate virtual impedance for circulating current elimination and deviation in power sharing. Moreover, simulation as well as experimental results showed that the proposed method successfully achieved reduction in circulating current with automatic power sharing while there is no compromise on the total output power handling capacity of the converters. The proposed method had more accurate power sharing and effective circulating current reduction than the conventional virtual impedance control method. The proposed method had a simple structure, easy digital control, and good independence. Overall, the proposed control method could improve the performance of BICs in a hybrid MG operating in island mode, making the system more efficient and secure. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC MG voltage.

A control strategy comprising of adjustable current reference coefficients for multiple BICs in hybrid MG was proposed [139]. Hybrid AC-DC microgrid consisted of PV, Wind turbine, Energy storage system & loads in AC microgrid and PV, energy storage system & loads in DC microgrid along with multiple BICs. A above mentioned control method was proposed for the bidirectional interlinking converters in hybrid MGs under unbalanced AC states. In such conditions, the active power transfer capability of bidirectional interlinking converters could be reduced due to limited current handling capacity which could cause an increase in error in DC voltage and power. These adverse effects could be enhanced if there is an increase in the number of parallel converters. The proposed control strategy introduced adjustable current reference coefficients for parallel bidirectional interlinking converters to enhance their active power transfer capability with zero active power oscillation. The strategy employed a new current sharing method, in which only one bidirectional interlinking converter, called the redundant bidirectional interlinking converter, needed to have a higher current rating compared to the other bidirectional interlinking converters. This approach ensured the steady state oscillation free output active power of the parallel bidirectional interlinking converters. Overall, the proposed control strategy could help to ensure the DC bus voltage regulation of hybrid AC-DC microgrids and improved their performance under unbalanced AC grid conditions. It offered a practical solution for enhancing the active power transfer capability of parallel bidirectional interlinking converters and reducing the adverse effects caused by unbalanced voltages. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC microgrid voltage in islanded mode and AC & DC microgrid power sharing in grid connected mode.

A control strategy comprising of coordinated power control strategy for multiple BIcs in hybrid microgrid was proposed [140]. Hybrid microgrid consists of PV, energy storage system & load in DC microgrid and PV, wind turbine & load in AC microgrid along with multiple bidirectional interlinking converters. Multiple sub grids based new hybrid AC-DC microgrid topology was introduced, which were connected to a respective AC & DC buses by bidirectional AC-DC interlinking converters and bidirectional DC/DC interlinking converters. A new topology and power management method for a hybrid MG was proposed to improve the management and efficiency of the system. The sub grids could vary for different applications. All the energy storage devices were concentrated to form a storage sub grid to improve management and efficiency. A new power management control method to regulate the power flow between subgrids was proposed for seamless operation of hybrid MG. So a decentralized power management strategy was proposed that controls power flow among different sub grids. The proposed strategy included a P-V droop control strategy for maintaining the common bus voltage and power sharing. The proposed coordinated control strategy considered the power capability & load types of sub grids and can ensure the power quality of sub grids with high proportion of critical loads. The strategy was simple in form, yet effective in managing power flow among multiple sub grids. The proposed strategy was decentralized, simple in form, and considers the power capability & load types of sub grids, making it suitable for different applications. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well.

A control strategy comprising of linear quadratic regulator based current control for multiple BICs in hybrid microgrid was proposed [141]. Hybrid microgrid consists of multiple distributed generation (DG) units, Wind turbine & load in AC microgrid and PV, battery energy storage system in DC microgrid along with multiple bidirectional interlinking converters. The proposed control technique ensured efficient and secure operation of the microgrid, especially in standalone mode with bidirectional interlinking converter playing a critical role in managing power sharing between sub grids, and its coordinated control with the battery energy storage system converter can further improve the efficiency of the power sharing scheme. The droop control method is a commonly used approach to generate a power reference for the bidirectional interlinking converter based on the deviation of system frequency and voltages. The linear quadratic regulator (LQR) with exponential weighting for current regulation was proposed as a robust control strategy that could quickly transfer power between sub grids and operate the microgrid robustly against various uncertainties. Moreover, the adjustable parameters of LQR provided much needed flexibility to enhance the performance of the bidirectional interlinking converter. It was promising to see the simulation results showing rapid power transfer between sub grids, robust operation of the microgrid under various conditions, and easy adjustment of LQR parameters to improve the performance of the bidirectional interlinking converter. These findings suggested that the proposed control strategies could effectively address the challenges of power sharing in a hybrid AC-DC microgrid and ensure its efficient and secure operation. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex with requirement of communication link between them. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Although it discussed in great detail about regulation of power sharing but it did not discuss the regulation of AC & DC microgrid voltage in islanded mode.

A control strategy comprising of improved active power control for multiple BICs in hybrid microgrid was proposed [142]. Hybrid microgrid consists of multiple distributed generation (DG) units & load in both AC & DC microgrid along with multiple bidirectional interlinking converters. The objective of this strategy was to improve the inertia of the AC bus frequency and the DC bus voltage in the microgrid and to achieve proportional current regulation among distributed generators (DGs). The strategy was based on the concept of VSM which is derived using the virtual inertia equation and the virtual capacitance equation. The VSM control was designed to manage the AC frequency and DC voltage simultaneously, which improved the dynamic response of the microgrid. The small signal and large signal characteristics of the bidirectional interlinking converters were analyzed to determine the optimal control parameters for the VSM control strategy. A proportional power sharing principle was also proposed to ensure that DGs share power in accordance with their power ratings. The contributions of this study were as follows: First, the virtual inertia dynamic of the AC bus frequency and the virtual capacitance dynamic of the DC bus voltage were performed by mimicking the external characteristic of a synchronous generator (SG). Second, the VSM-based control of the bidirectional interlinking converters is proposed by merging the virtual inertia equation and the virtual capacitance equation to form the power balance state of the bidirectional interlinking converters. Third, the small signal and large signal characteristics analysis of the proposed strategy were conducted to analyze the feature of the VSM control strategy with different control parameters. Fourth, a proportional power sharing principle was proposed to select the control parameters that enable DGs to share power in proportion to their power ratings. Overall, this study presented an innovative approach to improving the dynamic response and power sharing capability of hybrid AC-DC microgrids through the use of VSM-based active power control of multiple bidirectional interlinking converters. The proposed strategy can be useful for the development and operation of future microgrids. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid voltage in islanded mode and AC & DC microgrid power sharing in grid connected mode.

A control strategy comprising of improved power management coordinated control for multiple BICs in hybrid microgrid was proposed [143]. Hybrid microgrid consists of multiple DG units & load in both AC & DC microgrid along with multiple bidirectional interlinking converters.

An improved power management and control coordination strategy was proposed for autonomous hybrid AC-DC microgrids that consist of multiple sub-microgrids (SMGs) with different voltage levels. The aim of this new strategy was to reduce the continuous operation of bidirectional interlinking converters under all load conditions, which in turn avoided significant power loss on the bidirectional interlinking converter that could affect the operational feasibility of the hybrid MGs. The proposed control scheme included both primary and secondary level controllers to ensure power regulation so that goal of accurate power transfer among the multiple sub-microgrids is achieved. The proposed technique was designed to ensure accurate power transfer among the multiple sub-microgrids through secondary level controllers as well as while as minimizing the on-time of the bidirectional interlinking converter in the islanded mode. The study analyzed different use cases of transfer of power among multiple sub-microgrids using MATLAB/Simulink, with results indicating that the proposed approach proves to be more flexible and robust in achieving optimal level of power flow at different hierarchical control levels. Specifically, the study developed a modified power management and control strategy for the hybrid MG at the primary control level, where the priority of each SMG was to manage the power flow within its local boundary and avoided any unnecessary operation of the ILC to reduce power loss. Additionally, a new control technique was proposed to ensure continuous power flow among the SMGs when the hybrid MG operates at the secondary control levels, employing hierarchical control coordination as an essential stage in the proposed method. The study also introduced a new technique to define the parameters (voltage and frequency) that represent the exact active power transfer at the secondary control level, which are used as a reference to the ILC initiating the required power transfer across the SMGs. However, the presence of multiple bidirectional interlinking converters made the overall control architecture more complex. Moreover, droop control strategy to provide response in case of DG addition, tuning of parameters for PID controllers, PWM modulation and complex coordinate transformation was not discussed which means that addition of new DG would require the change in pid gain, thus making this technique not suitable for expandable microgrids as well. Moreover, it did not discuss the regulation of AC & DC microgrid voltage in islanded mode.

Summarizing the review of recent literature on control of hybrid AC-DC microgrid, following aspects can be drawn:

1. Control architecture is more complex in hybrid MG in context of regulation for power-sharing and voltage [66].
2. In grid connected and islanded mode, tradeoff between voltage regulation and power sharing

should be taken into account [67].

3. Control of hybrid AC-DC microgrid should ensure voltage regulation and power sharing for non-linear load as well as linear load [68].
4. BIC have been used to transfer power from AC Microgrid to DC Microgrid and vice versa in hybrid AC-DC microgrids. BICs can only act as GSGFM unit to regulate either AC voltage or DC voltage or GSGFE unit to regulate AC-DC power sharing. Then by using either multiple BICs with coordination control or multiple layer Proportional Integral Derivative (PID) control schemes, BICs are able to achieve multiple roles of GSGFM and GSGFE units to control multiple variables such as AC voltage, DC voltage and power sharing of AC & DC microgrids. There are some inherent issues associated with this approach such as Pulse Width Modulation (PWM), PID parameters tuning, cascading scheme delayed response issue, complex coordinate transformation, complex architecture in case of multiple BICs etc. Keeping in view above-mentioned issues, the implementation of PI control becomes intricate when attempting to address complex grid behaviors [144-145].

Keeping in view the above-mentioned literature review, a new control scheme is required that can ensure stability for AC-DC network, can ensure an appropriate communication-less DG steady state power allocation and can provide voltage and current regulation [146].

2.2.2 Model Predictive Control (MPC) in hybrid AC-DC microgrid

MPC was first applied in 1980s in different process plants e.g., oil refineries, chemical plants etc. After that, it has been adopted in the industries worldwide. Over the last decade, MPC strategies have emerged as a promising control technique for power electronics applications due to its simplicity and easy implementation, faster dynamic response and easy inclusion of constraints and non-linearity. There is no need to use pulse width modulator in MPC. MPC is a non-linear controlling technique that can solve optimization problem based on demand and generation forecasts in all type of real time scenarios. Moreover, handling power system constraints under non-linear loads is also a challenging task which can be solved by MPC using multivariable optimization problem [147]. MPC being a digital control technique have low control complexity as compared to other techniques. MPC does not need prior knowledge and modulation stage as compared to other techniques. Constraint inclusion is also possible in MPC whereas it is not possible in other techniques. Dynamic response of MPC is excellent as compared to other techniques. In MPC, switching frequency can be controlled or varied thus making it an excellent choice to control power converters. MPC can handle multiple input multiple input (MIMO) systems. MPC have got advantage over Proportional Integral (PI) technique as there is no modulation required in MPC. MPC does not need prior knowledge as compared to PI. Also switching frequency can be controlled in MPC while in PI, it is fixed. Constraint inclusion is also possible in MPC while in PI, it is not straight forward. Performance of MPC is excellent in steady state and transient conditions as compared to PI.

In MPC future value of the variable is predicted and then compared with the reference values of variable. Based on the comparison result (error), a cost function is implemented to reduce the error. Figure 2.14 shows the MPC algorithm working principle. Prediction horizon is the time period for which variable future value will be predicted using MPC algorithm. Let's suppose that variable current output value is calculated at time k. Then future value of the variable is calculated for [k:k+p]. This future value is then compared with reference value and the difference between them is called the error. Then cost function is being calculated to reduce the error. In the next cycles, same procedure is repeated. MPC is utilized for forecasting of generated power and load demand power in a MG. Accurate forecasting can lead to the better performance of MG. Especially with RDG intermittent nature, MPC can be used to predict the RDG output power from solar irradiation data, wind speed data etc. This can lead to better power planning ahead of actual load demand. Also load demand can be predicted as well from the historical data. So overall MPC can be used to ensure better performance of MG by predicting both generation and load demand power well before time [148]. Model predictive control technique is a non-linear technique with multi objective cost function defined to achieve multiple objectives through single controller as shown in figure 2.15 [149]. Each term in cost function has a specific weighing factor which is used to tune the importance of that term in relation to the other terms.

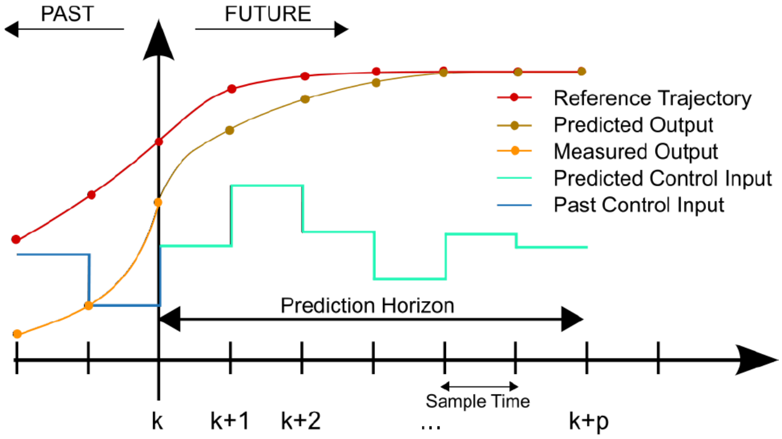


Figure 2.14 MPC algorithm working principle

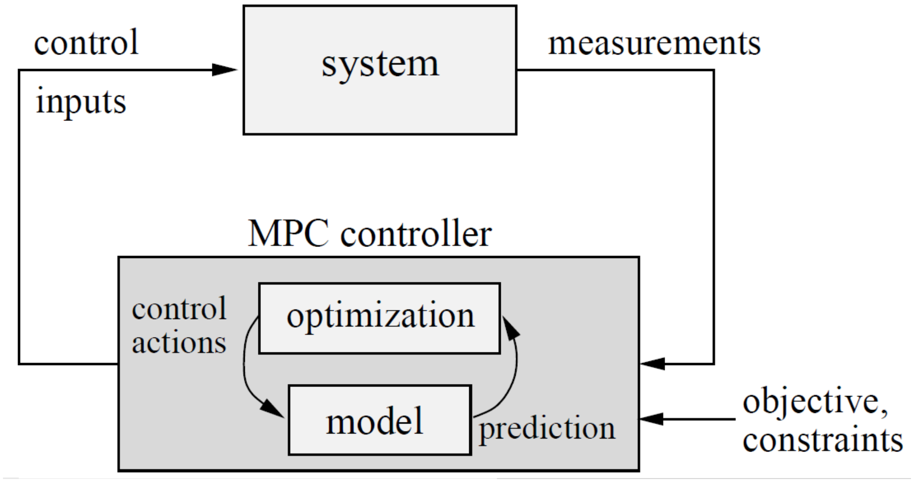


Figure 2.15 Block diagram of Model Predictive Control [149]

Table 2.1 compares different control techniques with MPC [150]. Hysteresis technique is a nonlinear control technique that uses relays to provide the switching signals. Linear control technique uses PID controllers to provide the switching signals. Sliding mode control is a nonlinear control technique that uses digital control technique to provide the switching signals. Artificial Neural Network uses human thinking (biological nervous system) to provide the switching signals. Deadbeat predictive control is the very first predictive control being used to control power converters. As shown in Table 2.1, MPC being a digital control technique have low control complexity as compared to other techniques. MPC does not need prior knowledge and modulation stage as compared to other techniques. Constraint inclusion is also possible in MPC whereas it is not possible in other techniques. Dynamic response of MPC is excellent as compared to other techniques. In MPC, switching frequency can be controlled or varied thus making it an excellent choice to control power converters.

Table 2.1 Comparison of existing techniques with MPC [150]

Parameters	**Hysteresis**	**Linear**	**Sliding Mode Control**	**Artificial Neural Network**	**Deadbeat predictive control**	**MPC**
Control Complexity	Low	Medium	High	High	Medium	Low-medium
Model & Parameters	Not Needed	Needed	Needed	Not Needed	Needed	Needed
Prior Knowledge	Not Needed	Not Needed	Not Needed	Needed	Not Needed	Not Needed
Modulation Stage	Not Needed	Needed	Needed	Needed	Needed	Not Needed

Constraint Inclusion	Not Possible	Not Possible	Possible	Not Possible	Not Possible	Possible
Dynamic Response	Excellent	Average	Good	Good	Good	Excellent
Switching Frequency	Variable (Uncontrollable)	Fixed	Fixed	Fixed	Fixed	Variable (Controllable)

Table 2.2 shows a comparison of MPC control technique with PI. MPC have got advantage over PI as there is no modulation required in MPC. MPC does not need prior knowledge as compared to PI. Also switching frequency can be controlled in MPC while in PI, it is fixed. Constraint inclusion is also possible in MPC while in PI, it is not straight forward. Performance of MPC is excellent in steady state and transient conditions as compared to PI. Model Predictive control methods can be classified into two basic groups: Continuous Control Set-MPC (CCS-MPC) and Finite Control Set-MPC (FCS-MPC) [151]. CCS-MPC utilizes the cost functions, as well as analytical ways to provide the optimal solutions of manipulated variables that can control the power electronic switch with using the PWM or SVM modulators. According to the nature of power converter that combinations of switching states are finite, FCS-MPC uses complete enumeration method to get prediction and optimization and does not use the modulator [152]. FCS-MPC usually provides a faster response time than CCS-MPC. Optimal voltage vector is being selected to minimize cost function that can control various parameters such as current [153], voltage [154] and switching frequency [155]. Owing to the high degree of flexibility in determining the cost function, the FCS-MPC method has been developed for many types of converters, including matrix converters [156-157] current source inverters [158-159] etc. A model predictive direct power control (MPDPC) having weighted model predictive control (MPC) function to control active and reactive power simultaneously only on AC grid was proposed [160].

Table 2.2: Comparison of MPC with PI [150]

Item Description	**PI Controller**	**MPC**
Type of Model	Linear model	Discrete time load-inverter model (for prediction)
Design for controller	PI parameter adjustment (root locus or pole placement)	Cost function definition
Modulation	PWM or SVM	No modulation
Implementation	Analogical or digital (after controller discretization)	Direct digital implementation

Switching Frequency	Static	Controllable (variable)
Multivariable	Coupled	Decoupled
Flexibility	Constraint inclusion is not straight forward	Constraint can be included directly in the cost function.
Concept Comprehension	Medium with SVM	Simple and Intuitive
Steady State Performance	Good in dq frame	Good in abc, αβ, and dq frames
Transient Performance	Moderate	Excellent

In this method, voltage vector is being selected according to cost function based on difference of current values of active and reactive powers from their reference values. Cost function consists of two terms for active and reactive power. Every term has got weight function p_{wf} and q_{wf}. Problem with this approach is that non- linear load cannot be handled due to fixed P_{ref} in Direct Power Control approach.

A modified model predictive control (MPC) for bidirectional AC–DC interlinking converter was proposed [161]. Proposed MPC controller was designed on the basis of Lyapunov function for energy storage systems. MPC controller works in inverter and rectifier mode. MPC controller regulates DC voltage in rectifier mode and AC voltage in inverter mode. However, it does not perform power sharing function in either of its mode; thus, working only in voltage-oriented control (VOC) mode.

A model predictive algorithm to control a bidirectional AC-DC converter was proposed [162], which is used in an energy storage system for power transferring between the three-phase AC voltage supply and energy storage devices. Here the controller works in inverter and rectifier modes, in which cost function have been developed to control respective currents. Objective of power sharing have been achieved while the objective of voltage control has been designated to respective controllers in both AC and DC Microgrids.

A coordinated control strategy for BIC in hybrid microgrid having hybrid energy storage and AC-DC loads was proposed [163]. Model Predictive power and voltage control (MPPVC) have been implemented for bidirectional interlinking converter to ensure optimal power sharing between AC and DC Microgrids as shown in figure 2.16. Then energy management system (EMS) has been implemented to achieve stable operations under varying load and generation conditions. In grid connected mode, bidirectional interlinking converter implements optimal power management by comparing current power value to fixed reference power value. So, it cannot handle situations where new load is added or removed from the grid. In islanded mode, bidirectional interlinking converter only controls AC voltage while DC voltage is being controlled by energy storage systems.

A MPC strategy for BIC in hybrid microgrid was proposed [164]. Hybrid AC-DC microgrid consists of solar panel, wind turbine, battery & load in DC microgrid. Solar panel is connected to the DC microgrid through DC/DC converter. Battery is connected to the DC microgrid through bidirectional DC/DC converter. Wind turbine is connected to the DC microgrid through AC-DC converter. Model Predictive voltage & power control (MPVP) have been implemented for bidirectional interlinking converter to ensure optimal power sharing between AC and DC microgrids. Model Predictive current & power control (MPCP) have been implemented for bidirectional DC/DC converter to mitigate the DC voltage fluctuations caused by renewable distributed generation units (solar & wind). Then energy management system (EMS) has been implemented to achieve stable operations under varying load and generation conditions. The proposed control algorithm worked well under different operating modes as compared to traditional proportional integral control method in grid connected mode with bidirectional interlinking converter implements optimal power management by comparing current power value to fixed reference power value. So, it cannot handle situations where new load is added or removed from the grid. In islanded mode, bidirectional interlinking converter only controls AC voltage while DC voltage is being controlled by battery energy storage system. So, it did not discuss the role of bidirectional interlinking converter in regulation of dc voltage.

A decentralized power management strategy and load sharing scheme based on model predictive controller for AC microgrids consisting of PV system and battery energy storage system connected with voltage source converter was proposed [165]. AC microgrid consists of two DG with each DG having PV source connected to DC/DC converter & battery energy storage system connected to bidirectional DC/DC converter with both their outputs connected to voltage source inverter. The proposed novel strategy is aimed at improving the voltage regulation in islanded mode, maintaining the dc link voltage, maintaining the state of charge balancing among batteries. Also the proposed novel strategy is aimed at achieving required active and reactive power sharing among converters while considering real time scenarios of fluctuating power generation, loading conditions, and feeder impedance mismatched etc. MPC based voltage control is implemented for both DC/DC converters connected to PV system & battery energy storage system. Output from PV system & battery energy storage system are fed to voltage source inverter which also has been controlled by MPC based voltage control. Droop control is also implemented to stop sudden frequency variations due to increase or decrease in load. MPC connected with DC/DC converter of PV source is used to regulate PV output voltage with respect to intermittent solar irradiance. MPC connected with DC/DC converter of battery energy storage system is used to regulate DC link voltage. MPC connected with voltage source converter is used to regulate AC voltage with load sharing being done by droop control. Overall MPC is used to regulate DC voltage and AC voltage in islanded mode. However the proposed MPC controllers cannot regulate AC and DC current in grid connected mode.

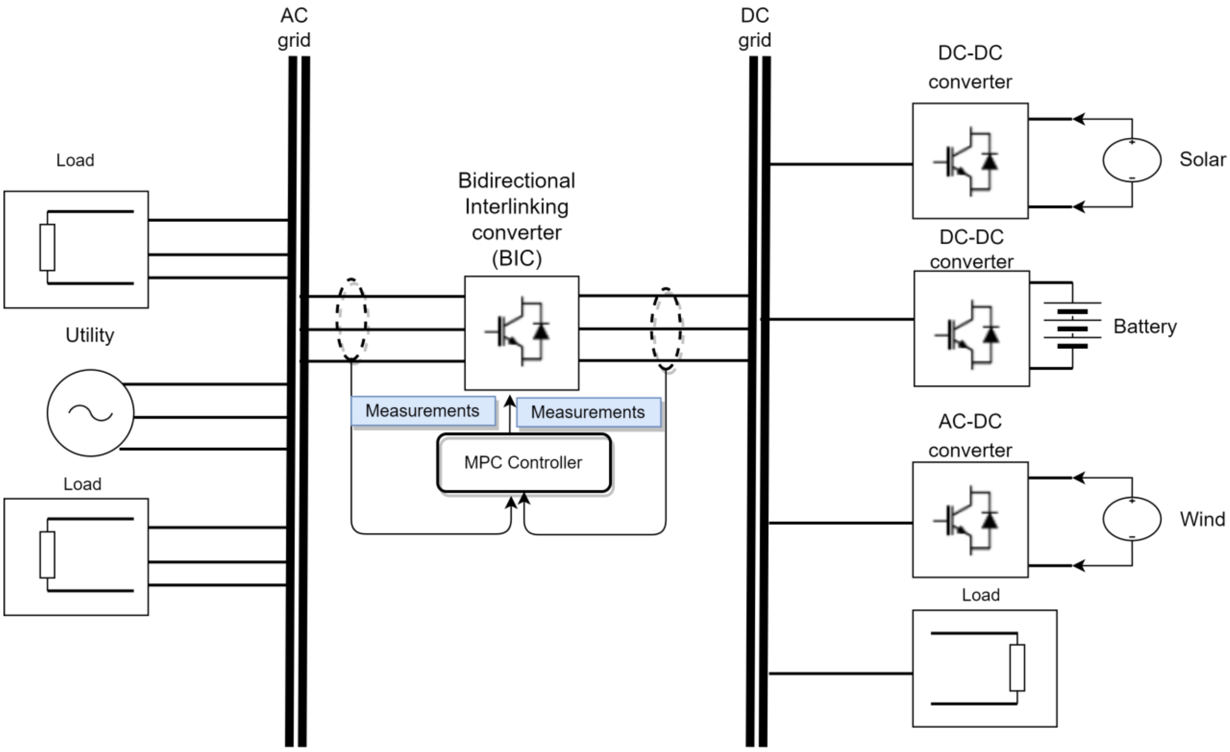


Figure 2.16 Hybrid AC-DC Microgrid with novel adaptive droop control algorithm [163]

Summarizing the literature review for MPC based control of hybrid AC-DC microgrid, no single BIC can control the AC voltage, AC current, DC voltage and DC current with MPC control architecture as well.

2.2.3 DC/DC converters

Various control strategies for the DC microgrid operation had been investigated i.e. DC GSGFM unit [166], operating under different modes [167], seamless mode transitions [168-169], etc. In DC MG, main challenge is to regulate the current and voltage while providing optimal power to the load. GSGFM DG converters can be represented as an ideal DC voltage source that can act as GSGFM DG to regulate voltage. On the other hand, the GSGFE DG are mainly designed to deliver power to an energized grid. They can be represented as an ideal current source connected to the grid in parallel with high impedance [170]. Operation and control of DC microgrids had been investigated [171–173] with core issues such as DC GSGFM units, different operating scenarios, transition between different modes and DC microgrid protection schemes [174]. Energy management system in DC microgrid [175-177] have been implemented using PI controllers. An autonomous three level voltage control strategy was proposed in [178] for DC MGs that divides the control into three voltage levels according to voltage variation in DC MG. The control strategy uses PI linear control to act as GSGFM DG to regulate voltage and optimal power sharing. It uses renewable energy sources only as power terminal.

A hierarchical control strategy for DC MGs implemented in two layers i.e., primary control implements dc voltage regulation and power sharing while secondary control implements a mechanism to reduce power sharing and improve microgrid stability [179]. Proposed strategy has been tested against four modes but in all these modes dc voltage regulation is been done either by energy storage systems or utility units while power sharing is being done by distributed generation units. Also transition between those modes are being done by secondary control thus making proposed control strategy very complex.

A hierarchical droop control mechanism was proposed in [180] for stable operation of isolated DC MG. Droop control is being used to maintain the balance of SOC between multiple energy storage systems in DC microgrids as shown in figure 2.17. Virtual inertia control is being used to control the power output from renewable energy based distributed generation units. Load priority scheme is being used to prioritize load power consumption according to the power available from distributed generation units. A fuzzy compensator has been used to decrease voltage deviations caused by droop control. Fuzzy control has its limitation due to the fact that it cannot handle situations outside its proposed fuzzy rules. Proposed strategy has been tested against four modes but in all these modes dc voltage regulation is been done either by energy storage systems and power sharing is being done by distributed generation units.

A hierarchical control scheme for DC microgrid was proposed in [181] that consists of photovoltaic (PV) unit, flywheel energy storage system and battery storage system. The proposed control scheme divides the dc bus voltage into five layers. DC bus voltage regulation is being done by flywheel and battery. The proposed control scheme cannot handle situation if DC bus voltage is disturbed to value other than proposed five-layer DC voltage. Also shifting of DC bus voltage regulation to renewable energy based distributed generation units or load shedding/ curtailment in case of low SOC of flywheel and battery have not been discussed.

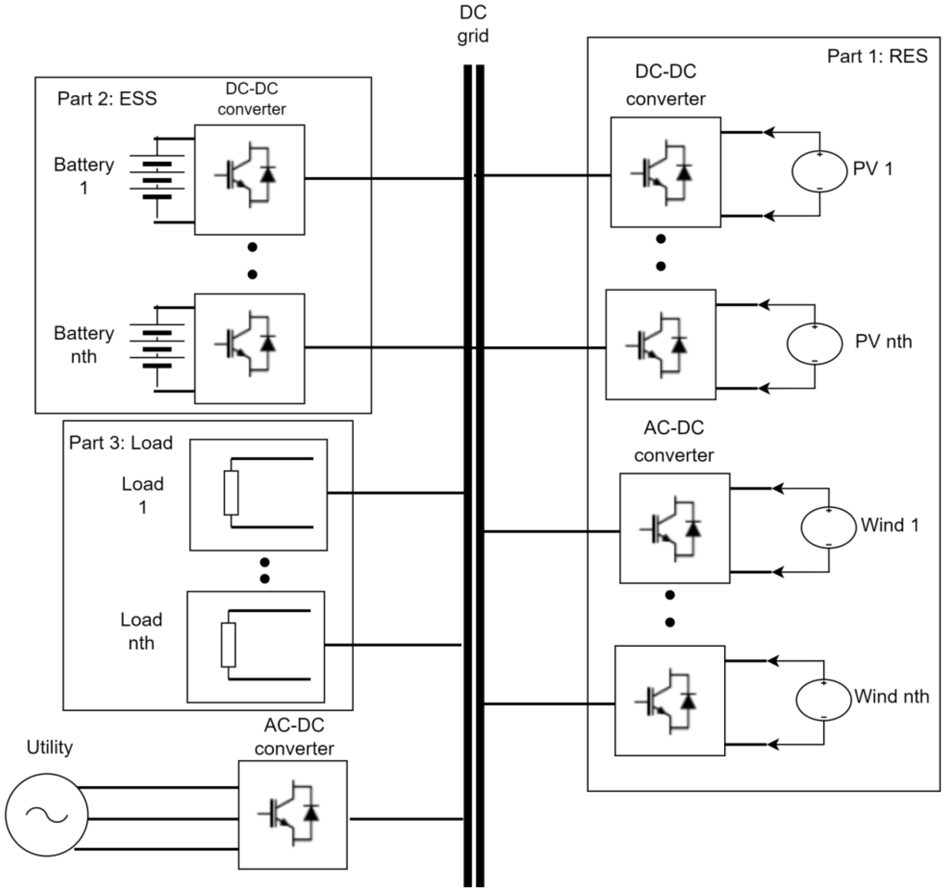


Figure 2.17 Structure of Hybrid DC Microgrid [180]

An adaptive droop resistance technique was proposed in [182] to regulate dc voltage. The proposed technique was easy to implement but it does not provide good dc voltage regulation. Also, current sharing accuracy is degraded as well due to difference in line resistances and corresponding voltages. A three-level hierarchical droop-based control scheme was proposed in [183] which is not affected by line resistances. The proposed control scheme is being derived from electrical dispatching standards for DC MG and ISA-95. The proposed control scheme does not provide accurate dc voltage regulation. An adaptive droop control strategy was proposed in [184] to minimize the circulating current and load sharing. Presence of virtual resistance is being ensured to reduce difference of current sharing values between different converters and circulating current as well. But dc voltage regulation is not accurate. A fuzzy logic based decentralized control strategy based on fuzzy logic was proposed in [185] to ensure balance of stored energy in multiple and distributed battery energy storage systems (while maintaining appropriate SOC of each energy storage system) by modifying the virtual resistances of the droop controllers for DC microgrid. It partially removes DC voltage deviation in DC grid voltage but it cannot completely eliminate the dc voltage deviation. A mode adaptive decentralized control was proposed in [186-187] for DC Microgrid having renewable energy distributed generation units and energy storage systems. Microgrid operation was divided into different modes keeping in view that there was no overloading condition between different modes. But no proper voltage levels are being selected to switch between different modes and sensors used to detect voltage were not accurate thus missing small voltage differences.

A distributed control was proposed in [188] for DC microgrids having parallel DC/DC converters to achieve better voltage regulation and proportional load sharing. The proposed control scheme ensures good voltage regulation and improved power sharing. But the proposed control scheme uses CAN communication so any problem in communication e.g., delay in transmission signals can cause instability in microgrid. A distributed cooperative control was proposed in [189-191] for DC microgrid with heterogeneous energy storage systems, distributed generation units and loads. The proposed control schemes are flexible and robust. But the proposed control schemes depend on communicating the parameters to controllers which may face delay in transmission signal during communication channel down time. Also, security issues are to be considered while transmitting them on communication channel. A unified distributed control strategy based on fuzzy logic was proposed in [192] for DC microgrid under grid connected and islanded mode. It ensures proper DC voltage regulation and improved power sharing. But a time consuming and slow process of trial-and-error method have been adopted to determine membership function. Fuzzy control has its limitation due to the fact that it cannot handle situations outside its proposed fuzzy rules.

A load management control strategy was proposed based on MPC for hybrid renewable energy sources [193]. Voltage regulation of the power line was achieved where the multi-renewable resources are integrated. In the investigation, the criteria for optimizing the cost and emission are employed by setting optimization objectives. MPC was being used to control voltage and power for demand-side management (DSM) in microgrid consisting of standalone Hybrid Renewable Energy Systems (HRES). Simulations were done for microgrid in MATLAB/Simulink to evaluate the performance of proposed DSM that can perform rescheduling to shift able loads. During grid-connected mode, current regulation was achieved through direct power MPC (DPMPC), and voltage regulation during islanded mode was achieved through Finite-control set MPC (FCS-MPC). An Energy management system (EMS) was proposed in [194] for a photovoltaic-based DC microgrid in which MPC-based AC-DC converter and PV is being used for current regulation, and ESS (Battery & Super Capacitor) is being used for DC voltage regulation. The roles of power converters are being fixed. PV is used to regulate power only. An EMS was proposed in [195] comprising of multiple layer control topology for DC MG comprising of fuel cell, battery pack and PV. A battery pack acts as GFM unit (DC voltage) while PV & fuel cell acts as GFE unit (power sharing). So again, PV-based DG's role is to regulate power only thus again fixing its role. An energy management system was proposed in [196] for DC microgrid with PV-based DG and dual-energy storage system comprising battery and super capacitor-based energy storage systems. A dual-energy storage system regulates the DC voltage, and PV-based DG regulates power. Again, the roles of power converters are being fixed. PV is used to regulate power only.

Other distributed control techniques such as model predictive control (MPC), sliding mode control (SMC) are also employed in DC MG [197-199]. Distributed (decentralized) control have been proposed as a primary and secondary control units to regulate DC voltage and current regulation in DC MG.

An Energy management system (EMS) was proposed in [200] for a photovoltaic-based DC microgrid in which MPC based AC-DC converter and PV is being used for current regulation and ESS (Battery & Super Capacitor) is being used for DC voltage regulation as shown in figure 2.18. PV is used to regulate power only. An EMS was proposed in [201] consisting of fuel cell, BESS and PV. BESS is used to regulate DC voltage while PV & fuel cell are used to regulate power. So again, PV is used to regulate power only. An energy management system was proposed in [202] for DC microgrid with PV based DG and dual energy storage system comprising of battery and super capacitor-based energy storage system. Dual energy storage system regulates the DC voltage and PV based DG regulates power. Again, PV is used to regulate power only. Stability analysis for isolated AC microgrids having PV-active generators is being conducted in [203] where ESS and PV DGs operate in both modes (GSGFM or GSGFE) with respect to specific operational conditions. Droop control technique is being used and stability analysis of selection of droop coefficient and its effect on stability of the microgrid is being conducted.

MPC based demand-side management (DSM) was proposed for microgrid [204]. Microgrid consists of RDG units with solar & wind and BESS. Simulations were done for microgrid in MATLAB/Simulink to evaluate the performance of proposed DSM that can perform rescheduling to shift able loads. During grid-connected mode, current regulation was achieved through direct power MPC (DPMPC), and voltage regulation during islanded mode was achieved through finite control set MPC (FCS-MPC). Here wind DG acts as GSGFM & it regulates the DC voltage while PV DG acts as GSGFE & it regulates the DC power. Again, PV-based DG's role is fixed, i.e., it acts as GSGFE to regulate power only.

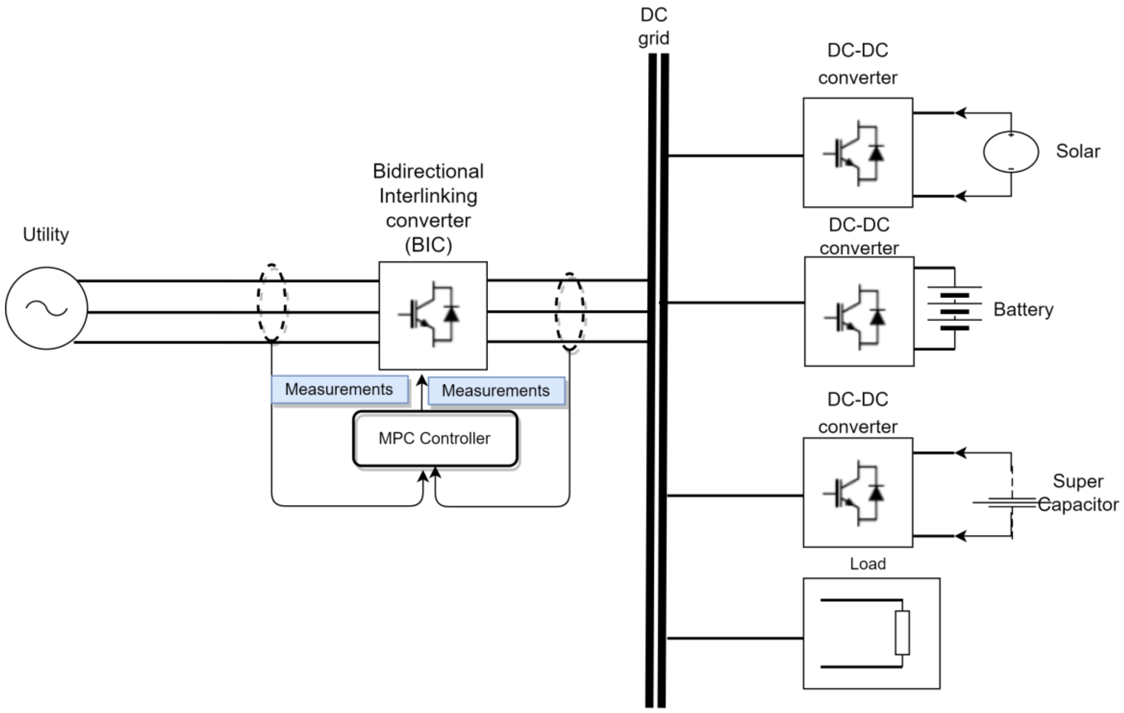


Figure 2.18 Hybrid AC-DC Microgrid with MPC based EMS for AC-DC converter [200]

A fast MPC-PI based control architecture for hybrid energy storage system (HESS) consisting of Superconducting magnetic energy storage (SMES) & battery energy storage system (BESS) based DC MG. DC MG consists of PV, micro gas turbine, wind and HESS. MPC-PI based control has been used to control voltage and power for a microgrid [73]. Voltage regulation was achieved by SMES through PI-MPC while current regulation is achieved by HESS through FCS-MPC. Again, BESS-based DG's role is fixed, i.e., it acts as GSGFE to regulate power only. There are some inherent issues associated with PID such as Pulse Width Modulation (PWM), PID parameters tuning, cascading scheme delayed response issue, complex coordinate transformation, etc. Keeping in view above-mentioned issues, the implementation of PI control becomes intricate when attempting to address complex grid behaviors.

A review paper on MPC was presented that highlighted the contribution of MPC in fault-tolerant control, power quality, and networked microgrids [205]. MPC application at converter level and grid level for hierarchical control has been discussed in detail. The conclusion drawn was that MPC performs better than other linear and non-linear techniques for voltage regulation and current regulation. Another conclusion was that with increasing penetration of RDG units into existing power network, advanced MPC with intelligent controls backed by mathematical formulations can offer a better solution for stable grid operations.

PID based control architecture for frequency regulation has been proposed in [206] for hybrid MG. Hybrid MG consisted of PV, wind and ESS. The gains of PID controller were tuned by QCSHO algorithm for voltage regulation. There are some inherent issues associated with PID such as Pulse Width Modulation (PWM), PID parameters tuning, cascading scheme delayed response issue, complex coordinate transformation, etc. Keeping in view above-mentioned issues, the implementation of PI control becomes intricate when attempting to address complex grid behaviors. MPC has been used to control power for a microgrid consisting of PV and ESS [207]. PV power is being fed into the load and for charging of ESS. Again, PV is used to regulate power only. Current regulation has been realized by classical PID control and state machine control in hybrid AC-DC microgrid with PV and ESS [208]. PV power is being fed into the load and for charging of ESS. Again, PV is used to regulate power only. There are some inherent issues associated with PID such as Pulse Width Modulation (PWM), PID parameters tuning, cascading scheme delayed response issue, complex coordinate transformation, etc. Keeping in view above-mentioned issues, the implementation of PI control becomes intricate when attempting to address complex grid behaviors.

MPC-PI based control has been used to control voltage and power for a microgrid consisting of hybrid energy storage system (HESS) and PV [72]. Voltage regulation and current regulation was achieved by PI while Super Capacitor (SC) SoC variation is managed by MPC. There are some inherent issues associated with PID such as Pulse Width Modulation (PWM), PID parameters tuning, cascading scheme delayed response issue, complex coordinate transformation, etc. Keeping in view above-mentioned issues, the implementation of PI control becomes intricate when attempting to address complex grid behaviors.

2.3 Summary

Summarizing the literature review for hybrid AC-DC microgrid, following conclusions can be drawn:

1. BICs can only act as GSGFM unit to regulate either AC voltage or DC voltage or GSGFE unit to regulate AC-DC power sharing using single layer Proportional Integral Derivative (PID) control scheme [68]. Then by using either multiple BICs with coordination control or multiple layer PID control schemes, BICs are able to achieve multiple roles of GSGFM and GSGFE units to control multiple variables such as AC voltage, DC voltage and power sharing of AC & DC microgrids. There are some inherent issues associated with PI such as Pulse Width Modulation (PWM), PID parameter tuning, cascading scheme delayed response issue, complex coordinate transformation, complex architecture in case of multiple BICs etc. Keeping in view above-mentioned issues, the implementation of PI control becomes intricate when attempting to address complex grid behaviors.

2. RDG are only used as GSGFE unit because of their intermittent nature [69-70]. So, the role of RDG is fixed i.e., they regulate current only. But RDG at their rated power can be used as GSGFM DG.

3. It is certain that BESS allows increasing levels of RDG penetration in the power system; however the primary objective of using BESS in combination with RDG is not to eliminate conventional and polluting generation units, but rather to decrease the no. of units required to stabilize RDG in the hybrid microgrid [49]. Such no. of units required to complement RDG in the hybrid microgrid are typically the not efficient rather they are very expensive. Offsetting the consumption of those units can bring average unit cost down and greenhouse gas emissions Using RDG as GSGFM DG can help to diminish the use of BESS.

4. In islanded mode, BESS are operated as GSGFM units to regulate voltage. Charging of BESS is done in two stages. In first stage, charging is done on the basis of difference between generated and load power. So, charging current is limited and BESS operate as GSGFM unit. In second stage, as BESS achieve threshold voltage (almost fully charged), its voltage must be kept constant and for that BESS should operate as GSGFE unit, so that its current begins to taper approaching asymptotically to zero, while charging continues. The authors have adopted and refined this idea based on [71].

5. MPC is used to operate PV & HESS in GSGFE modes [72-73]. MPC can be used to operate PV in both GSGFM and GSGFE modes but it will need to devise multiple control objective in MPC cost function. MPC provides a framework for multiple control objectives in a cost function by associating weighing factor with each objective. It is worth pointing out that, the performance of MPC is deeply influenced by the weighing factors, the tuning of which is still a challenge to be undertaken [74-75].

In this chapter, literature review of applications being considered in this thesis is presented i.e. BIC & hybrid AC-DC networks, DC/DC converters based microgrids and role of model predictive control. In each application the literature review is presented followed by summarizing the gaps to which our proposed methodology provides a solution. In the next chapter the details of the proposed variable weighing factor based MPC framework for BIC are explained.

Chapter 3

Control of the Bidirectional Interlinking Converter in Hybrid AC-DC Network

3.1 Introduction

In hybrid AC-DC network, both AC & DC grids are connected through Bidirectional interlinking Converter (BIC). BIC is responsible for integration of all DGs, BESS and load in both AC and DC microgrids. Moreover, optimal power flow and control of voltages and power in both microgrids is ensured.

In this chapter, 2L-VSI and VSR topologies have been used for BIC as shown in Figure 3.1. Bidirectional interlinking converter (BIC) topology is used to transfer power from DC grid to AC grid and vice versa. BIC acts as bidirectional converter through six IGBT switches (S1-S6) connected to AC line through series resistance (R_s) and filter inductance (L_s). It has two operating modes. First is the rectifier mode in which the BIC operates as a GSGFMR or GSGFER and allows current or voltage transfer from AC to DC bus as shown in Fig.3.2 (a). Second one is the inverter mode in which BIC acts as a GSGFMI or GSGFEI and allows current or voltage transfer from DC to AC bus as shown in Fig.3.2 (b).

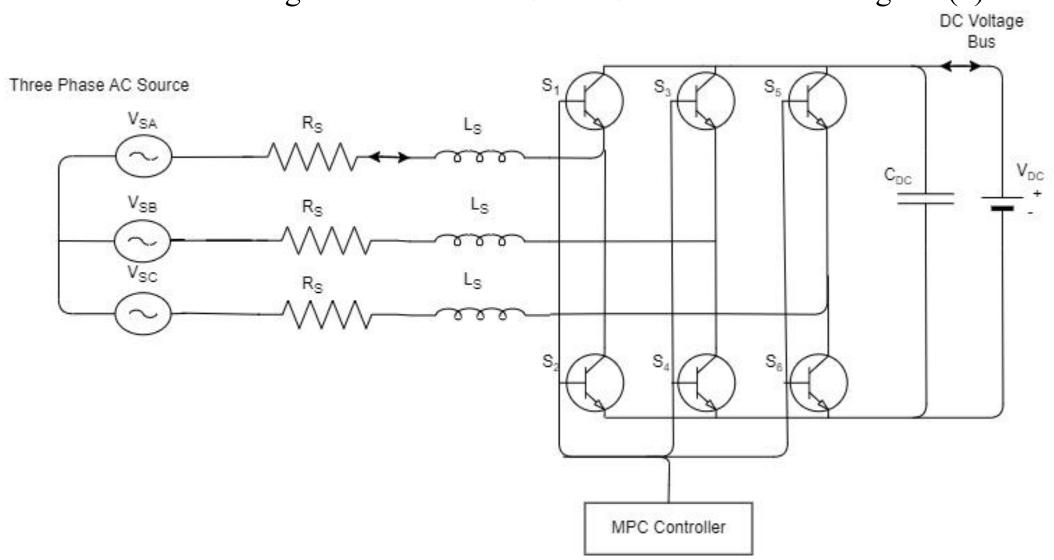
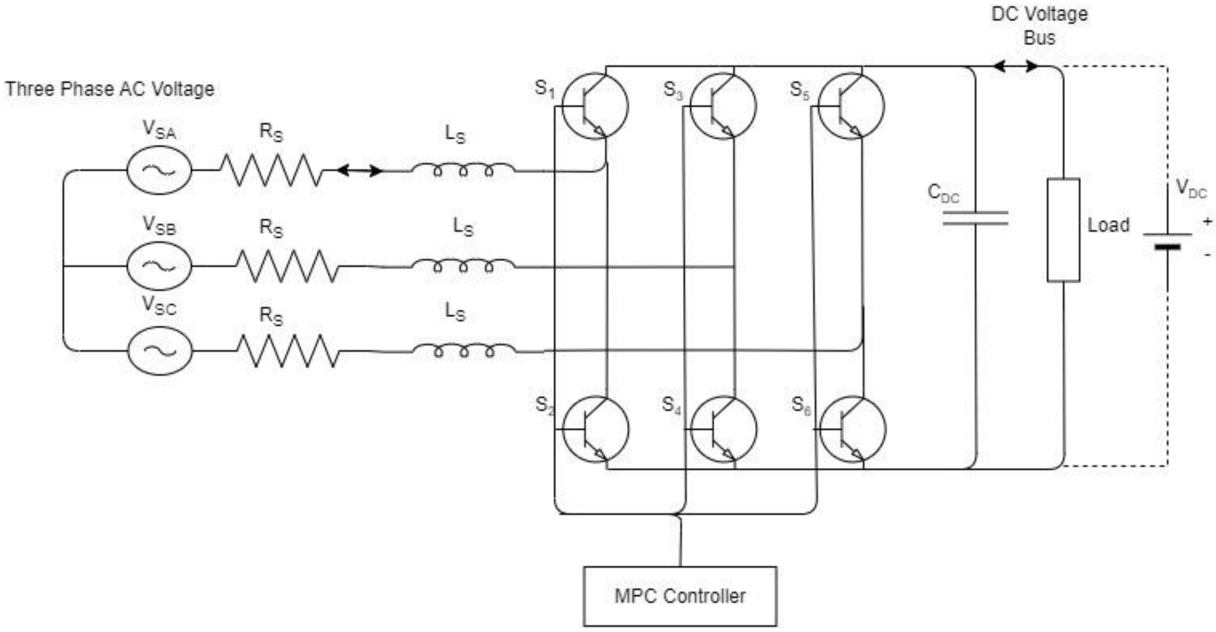
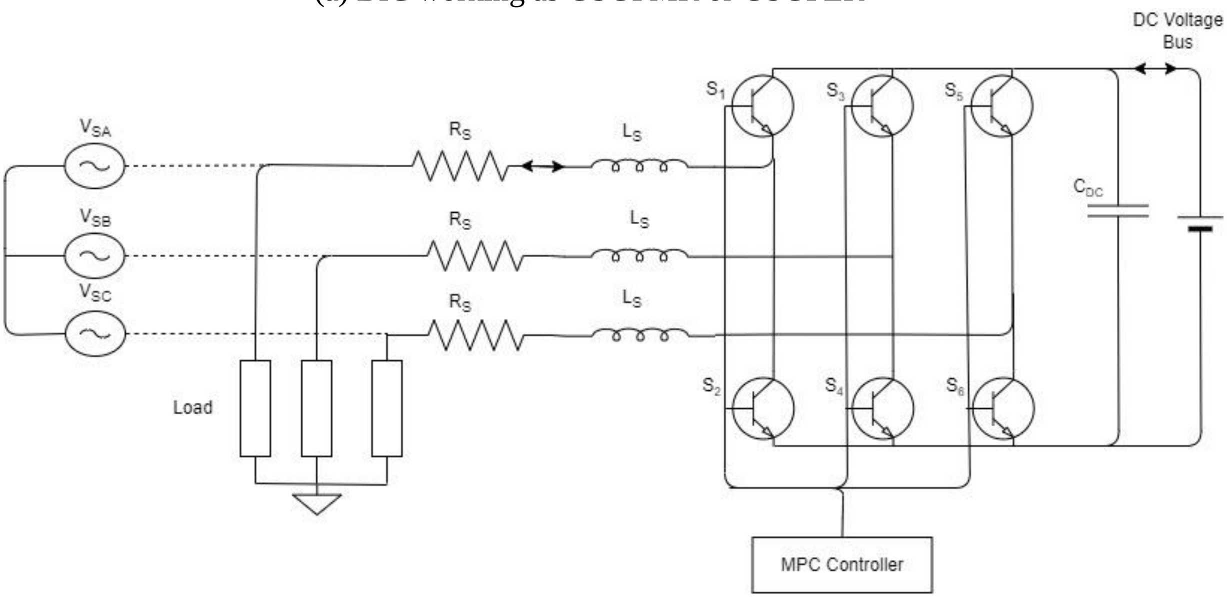


Figure 3.1 Three phase BIC topology



(a) BIC working as GSGFMR or GSGFER



(b) BIC working as GSGFMI or GSGFEI

Figure 3.2 BIC working in rectification or inversion mode

3.2 Problem Formulation

BICs can only act as GSGFM unit to regulate either AC voltage or DC voltage or GSGFE unit to regulate AC-DC power sharing using single layer Proportional Integral Derivative (PID) control scheme [68]. Then by using either multiple BICs with coordination control or multiple layer PID control schemes, BICs are able to achieve multiple roles of GSGFM and GSGFE units to control multiple variables such as AC voltage, DC voltage and power sharing of AC & DC microgrids. There are some inherent issues associated with PI such as Pulse Width Modulation (PWM), PID parameter tuning, cascading scheme delayed response issue, complex coordinate transformation, complex architecture in case of multiple BICs etc. Keeping in view above-mentioned issues, the implementation of PI control becomes intricate when attempting to address complex grid behaviors.

3.3 Proposed Technique

MPC based control algorithm is proposed for BIC to regulate the highest deviated parameter (AC-DC voltage or current) in all non-linear conditions by performing multi-variable control using variable weighing factor algorithm. The proposed algorithm enables BIC to act as a GSGFMI or GSGFMR or GSGFEI or GSGFER. The proposed algorithm can work for BIC in both islanded mode and grid-connected mode. In grid-connected mode, BIC is acting as GSGFER or GSGFEI. In islanded mode, BIC is acting as GSGFMR or GSGFMI so references will be coming from AC grid. The configurations of different modes are already shown in Figure 3.2. Irrespective of source of the references coming from, the proposed algorithm will work as discussed below.

3.4 Model Predictive Control (MPC) Based Variable Weighing Factor Algorithm for BIC

3.4.1 Variable weighing factor algorithm for BIC

Following principles will be followed by variable weighing factor algorithm:

- MPC controller have the capability to control two variables i.e., voltage and current.
- Either voltage or current have to be controlled, is to be decided by weighing factor of MPC cost function.
- Weighing factor would be calculated by evaluating grid condition.
- Weighing factor would be decided such that bidirectional interlinking converter would control the variable that will have most deviation from its reference value. Voltage would be regulated by acting as GSGFM and current would be regulated by acting as GSGFE. As that variable with most deviation comes close to reference value, then bidirectional interlinking converter then will then control other variable having most deviation from its reference value, thus operating in flip flop manner.

3.4.2 MPC cost function

MPC cost function for BIC is written below:

$$Cost(BIC) = \lambda_{VAC}\left(V_{refAC} - V_{outAC}\right)^2 + \lambda_{IAC}\left(I_{refAC} - I_{outAC}\right)^2 + \lambda_{VDC}\left(V_{refDC} - V_{outDC}\right)^2 + \lambda_{IDC}\left(I_{refDC} - I_{outDC}\right)^2 \quad (3.1)$$

Above mentioned cost function, includes weighing factor for 4 variables i.e. AC voltage, AC current , DC voltage and DC current. Single cost function is used in BIC to regulate these 4 variables. Figure 3.3 shows the MPC technique being used to control voltages and currents. According to IEEE Standard 1547 and CERTS microgrid test plan [210], any DG have an interconnection clearing response time of 1sec in case of overvoltage from 121V to 132V and of 2 sec in case of under voltage between 55V to 99V i.e., in islanded mode BIC will first regulate AC voltage by acting as GSGFMI so that AC grid voltage should not exceed beyond 121 V for more than 500msec. If over voltage or under voltage condition persists for more than 500ms then BIC will regulate current by acting as GSGFEI or GSGFER to inject or withdraw AC current. According to IEEE Standard 1547 and CERTS microgrid test plan, if AC grid voltage exceeds more than 132V or less than 55V then DG should regulate it within 0.16sec i.e., in our case BIC will first regulate AC voltage by acting as GSGFMI in islanded mode so that AC grid voltage value should be between 99V to 121 V for more than 0.08 sec. If over voltage or under voltage condition persists for more than 0.08 sec then BIC will regulate current by acting as either GSGFEI or GSGFER to inject or withdraw AC current so that AC grid voltage can be brought to less than 121 V or more than 99V.

Case 1: Voltage deviation in DC grid is less than allowable limit of 10% of rated voltage:

If $(V_{refDC} - V_{outDC}) < 30$V

Then λ_{VDC} = Error (ε); λ_{VAC}=λ_{IAC}=λ_{IDC} = 0;

Case 2: Voltage deviation in AC grid is higher than allowable limits:

If $(V_{refAC} - V_{outAC}) < 22$V

Then λ_{VAC} = Error (ε); λ_{VDC}=λ_{IAC}=λ_{IDC} = 0;

Case 3: Voltage deviation in DC grid is higher than allowable limits:

If $(V_{refDC} - V_{outDCsource}) > 30$V

Then λ_{IDC} = Error (ε); λ_{VAC}=λ_{VDC}=λ_{IAC} = 0;

Case4: AC grid voltage exceeds 132V or less than 55V

If -55V $<(V_{refAC} - V_{outACsource}) > 22$V

Then λ_{IAC} = Error (ε); λ_{VDC}=λ_{VAC}=λ_{IDC} = 0;

3.4.3 Bidirectional interlinking converter (BIC) circuit

Figure 3.3 shows the bidirectional interlinking converter (BIC) topology used to transfer power from DC grid to AC grid and vice versa. BIC acts as bidirectional converter through six IGBT switches (S1-S6) connected to AC line through series resistance (R_s) and filter inductance (L_s). First is the rectifier mode in which the BIC operates as a GSGFMR or GSGFER and allows current or voltage transfer from AC to DC bus. Second one is the inverter mode in which BIC acts as a GSGFMI or GSGFEI and allows current or voltage transfer from DC to AC bus.

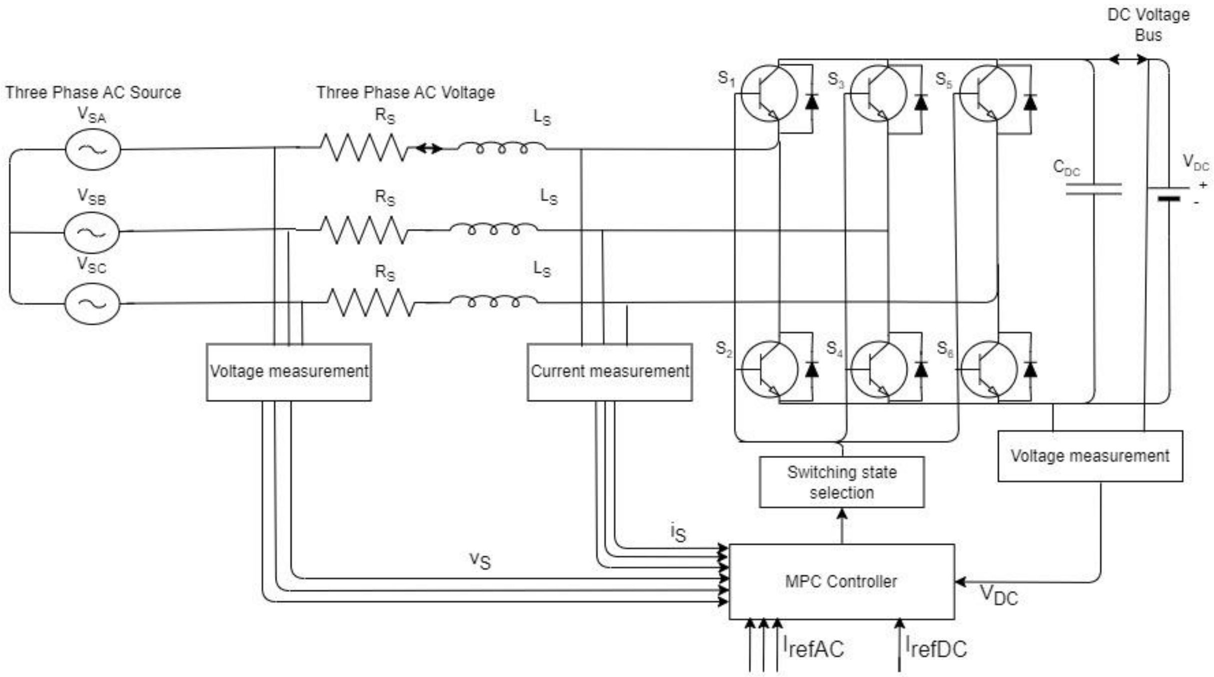


Figure 3.3 MPC control technique for BIC

3.4.4 Working Principle

Three Phase Representation of switching states in terms of gating signals S_a, Sb and S_c is:

$$S_a = \begin{cases} 1, & S_1 \text{ is on and } S_2 \text{ is off} \\ 0, & S_1 \text{ is off and } S_2 \text{ is on} \end{cases}$$

$$S_b = \begin{cases} 1, & S_3 \text{ is on and } S_4 \text{ is off} \\ 0, & S_3 \text{ is off and } S_4 \text{ is on} \end{cases}$$

$$S_c = \begin{cases} 1, & S_5 \text{ is on and } S_6 \text{ is off} \\ 0, & S_5 \text{ is off and } S_6 \text{ is on} \end{cases}$$

Therefore, the switching function vector ($\vec{S}$) of BIC can be expressed as:

$$\vec{S} = \frac{2}{3}(S_a + \vec{\omega} S_b + \vec{\omega}^2 S_c) \tag{3.2}$$

Where, $\vec{\omega} = e^{j2\pi/3} = -0.5 + j0.866$ is a vector representing 120° phase displacement between three phases of AC bus.

3.4.5 Bidirectional Current Control

In this mode, BIC works as GSGFE to regulate DC current by flow of power from AC microgrid to DC microgrid or vice versa as shown in Figure 3.3.

The output voltage space vector ($\overrightarrow{v_{conv}}$) of BIC is as:

$$\overrightarrow{v_{conv}} = \frac{2}{3}\,(v_{ao} + \vec{\omega} v_{bo} + \vec{\omega}^2 v_{co}) \tag{3.3}$$

The relationship between $\overrightarrow{v_{conv}}$, switching function vector ($\vec{S}$) and DC bus voltage (Vdc) can be defined as

$$\overrightarrow{v_{conv}} = \vec{S}\; x\; V\text{dc}. \tag{3.4}$$

There are eight possible voltage space vectors in 2L-VSC configuration as listed in Table 3.1. Loading situation or current voltage value allows power transfer between AC grid and DC grid via BIC. So, BIC works in two modes i.e. Rectifier mode and Inverter mode. Figure 3.4 shows the proposed MPC bidirectional current control algorithm. The detailed description of working of both modes are explained in next subsections:

Table 3.1 Voltage switching table of the bidirectional interlinking converter (BIC)

Switching states			Voltage Space Vector
S_a	S_b	S_c	$\overrightarrow{v_{conv}}$
0	0	0	$\overrightarrow{v_1} = 0$
0	0	1	$\overrightarrow{v_2}$ = [-(1/3)– j($\sqrt{3}/3$)] *V$_{dc}$
0	1	0	$\overrightarrow{v_3}$ = [-(1/3) + j($\sqrt{3}/3$)]*V$_{dc}$
0	1	1	$\overrightarrow{v_4}$ = -(2/3)*V$_{dc}$
1	0	0	$\overrightarrow{v_5}$ = (2/3)*V$_{dc}$
1	0	1	$\overrightarrow{v_6}$ = [(1/3) – j($\sqrt{3}/3$)] *V$_{dc}$
1	1	0	$\overrightarrow{v_7}$ = [(1/3)+ j($\sqrt{3}/3$)] *V$_{dc}$
1	1	1	$\overrightarrow{v_8} = 0$

Kirchhoff's voltage law can be used to define relationship between the input voltage and AC grid output voltage [162]:

$$\overrightarrow{v_s} = L_s \frac{d\overrightarrow{i_{s\_rec}}}{dt} + R_s \overrightarrow{i_{s\_rec}} + \frac{2}{3}\,(v_{ao} + \vec{\omega} v_{bo} + \vec{\omega}^2 v_{co}) - \frac{2}{3}\,(v_{no} + \vec{\omega} v_{no} + \vec{\omega}^2 v_{no}) \tag{3.5}$$

$$\overrightarrow{v_s} = \frac{2}{3}\,(v_{sa} + \vec{\omega} v_{sb} + \vec{\omega}^2 v_{sc})$$

$$\overrightarrow{i_s} = \frac{2}{3}\,(i_{sa} + \vec{\omega} i_{sb} + \vec{\omega}^2 i_{sc}) \tag{3.6}$$

Where v_{sc}, v_{sb}, and v_{sa} represents three phase voltages and i_{sc}, i_{sb}, and i_{sa} represents three phase currents.

$$\frac{2}{3}\,(v_{no} + \vec{\omega} v_{no} + \vec{\omega}^2 v_{no}) = \frac{2}{3}\, v_{no}(1 + \vec{\omega} + \vec{\omega}^2) = 0 \quad (3.7)$$

So, relationship between the input voltage vectors and AC grid output voltage can be defined from (3.3), (3.5) and (3.6) as [192]:

$$\vec{v_s} = L_s \frac{d\vec{\iota_s}}{dt} + R_s \vec{\iota_s} + \overrightarrow{v_{conv}} \quad (3.8)$$

Where $\overrightarrow{v_{conv}}$ = output voltage space vector

$\vec{\iota_s}$ = inductor current vector

$\vec{v_s}$ = space vector model of three-phase ac voltage

So input current dynamics of the BIC is:

$$\frac{d\vec{\iota_s}}{dt} = \frac{1}{L_s}\vec{v_s} + \frac{R_s}{L_s}\overrightarrow{\iota_s} - \frac{1}{L_s}\overrightarrow{v_{conv}} \quad (3.9)$$

Since MPC is a discrete-time based controller, so time-domain equations of BIC for both the modes of operation represented in (3.10) and (3.11) respectively, have been converted into discrete-time domain. Euler approximation have been used to find the current and voltage future values in kth sampling interval, from voltages and currents of previous $(k-1)$th sampling interval:

$$\mathrm{dx/dt} = [\mathrm{x(k)} - \mathrm{x(k-1)}]/\mathrm{Ts} \quad (3.10)$$

By using future value of the above approximation, future values of currents and voltages of BIC in both modes can be predicted in next $(k+1)$ sampling instant. Future value of input current in (k+1) sampling instant for BIC can be predicted from Euler approximations as:

$$\vec{\iota_s}(k+1) = \frac{1}{R_s T_s + L_s}\{L_s i_s(k) + T_s[v_s(k) - \overrightarrow{v_{conv}}(k)]\} \quad (3.11)$$

Rectifier mode of operation

Future value of input current in (k+1) sampling instant in rectifier mode for BIC can be predicted from Euler approximations as:

$$\overrightarrow{\iota_{s\_rec}}(k+1) = \frac{1}{R\ \ T_s + L_s}\left\{L_s i_{s\_rec}(k) + T_s[v_s(k) - \overrightarrow{v_{conv\_rec}}(k)]\right\} \quad (3.12)$$

Inverter Mode of Operation

Again, the future values of inverter currents $(k+1)$ sampling instant in inverter mode for BIC can also be evaluated as:

$$\overrightarrow{\iota_{s\_inv}}(k+1) = \frac{1}{R_s T_s + L_s}\left\{L_s i_{s\_inv}(k) + T_s[\overrightarrow{v_{conv\_inv}}(k) - v_s(k))]\right\} \quad (3.13)$$

3.4.6 Bidirectional Voltage Control

The methodology of MPC to control three-phase AC and DC grid voltages through BIC is described in this section. Figure 3.5 shows the proposed MPC bidirectional voltage control algorithm. In discrete-time domain. The future voltage vector $\vec{v}(k+1)$ can be written as:

$$\vec{v}(k+1) = \overrightarrow{v_{conv}}(k+1) + \square(\mathrm{k+1}) \tag{3.14}$$

Where, □(k+1) gives quantization error for voltage vector. The future error vector of the input current from (3.12) is

$$\overrightarrow{\iota_{error}}(k+1) = \overrightarrow{\iota_s}(k+1) - \overrightarrow{\iota_{ref}}(k)$$
$$= \frac{1}{R_S T_S + L_S}\{L_s i_s(k) + T_s[v_s(k) - \overrightarrow{v_{conv}}(k)]\} - \overrightarrow{\iota_{ref}}(k) \tag{3.15}$$

Basic purpose of model predictive control is to make current tracking error ($\overrightarrow{\iota_{error}}$) zero which means that current ($\overrightarrow{\iota_s}$) follow the reference current value ($\overrightarrow{\iota_{ref}}$) for both both the modes i.e., rectifier and inverter modes. Lyapunov direct method have been utilized to make current tracking error zero and is evaluated as:

$$L = \frac{1}{2}[\overrightarrow{\iota_{error}\ (k)]}^T[\overrightarrow{\iota_{error}\ (k)]} \tag{3.16}$$

Rate of change (Del Δ) of the Lyapunov function from (3.14) and (3.16) is:

$$\Delta L(k) = L\ (\overrightarrow{\iota_{error}}(k+1) - L\ (\overrightarrow{\iota_{error}}(k))) \tag{3.17}$$

Lyapunov function for current tracking error will be

$$L\ (\overrightarrow{\iota_{error}}(k+1) = \frac{1}{2}[\overrightarrow{\iota_{error}\ (k+1)]}^T[\overrightarrow{\iota_{error}\ (k+1)]} \tag{3.18}$$

Current tracking error from (3.15) will put (3.18) to:

$$\Delta L(k) = \frac{1}{2}[\frac{1}{R_S T_S + L_S}\{L_s\overrightarrow{\iota_s}\ (k) + T_s[v_s(k) - \overrightarrow{v_{conv}}(k) - \delta(k+1)] - \overrightarrow{\iota_{ref}}(k)\}]^T \ \mathrm{x}\ \frac{1}{2}[\frac{1}{R_S T_S + L_S}$$
$$\{L_s\overrightarrow{\iota_s}\ (k) + T_s[v_s(k) - \overrightarrow{v_{conv}}(k) - \delta(k+1)] - \overrightarrow{i_{ref}}(k)\}] - \frac{1}{2}[\overrightarrow{\iota_{error}\ (k)]}^T[\overrightarrow{\iota_{error}\ (k)]}$$

(3.19)

The discrete voltage vector at next sampling instant for the BIC is

$$\overrightarrow{v(k+1)} = \frac{L_S}{T_S} i_s(k) + \overrightarrow{v_s(k)} - \frac{R_S\,T_S + L_S}{T_S}\overrightarrow{\iota_{ref}}(\mathrm{k}) \tag{3.20}$$

Rectifier mode of operation

The future voltage vector for next sampling instant for the rectifier mode is

$$\overrightarrow{v_{rec}(k+1)} = \frac{L_S}{T_S} i_{S_{rec}} + v_s(k) - \frac{R_S\,T_S + L_S}{T_S}\overrightarrow{\iota_{ref\_rec}}(\mathrm{k}) \tag{3.21}$$

Inverter Mode of Operation

The future voltage vector for next sampling instant for the inverter mode is

$$\overrightarrow{v_{inv}(k+1)} = -\frac{L_S}{T_S} i_{S_{inv}} + v_s(k) + \frac{R_S\,T_S + L_S}{T_S}\overrightarrow{\iota_{ref\_inv}}(\mathrm{k}) \tag{3.22}$$

3.4.7 Stability Analysis

Lyapunov direct method is being used to derive equations for BIC to act as GSGFMI or GSGFMR. In this section, stability analysis of GSGFMI equation (3.22) and GSGFMR equations (3.23) will be done with direct lyapunov method.

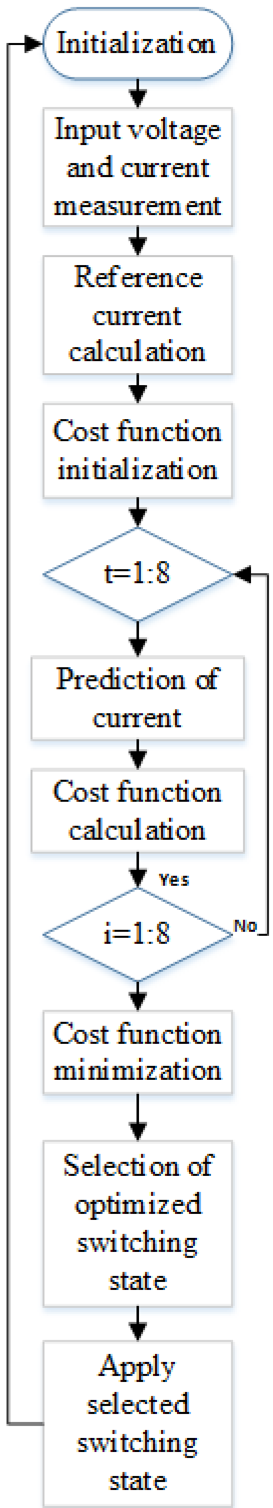


Figure 3.4 MPC bidirectional current control algorithm

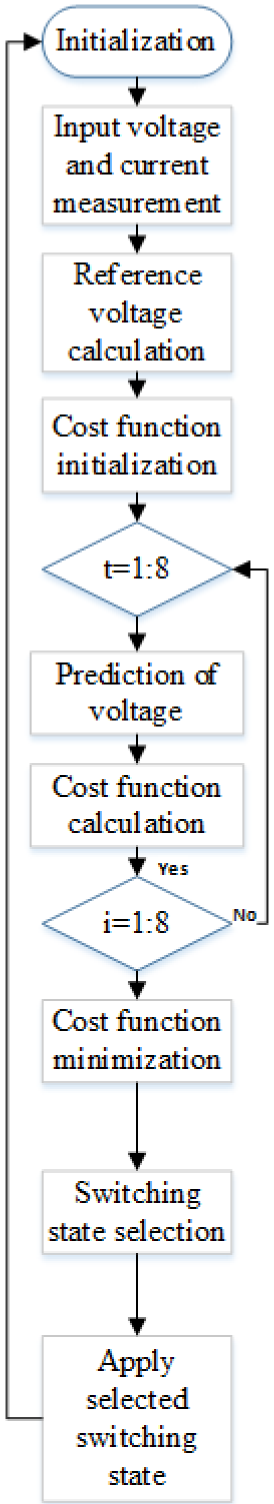


Figure 3.5 MPC bidirectional voltage control algorithm

Stability Analysis with Direct Lyapunov method

Lyapunov direct method is being used to verify the stability of voltage regulation capability of BIC. The stability criteria given by lyapunov direct method for a function $L\ (\overrightarrow{\iota_{error}}(k))$ of GSGFMI equation (3.22) and GSGFMR equations (3.23) is ultimately and uniformly bounded [195]:

$$L\left(\overrightarrow{\iota_{error}}\ (k)\right) \geq c_1|\overrightarrow{\iota_{error}}\ (k)|^l \qquad \forall \overrightarrow{\iota_{error}}\ (k)\ \in G$$
$$L\left(\overrightarrow{\iota_{error}}\ (k)\right) \leq c_2|\overrightarrow{\iota_{error}}\ (k)|^l \qquad \forall \overrightarrow{\iota_{error}}\ (k)\ \in G \tag{3.24}$$
$$L\left(\overrightarrow{\iota_{error}}\ (k+1)\right) -\ L\left(\overrightarrow{\iota_{error}}\ (k)\right) < -c_3|\overrightarrow{\iota_{error}}\ (k)|^l + c_4$$

In above equations, c_1-c_4 all are constant with positive value, $l \geq 1$, $G \subseteq\ R^n$ is invariant set with positive constant values. $\Gamma \subset G$ belongs to set of compact values. Future voltage vector $\vec{v}\ (k+1)$ is being applied for BIC rectifier mode equation (3.22) and inverter mode equation (3.23), then derivative (Del Δ) of the Lyapunov function is:

$$\Delta \mathrm{L(k)} \leq -\tfrac{1}{2}[\overrightarrow{\iota_{error}}\ (k)]^T[\overrightarrow{\iota_{error}}\ (k)] + \tfrac{1}{2}(T_s/(R_sT_s\ +\ \mathrm{L}))^2 \tag{3.25}$$

Stability condition outlined in (3.24) is being verified through constant values:

$$c_1 = c_2 = 1;\ c_3 =\ \tfrac{1}{2};\ c_4 = \tfrac{1}{2}(T_s/(R_sT_s\ +\ \mathrm{L}))^2 \tag{3.26}$$

So, using these constant values, all the variables in Lyapunov function comes out to be uniformly bounded. So derivative (Del Δ) of the Lyapunov function in (3.23) is:

$$\Delta \mathrm{L(k)} \leq -2c_3L\left(\overrightarrow{\iota_{error_{\iota nv}}}\ (k)\right) + c_4 \tag{3.27}$$

In Lyapunov's direct method, value for derivative of the Lyapunov function shown in (3.27) should be negative which shows that the considered system is stable as shown in Appendix A.1 [211]. The stability of the proposed varying weighing factor based MPC algorithm is checked in section 3.6 results as well. During rectifier mode of operation and inverter mode of operation both voltages and currents are disturbed and response by MPC controller is monitored which showed that disturbances are mitigated by reaching steady state condition within 0.05sec depicting a fast dynamic response. More details can be found out in section 3.6 from case 1 to case 4 results.

3.5 Setting up variable weighing factor

An auto-tuning method to select the value of weighing factor (λ_{VDC} & λ_{IDC}) has been proposed in this section. This method directly affects the robustness and overall performance of the proposed MPC controller in abnormal or fault conditions. In this method, calculations to select optimal weighing factors are performed in every sampling interval. The weighing factors are calculated dynamically, such that highest priority is assigned to a given objective which has large error that should be corrected. So, weighing factor represents the urgency of correcting the largest error. In Fig. 3.6, (ε) represents the amplitude of the error which is to be corrected by increasing or decreasing converter output. If a large fixed error (Kε) exists, it is essential to apply appropriate switching state of the converter using MPC to reduce the error.

On the other hand, if a small error (ε) exists, a correction is not as important and higher priority can be given to other objectives. Since ξ provides a good measure of the existing error and, because of the "urgency" of correcting it, the weighing factor could be defined proportionally to ξ. However, this would mean that the weighing factor would be almost zero whenever the error is small, which would increase the error. To avoid this, a minimum value of the weighing factor is taken as 1 in this chapter. This value is used whenever the error is lower than a predefined boundary of ε, as shown in Fig. 3.6. The limit ε represents the maximum admissible error in normal operation. Once the error surpasses ε, the weighing factor increases linearly with the error. The selection of optimal weighing factors involves predicting errors of all the controllers' objectives which are current & voltage in both operational modes. For every controller, controller objective may vary in both modes, i.e., for AC-DC converter, controller objective is to predict error for voltage and current in grid-connected mode, for Solar, wind & battery DG's controller objective is to predict error for voltage & power in standalone mode and power in grid-connected mode.

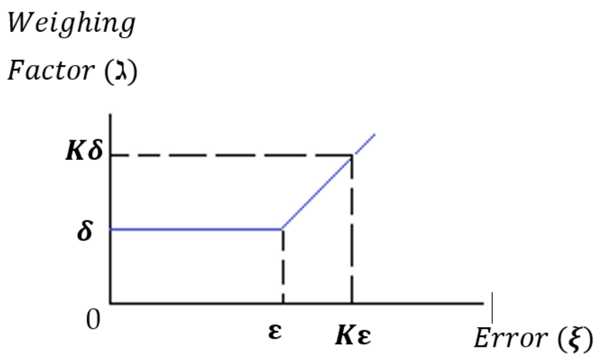


Figure 3.6 Weighing factor as a function of the error.

Traditionally in MPC Controllers, the cost function is minimized, and a corresponding switching vector is applied. The proposed algorithm performs auto-tuning of the weighing factor and then minimizes the cost function for the next sampling period. So, the cost function in Eq. 3.1 is being split into two parts with each part affecting individual control objectives:

$$g_V = \frac{1}{V_{rated}} |V_{ref}(k+1) - V_{out}(k+1)| \le \psi_V \quad (3.28)$$

$$g_I = \frac{1}{I_{rated}} |I_{ref}(k+1) - I_{out}(k+1)| \le \psi_I \quad (3.29)$$

Ψ_V and Ψ_I are the tracking errors for voltage and current regulation objectives. A minimum value of cost function (g_V & g_I) and their corresponding possible switching states have been selected as follows:

$$\xi_V = \min g_V \tag{3.30}$$

$$\xi_I = \min g_I \tag{3.31}$$

Now above-mentioned minimum values are compared with a small number (ε):

$$\xi_V \leq \varepsilon \rightarrow \lambda_{VDC} = \delta \tag{3.32}$$

$$\xi_I \leq \varepsilon \rightarrow \lambda_{IDC} = \delta \tag{3.33}$$

The above equations state that if cost functions (g_V & g_I) are smaller than ε, then weighing factors (λ_{VDC}& λ_{IDC}) are assigned a small number δ initially. However, if the condition in the above equations is not satisfied, then weighing factors (λ_{VDC}& λ_{IDC}) are assigned high values to set the highest priority in their relevant cost function for (k+1) sampling interval minimization cycle as follows:

$$\xi_V \leq K\varepsilon \rightarrow \lambda_{VDC} = K\delta \tag{3.34}$$

$$\xi_I \leq K\varepsilon \rightarrow \lambda_{IDC} = K\delta \tag{3.35}$$

Where $K \in \{2,3, \dots, N\}$.

The algorithm for weighing factor selection based on absolute errors ξ_V and ξ_I is shown in Figure 3.9. Above equation quantized $\boldsymbol{\xi_V}$ & $\boldsymbol{\xi_I}$ through which weighing factors are determined by comparing $\boldsymbol{K}$ multiples of $\boldsymbol{\varepsilon}$ until equation (3.34) & (3.35) confirms variable objective. Weighing factors ($\boldsymbol{\lambda_{VDC}}$& $\boldsymbol{\lambda_{IDC}}$) are multiplication of $\boldsymbol{K}$ by $\boldsymbol{\varepsilon}$. Three weights $\boldsymbol{K3}, \boldsymbol{K2}$ & $\boldsymbol{K1}$ have been shown with K3 being assigned to the variable having more ξ shown in Fig. 3.7. This algorithm will be run every cycle of sampling time, so weighing factors will be tuned online to minimize the cost function (3.28) & (3.29) for the next cycle.

The above equations state that if cost functions (g_V and g_I) are smaller than $\boldsymbol{\varepsilon}$, then weighing factors (λ_{VDC} and λ_{IDC}) assumed as smaller constant δ (initial value). However, if the condition in the above equations is not satisfied, then weighing factors (λ_{VDC} and λ_{IDC}) are assigned much higher values to minimize the cost function in (k + 1) sampling interval, as follows:

$$\begin{gathered} \xi_V \leq K\varepsilon \rightarrow \lambda_{VDC} = K\delta \\ \xi_I \leq K\varepsilon \rightarrow \lambda_{IDC} = K\delta \end{gathered} \tag{3.36}$$

where $K \in \{2,3, \dots, N\}$.

For assigning weighing factors (λ_{VDC} and λ_{IDC}), δ is assumed as an initial value by using the branch and bound algorithm. The algorithm is applied to get the exact value of the weighing factor in one significant figure for which quantized error (ξ_V and ξ_I) is equal to zero.

In the branch and bound algorithm, exploration of the best possible weighing factor that minimizes the cost function is conducted for different values of "*K*", and that value of *K* with one significant figure is selected for which quantized error is equal to zero. A flow diagram of the branch and bound algorithm is shown in Figure 3.8.

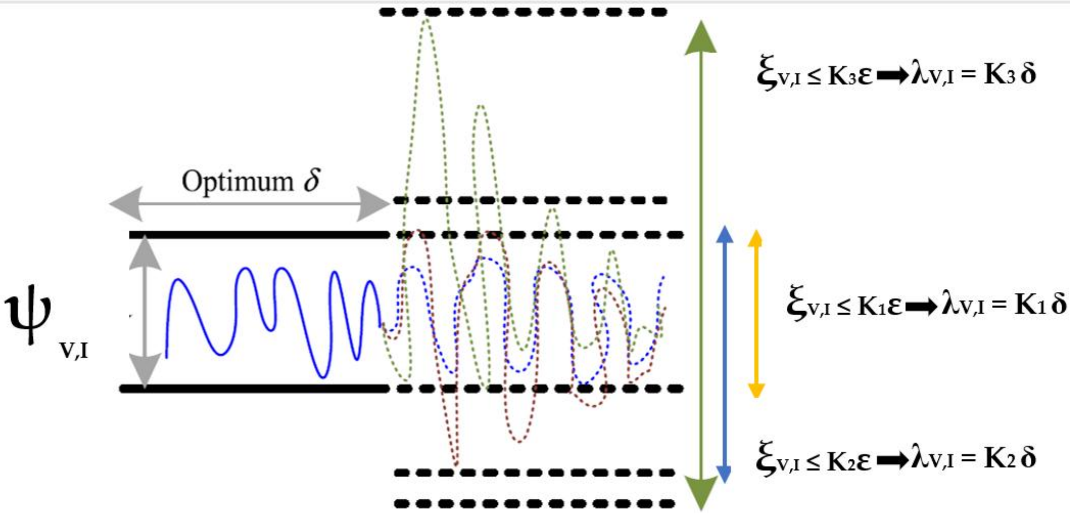


Figure 3.7 Tuning of weighing factors with respect to tracking error.

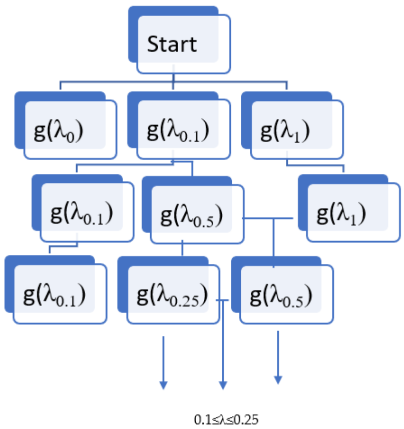


Figure 3.8 Flow diagram of branch and bound algorithm

3.6 Results

The proposed MPC algorithm is implemented in MATLAB/Simulink to validate its performance. BIC has been operated in inverter and rectifier mode to validate the results. Table 3.2 shows the values of the parameters used in BIC simulation. Formula for filter design is given below with calculations in appendix [212]:

$$L = \frac{V_{DC}}{4F_{SW}\Delta I_{pmax}} \tag{3.37}$$

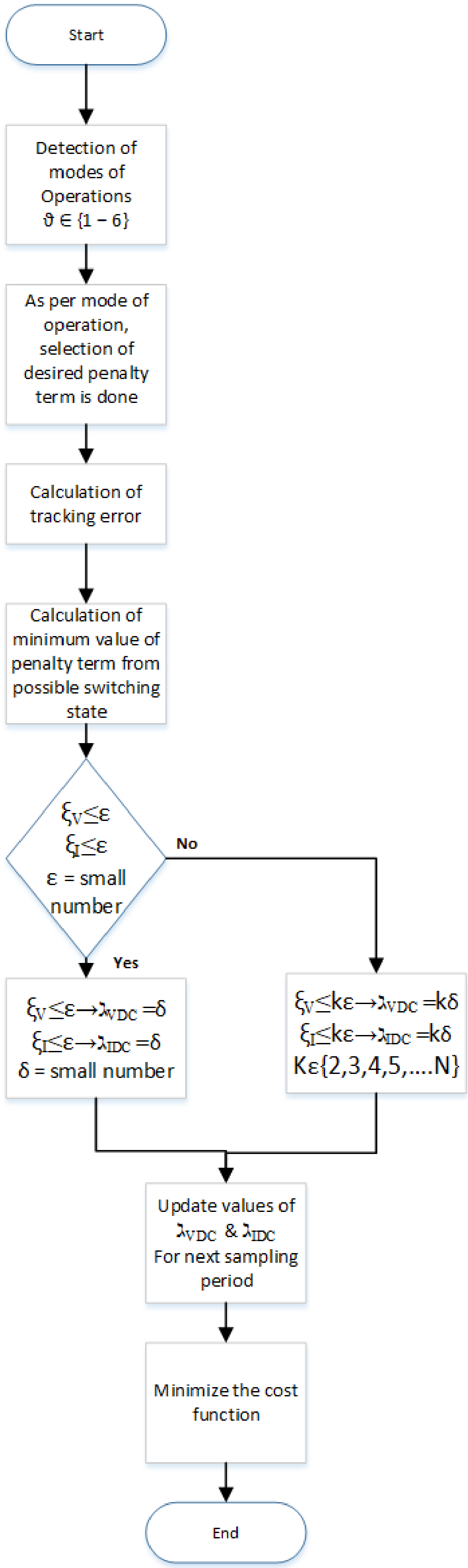


Figure 3.9 Setting up weight factor for variable weighing factor algorithm

Table 3.2 Simulation Parameters [161]

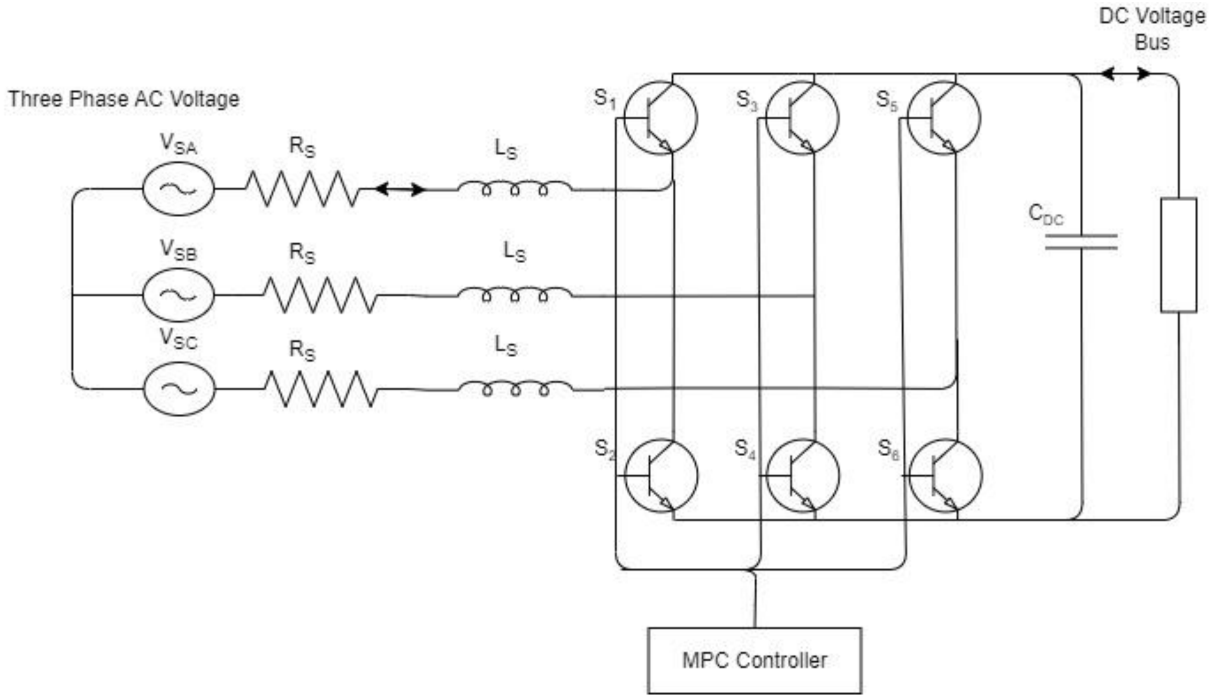
Parameters	Values
Rated Power	1.5 KW
AC grid voltage	110 V
AC grid frequency	60 Hz
DC grid voltage	300 V
Inductance	5 mH
Resistance	0.1 Ω
Sampling time (Ts)	50 µsec
DC Load 1	0.75 KW
DC Load 2	1.5 KW
AC Load 1	0.33 KW
AC Load 2	0.66 KW
Capacitor	1000 uF

Table 3.3 BIC roles in different cases

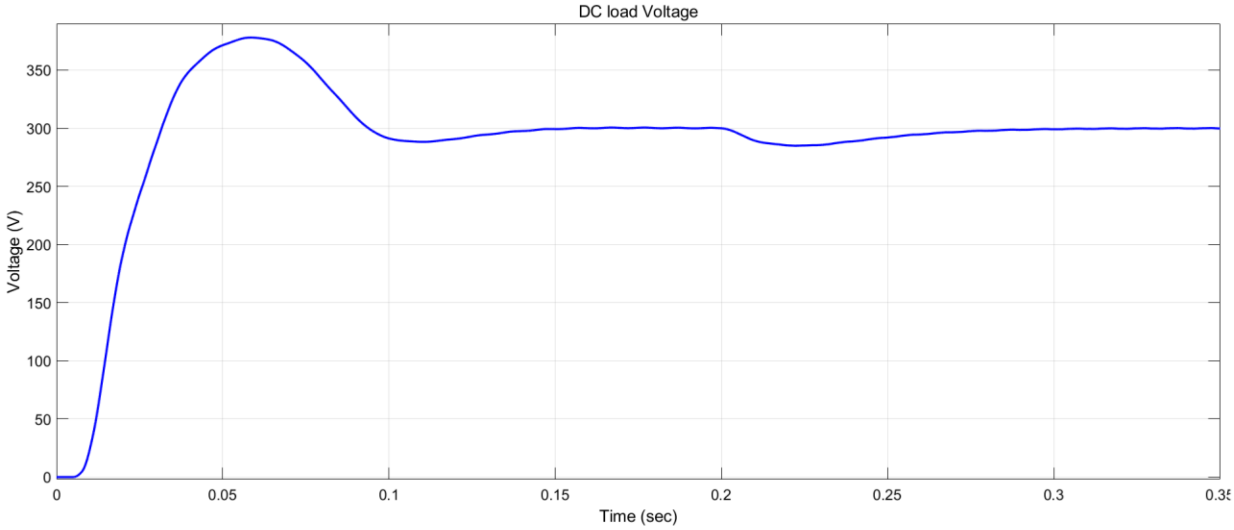
Cases	Highest deviation	BIC role
Case-1	DC Voltage	GSGFMR
Case-2	AC voltage	GSGFMI
Case-3	DC current	GSGFER
Case-4	AC current	GSGFEI

Case-1

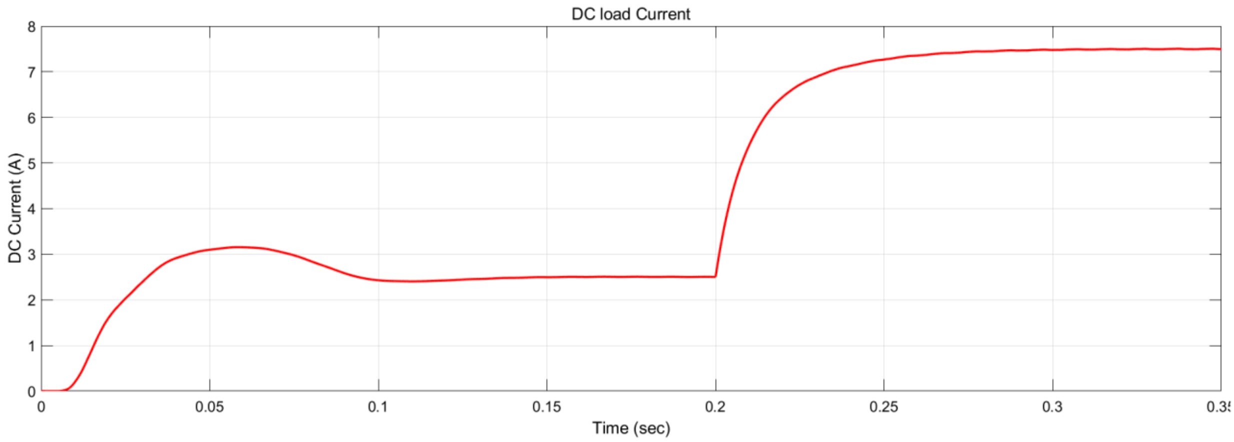
In this case, BIC acting as GSGFMR to regulate DC voltage is simulated. First, load 1 is connected. After the initial transients, BIC stabilizes the DC voltage at 300V at 0.12sec as shown in Fig. 3.10 (b) and at that point, weighing factor achieves zero value as shown in Fig. 3.10 (d). After that, BIC response to DC voltage fluctuation has been tested. In Figure 3.10 (b), at t = 0.2sec, small voltage fluctuation was introduced by adding load 2. Due to addition of DC load, DC voltage reduces to 280V and weighing factor achieves value of 20. BIC acts as GSGFMR, restores the voltage to 300V in 0.06sec. At that point weighing factor again achieves zero value.



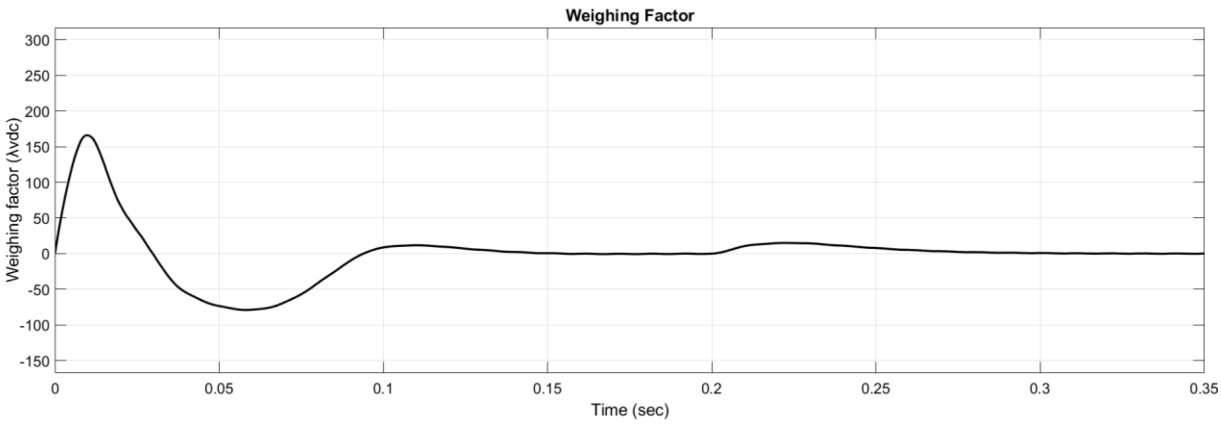
(a) BIC circuit acting as GSGFMR



(b) DC voltage with BIC acting as GSGFMR



(c) DC current with BIC acting as GSGFMR

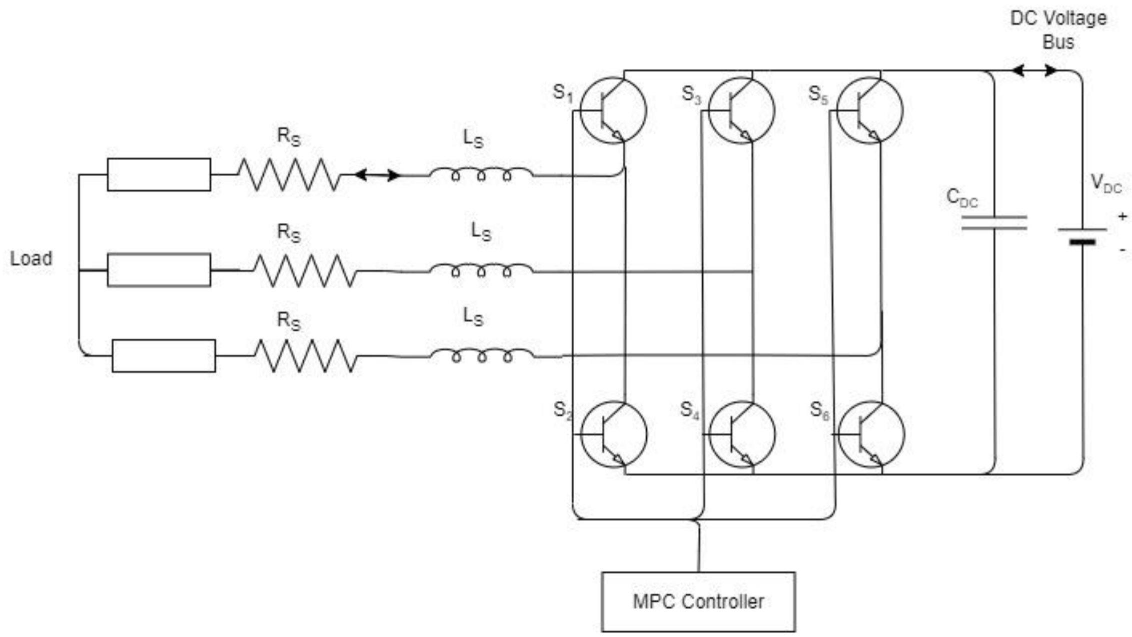


(d) Weighing Factor for BIC acting as GSGFMR

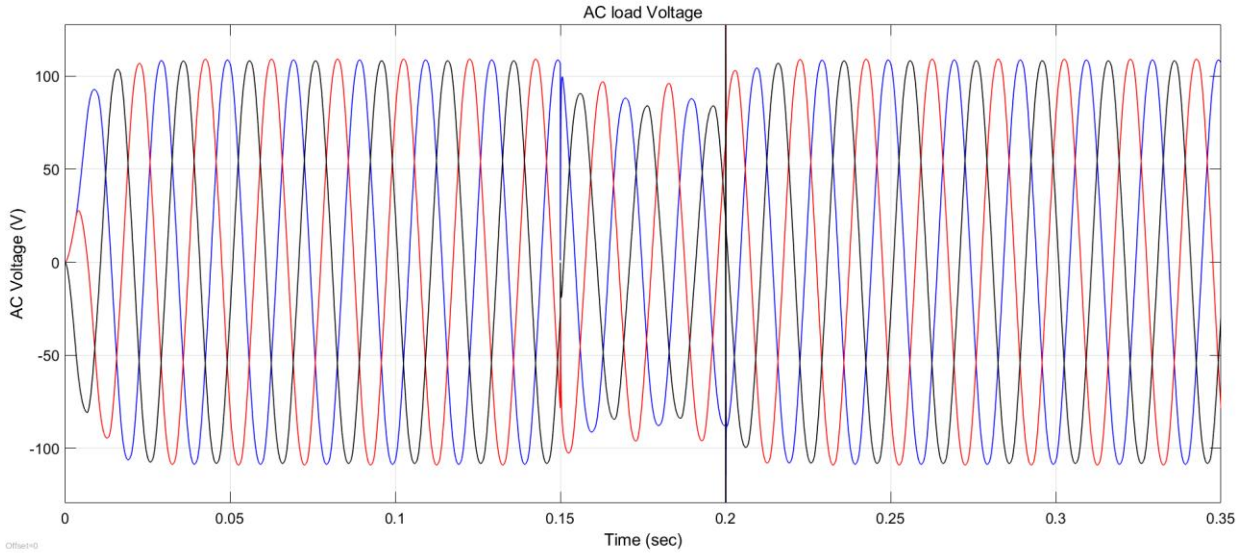
Figure 3.10 "DC voltage and current waveforms with BIC acting as GSGFMR"

Case-2

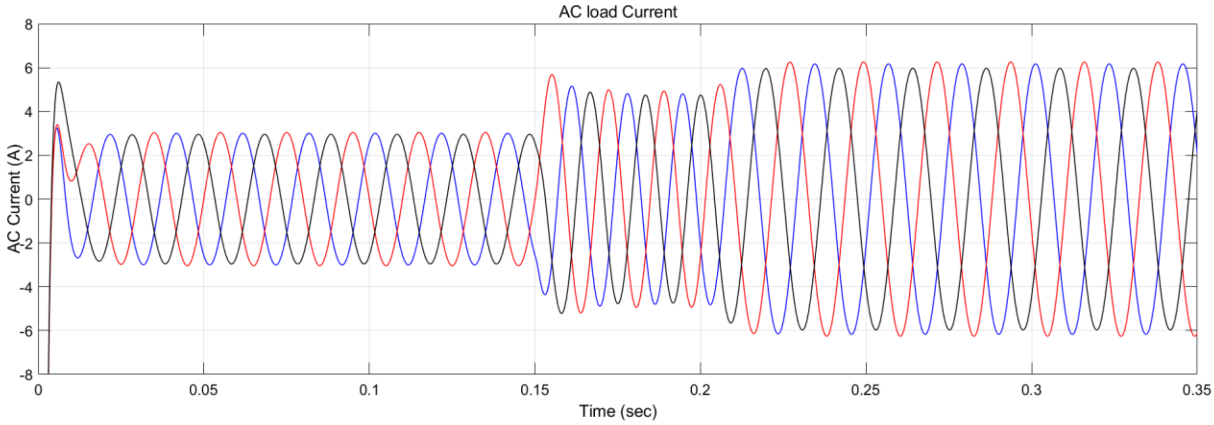
In this case, BIC acting as GSGFMI to regulate AC voltage is simulated as shown in Fig. 3.11 (a). First, AC load 1 is connected. After the initial transients, BIC stabilizes the AC voltage at 110V at 0.04 sec as shown in Fig. 3.11 (b) and at that point, weighing factor achieves zero value as shown in Fig. 3.11 (d). After that, BIC response to AC voltage fluctuation has been tested. In Figure 3.11 (b), at t = 0.15 sec, small voltage fluctuation was introduced by adding AC load 2. Due to addition of AC load, AC voltage reduces to 90V and weighing factor achieves value of 20. BIC acts as GSGFMI, restores the voltage to 110V in 0.06sec. At that point weighing factor again achieves zero value.



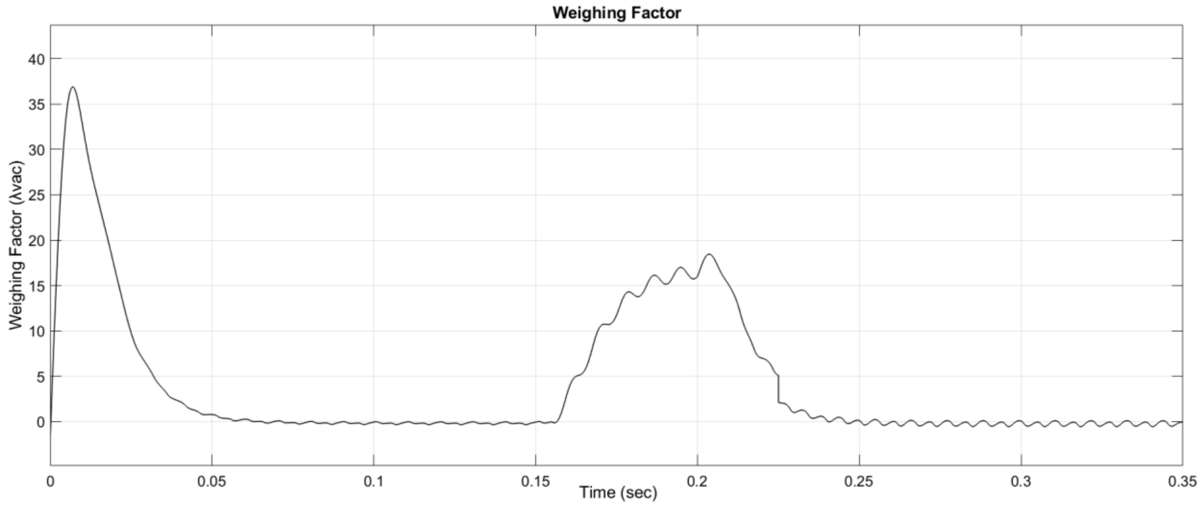
(a) BIC circuit acting as GSGFMI



(b) AC voltage with BIC acting as GSGFMI



(c) AC current with BIC acting as GSGFMI

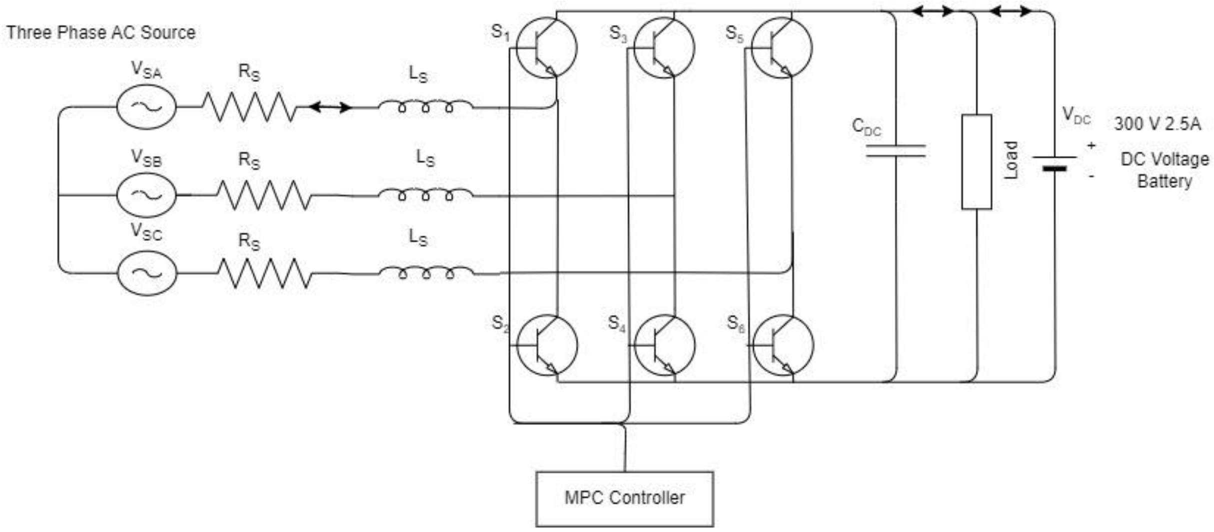


(d) Weighing Factor for BIC acting as GSGFMI

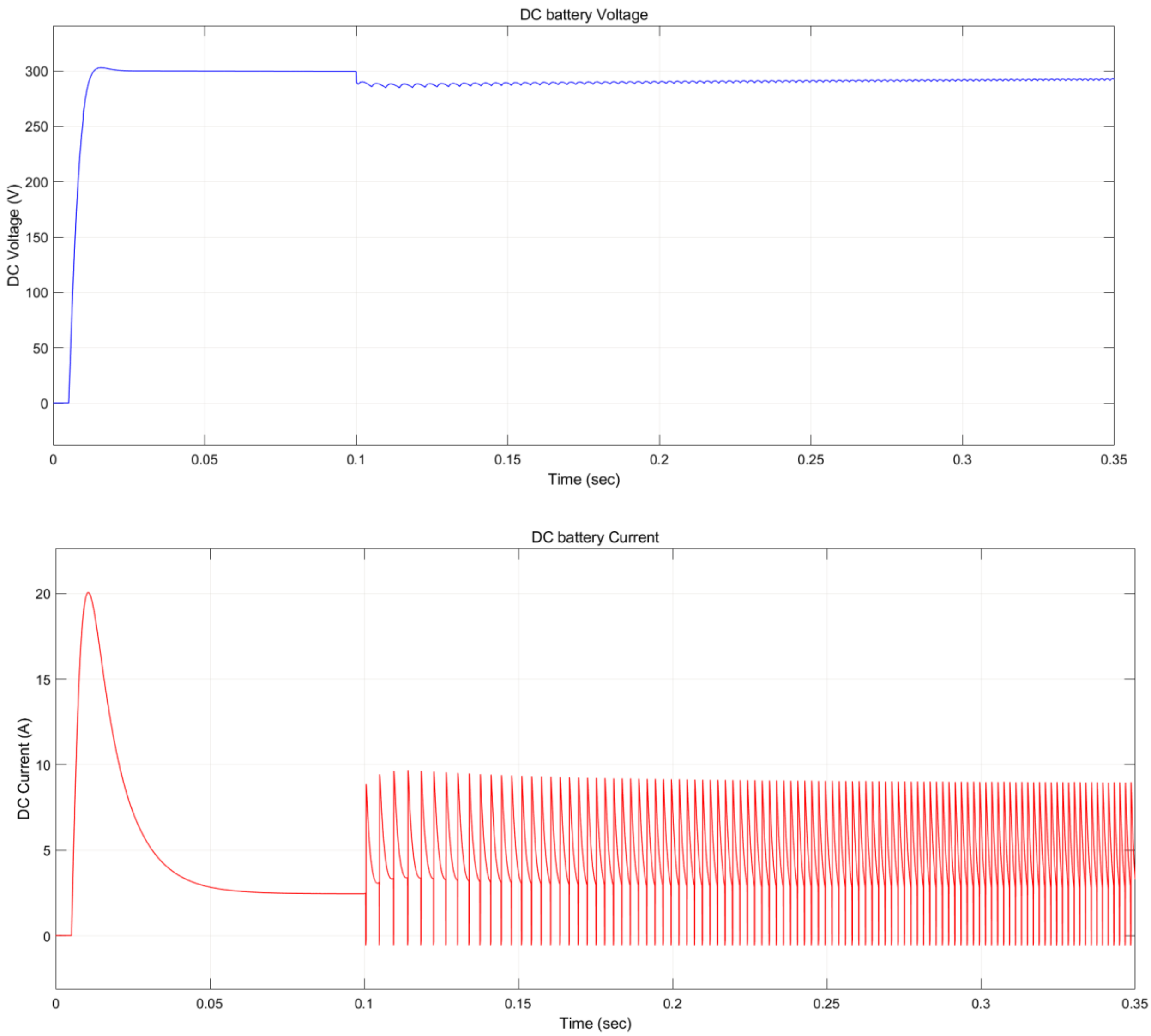
Figure 3.11 "DC voltage and current waveforms with BIC acting as GSGFMI"

Case-3

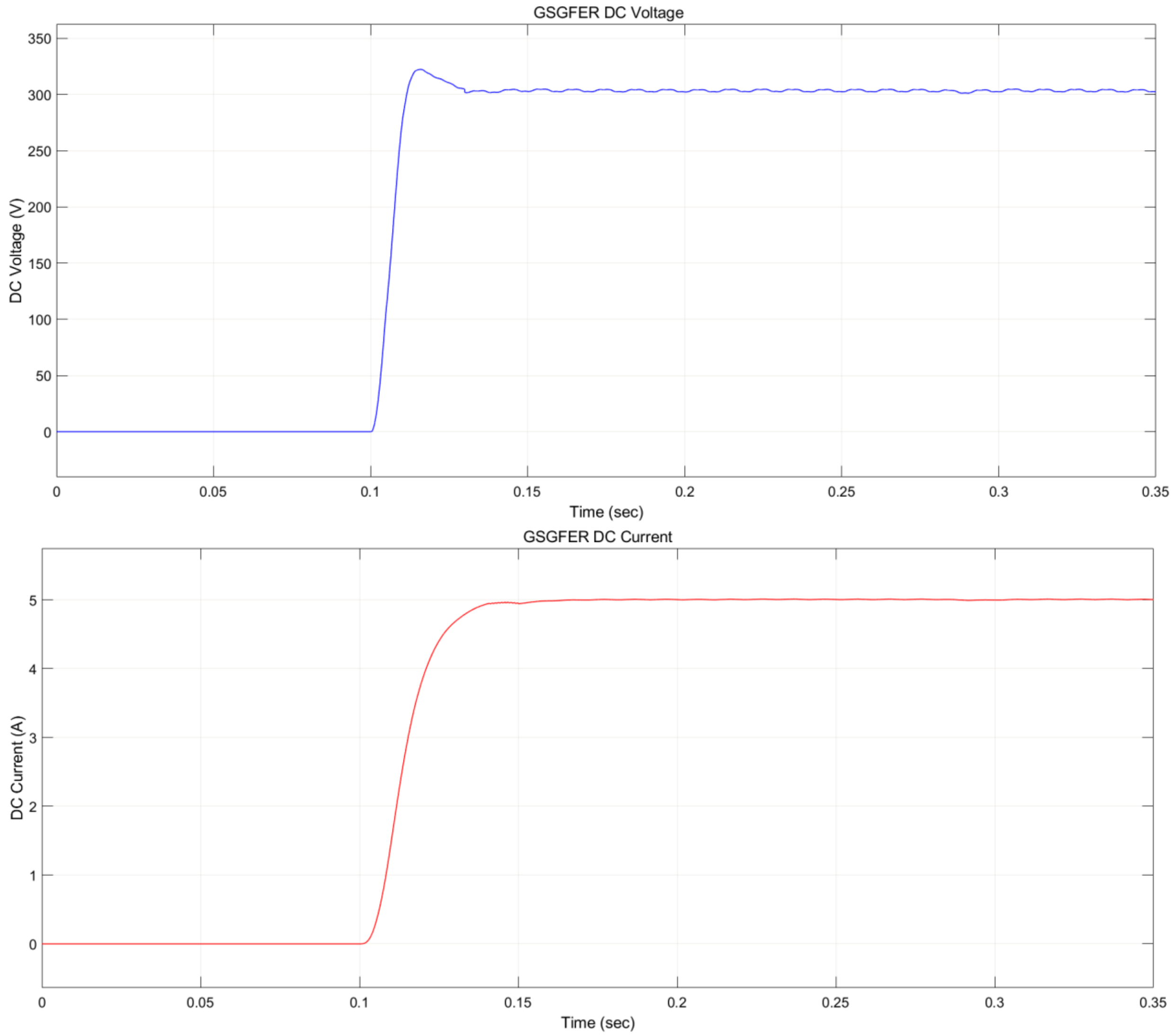
In this case, BIC acting as GSGFER to regulate DC current is simulated as shown in Fig. 3.12 (a). First of all, DC load 1 is connected. After the initial transients, DC battery stabilizes the DC voltage to 300V and DC current to 2.5A at 0.02 sec as shown in Fig. 3.12 (b). At 0.1sec, DC load 2 is connected and voltage and current waveforms of DC battery is distorted, as it cannot support DC load 2 as shown in Fig. 3.12 (b). After that, BIC response to AC voltage fluctuation has been tested. At this point, BIC start acting as GSGFER and start injecting 5A current to support DC load 2 as shown in Fig. 3.12 (c). DC current stabilizes to 5A at 0.15sec thus; GSGFER stabilizes DC current in 0.05 sec. Initially BIC is not acting as GSGFER so weighing factor is zero but at 0.1 sec with BIC acting as GSGFER, weighing factor achieves value of 5 and ultimately it achieves zero value at 0.15sec as shown in Fig. 3.12 (d). Fig. 3.12 (e) shows voltage and current waveforms of DC load showing current regulation achieved successfully by BIC acting as GSGFER within 0.05 sec.



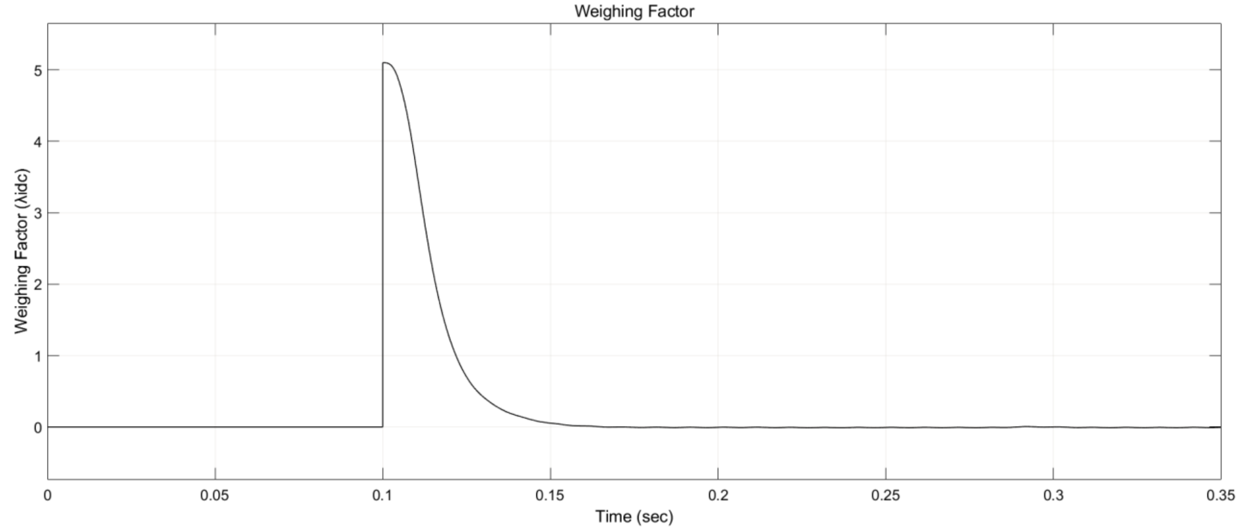
(a) BIC circuit acting as GSGFER



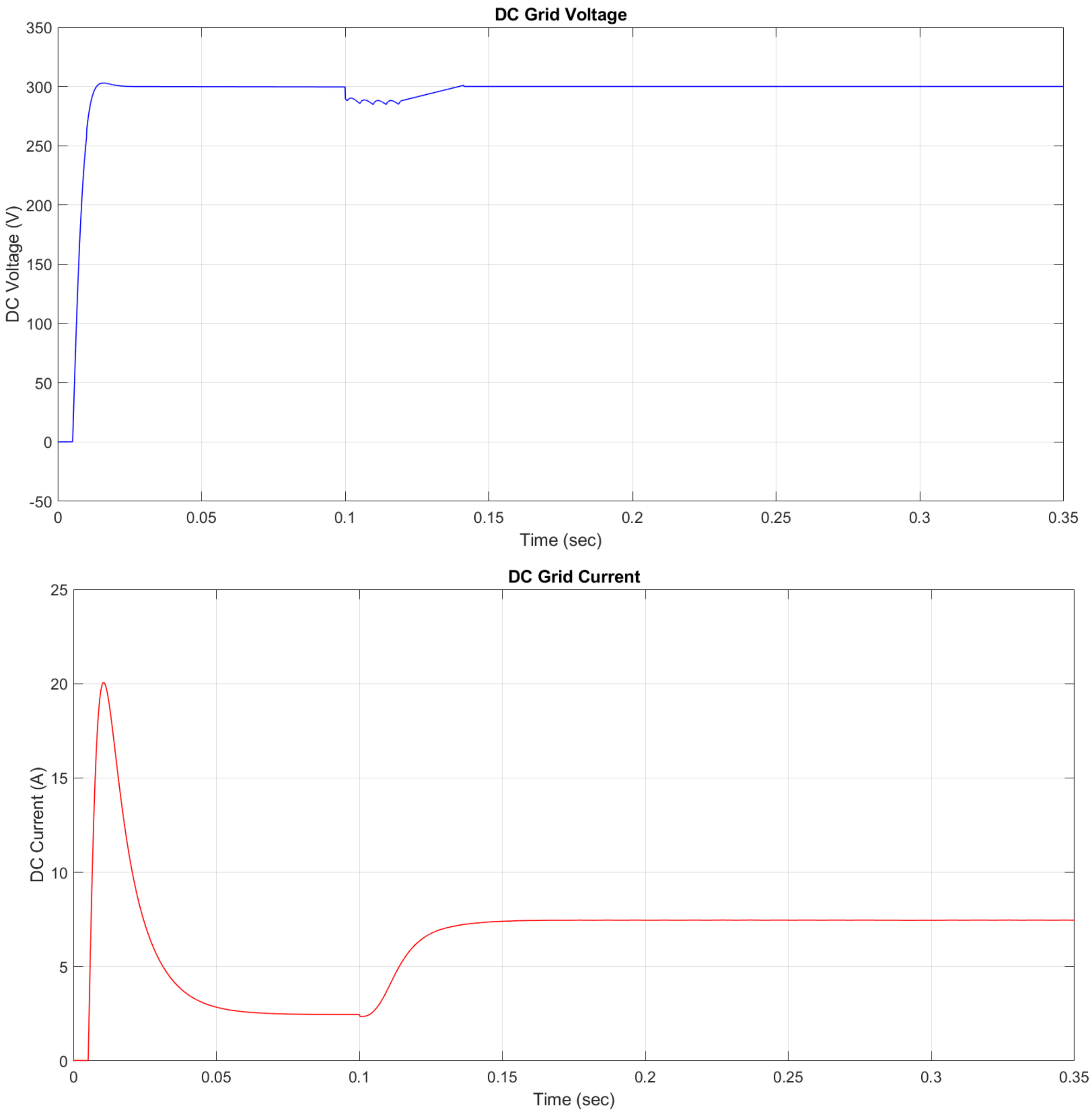
(b) DC voltage & Current of DC voltage Source



(c) DC voltage & current with BIC acting as GSGFER



(d) Weighing Factor for BIC acting as GSGFER



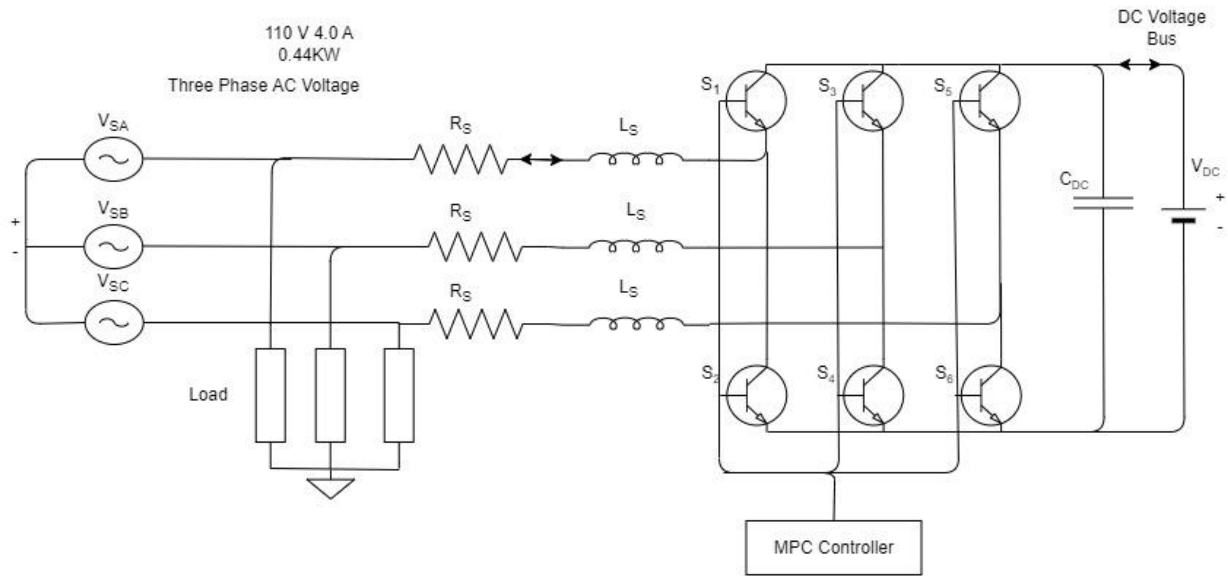
(e) DC load voltage & current

Figure 3.12 “DC voltage and current waveforms with BIC acting as GSGFER”

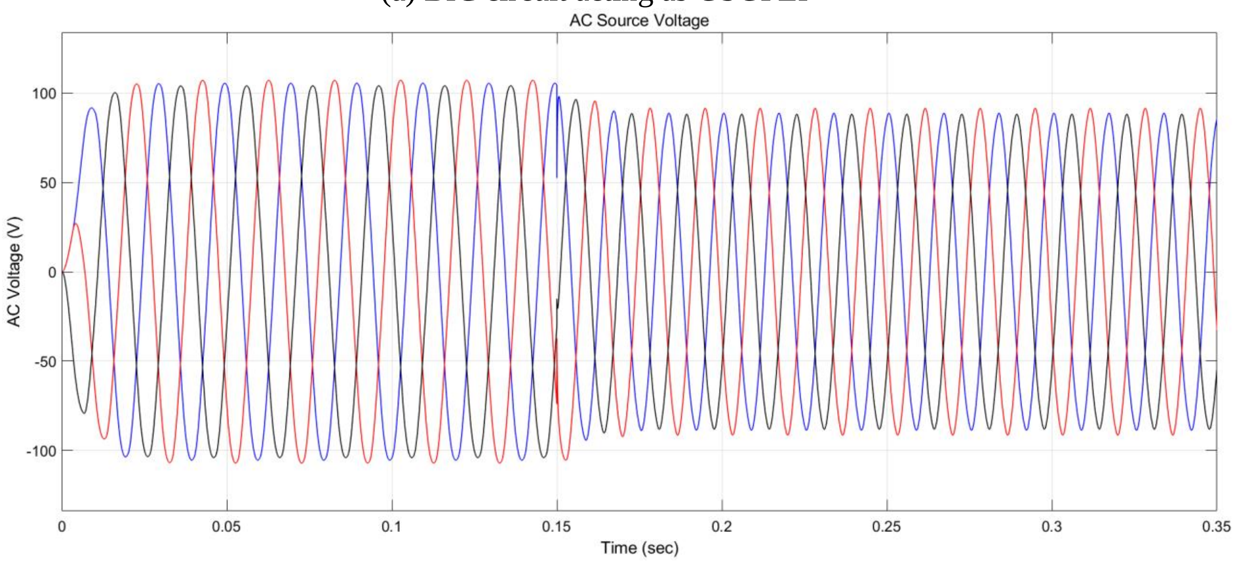
Case-4

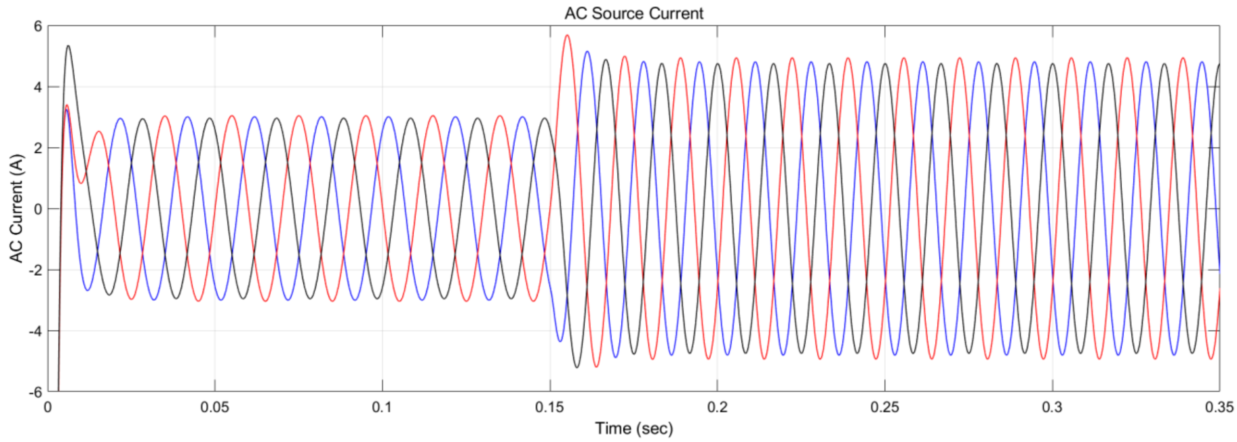
In this case, BIC acting as GSGFEI to regulate AC current is simulated as shown in Fig. 3.13 (a). First of all, AC load 1 is connected. After the initial transients, AC Voltage Source stabilizes the AC voltage to 110V and AC current to 3A at 0.02 sec as shown in Fig. 3.13 (b). At 0.15sec, AC load 2 is connected and voltage and current waveforms of AC voltage source is distorted, as it cannot support AC load 2 as shown in Fig. 3.13 (b). After that, BIC response to AC voltage fluctuation has been tested. At this point, BIC start acting as GSGFEI and start injecting 1.1A current to support AC load 2 as shown in Fig. 3.13 (c).

AC current stabilizes to 6A at 0.17sec thus; GSGFEI stabilizes AC current in 0.02 sec. Initially BIC is not acting as GSGFER so weighing factor is zero but at 0.15 sec with BIC acting as GSGFEI, weighing factor achieves value of 1.1 and ultimately it achieves zero value at 0.17sec as shown in Fig. 3.13 (d). Fig. 3.13 (e) shows voltage and current waveforms of AC load showing current regulation achieved successfully by BIC acting as GSGFEI within 0.02 sec.

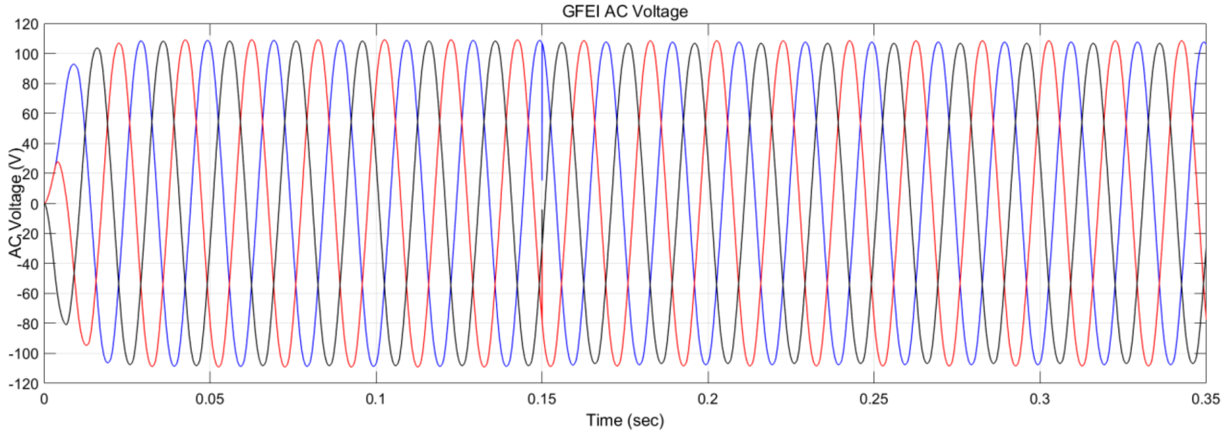


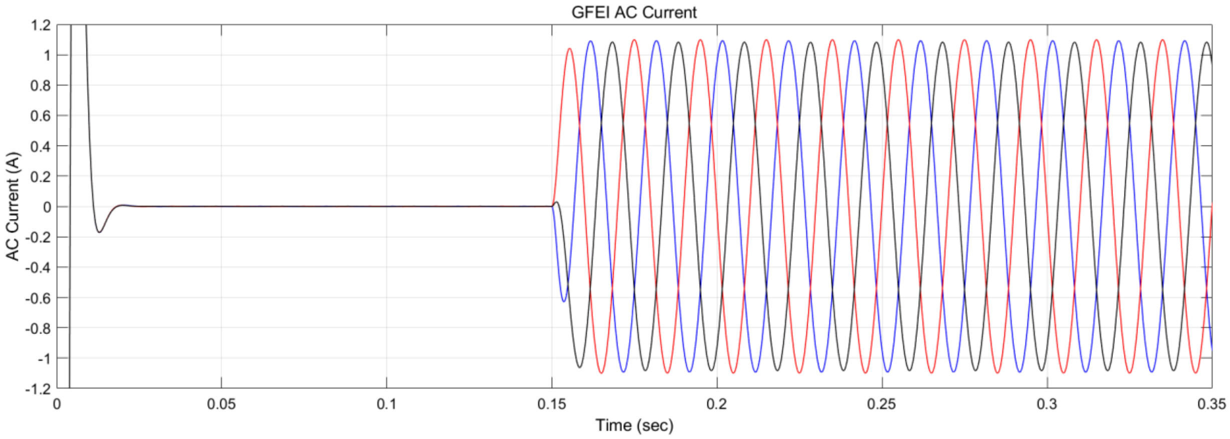
(a) BIC circuit acting as GSGFEI



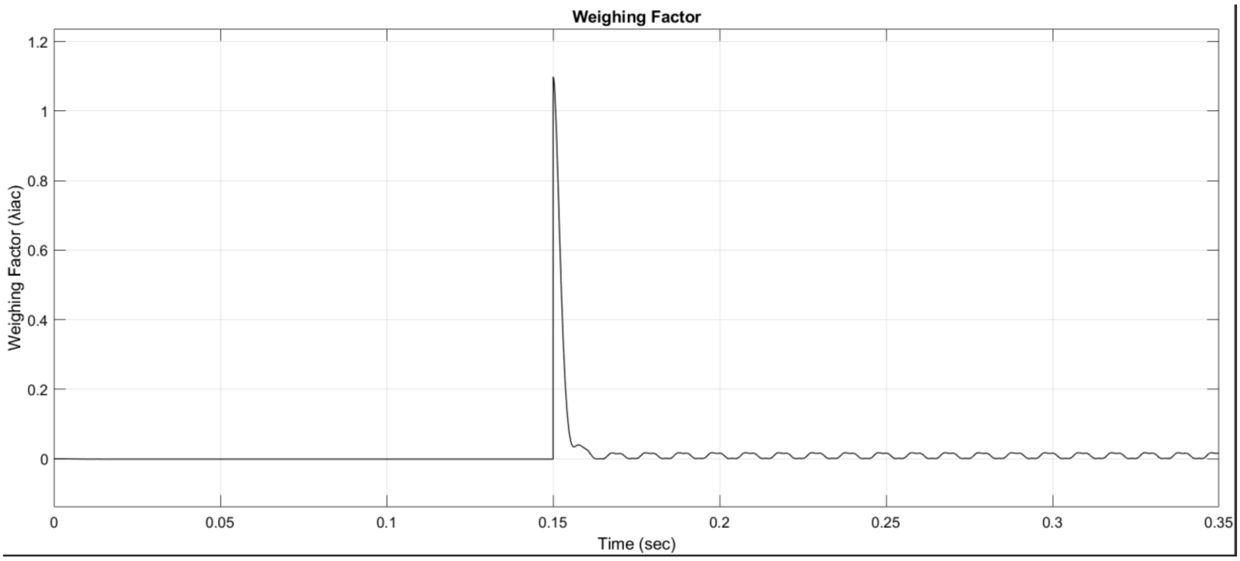


(b) AC voltage & Current of AC voltage Source

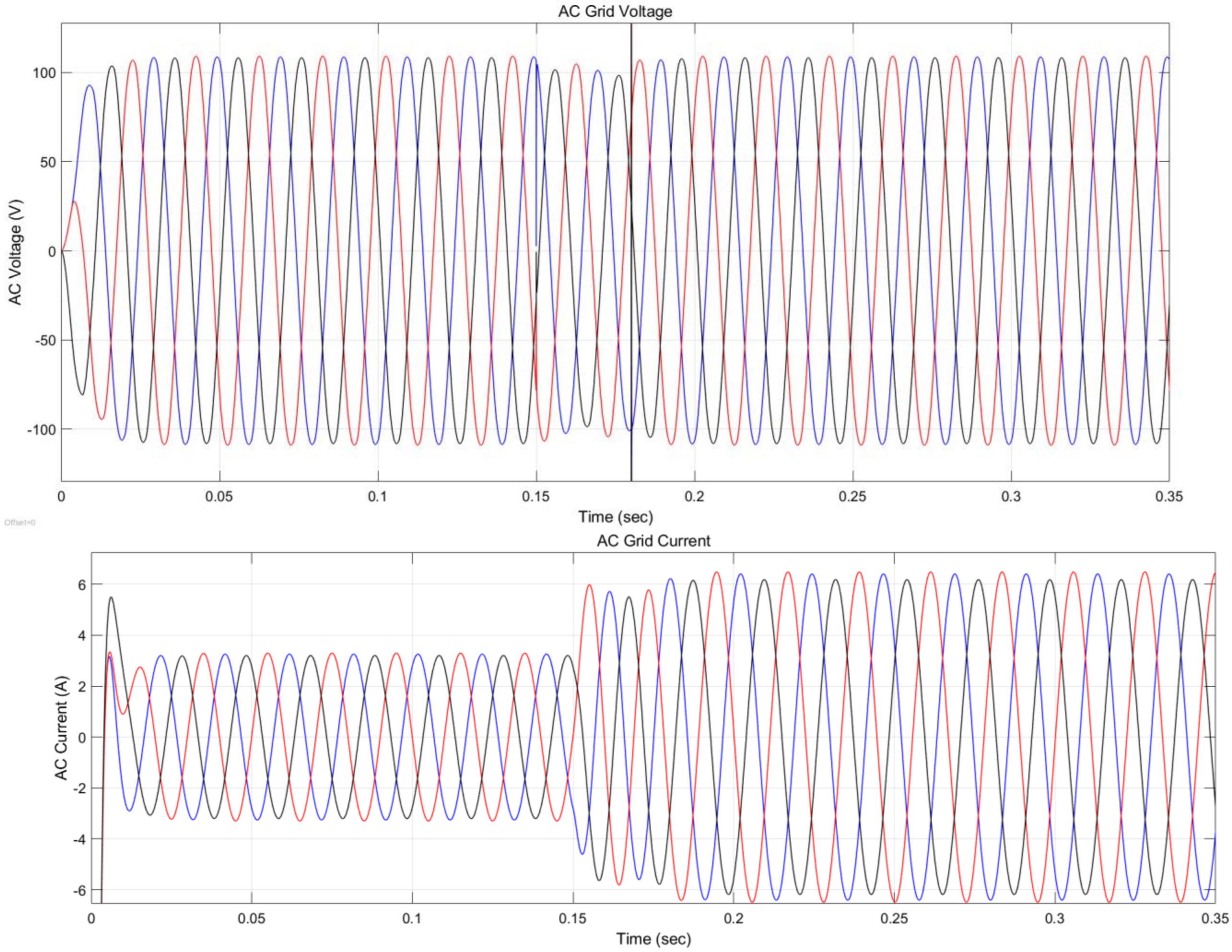




(c) AC voltage & current with BIC acting as GSGFEI



(d) Weighing Factor for BIC acting as GSGFEI



(e) AC load voltage & current

Figure 3.13 “AC voltage and current waveforms with BIC acting as GSGFEI”

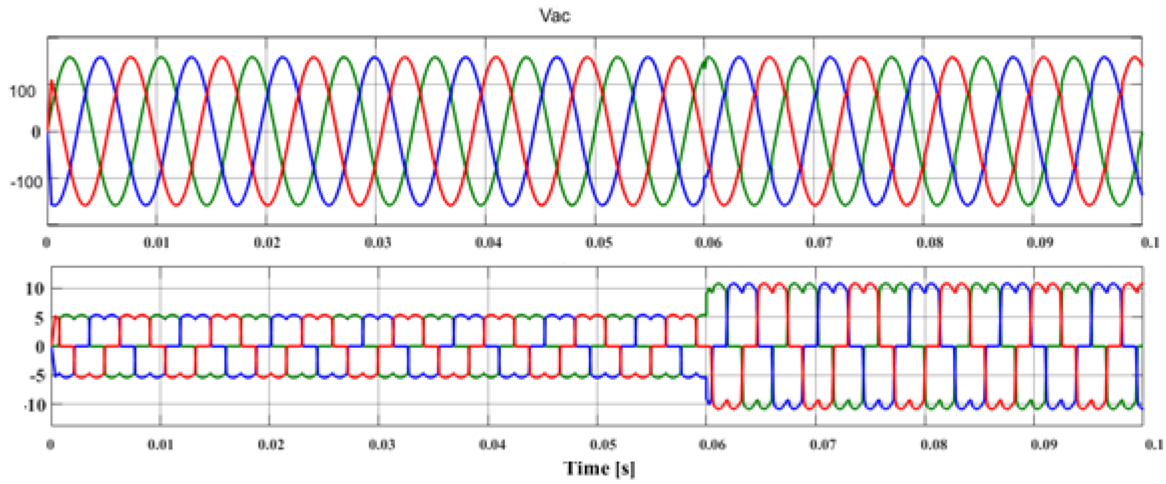


Figure 3.14 “AC voltage and current waveforms with load addition with PI controller”

Figure 3.14 shows PI controller performance for load change that occurred at t= 0.06 sec. At t= 0.06 sec, load was doubled. Voltage remains stable around 110V AC but current waveform is distorted, as PI controller cannot handle load change well. PI controller is implemented as per below diagram. K_p and K_i are calculated from below mentioned formulas:

$$\tau_S = {}^{1}\!/_{{f_{sw}}/_{10}} = {}^{1}\!/_{{3000}/_{10}} = 3.33ms$$

$$K_p = {}^{L}\!/_{\tau_S} = {}^{5mH}\!/_{3.33ms} = 1.5$$

$$K_i = {}^{R}\!/_{\tau_S} = {}^{0.1\Omega}\!/_{3.33ms} = 30$$

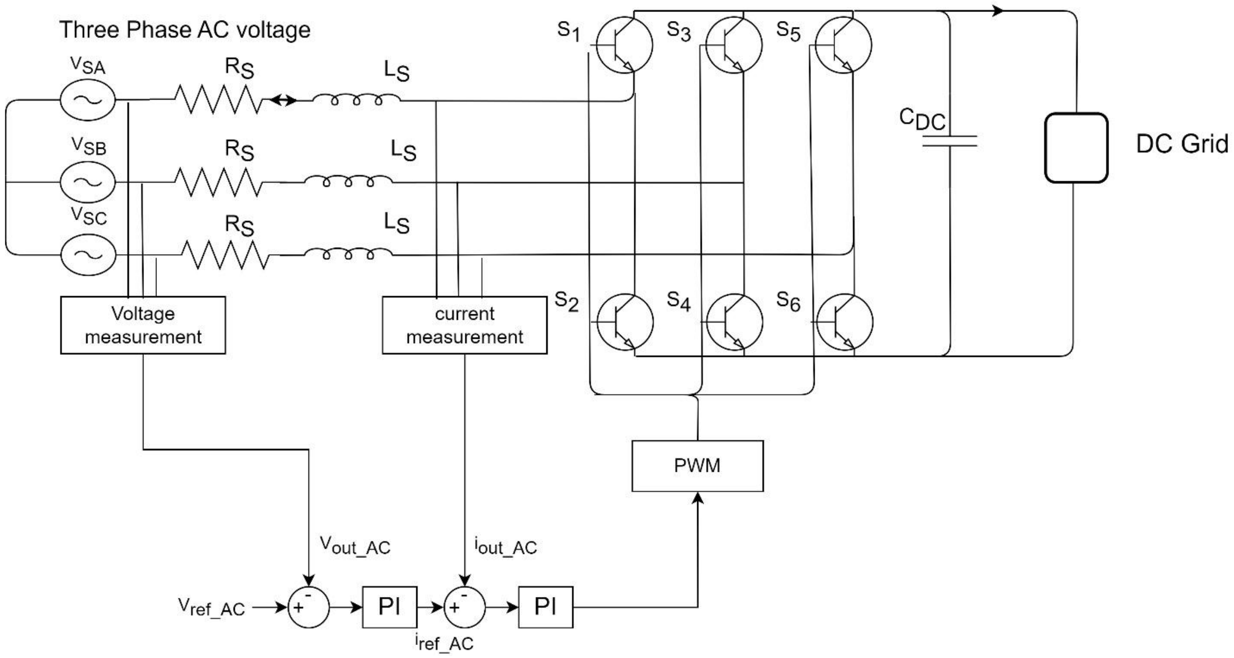


Figure 3.15 PI implementation of BIC

Table 3.4 Comparison of different control methods.

Year of Publication	Reference	Control Technique	%Voltage THD under Load	Controller Complexity
2022	[213]	PI	1.5	Low
2023	[214]	Dead Beat	1.4	Medium
2023	[215]	PR	1.06	Low
2021	Proposed	MPC	1.03	Medium

Table 3.4 shows the total harmonic distortion (THD) amongst different control techniques. MPC exhibits low THD thus making its performance better as compared to other techniques. Screenshot of THD achievement in MATLAB is attached at Appendix A.2.

3.6 Summary

- MPC based variable weighing factor algorithm is proposed for BIC to regulate the highest deviated parameter (AC-DC voltage or power) in all non-linear conditions by performing multi-variable control using variable weighing factor in the hybrid cost function. The proposed algorithm enables BIC to act as a GSGFM DG (GSGFMI or GSGFMR) or GSGFE DG (GSGFEI or GSGFER). The control objectives are to regulate voltages & power (both AC and DC) to their reference values in steady state.
- It has been seen that the MPC based control methods are robust and they ensure fast dynamic response and mode changing capability.
- The results reveal that the proposed MPC based variable weighing factor algorithm effectively regulate the highest deviated parameter while increasing the efficiency of hybrid AC-DC microgrid with THD value less than 1.1 %.

Chapter 4

Control of Bidirectional DC/DC Converter

4.1 Introduction

In DC MG, the main goal is to provide voltage and current regulation for optimal power in the grid [64]. GSGFM converters provide voltage regulation that can be can be represented as an ideal DC voltage while GSGFE converters provide current regulation that can be represented as an ideal current source connected to the grid in parallel with high impedance [67].

4.2 Problem Formulation

Summarizing the literature review for DC microgrid discussed in chapter 2, following conclusions can be drawn:

1. RDG are only used as GSGFE units because of their intermittent nature [69-70]. Therefore, the role of RDG is fixed, i.e., they regulate current only. However, RDG at their rated power can be used as GSGFM DG.
2. In islanded mode, BESS are operated as GSGFM units to regulate voltage. Charging of BESS is achieved in two stages. In the first stage, charging is achieved on the basis of the difference between generated and load power. Hence, charging current is limited and BESS operates as a GSGFM unit. In the second stage, as BESS achieves threshold voltage (almost fully charged), its voltage must be kept constant and, for that, BESS should operate as a GSGFE unit, so that its current begins to taper approaching asymptotically zero, while charging continues. The authors have adopted and refined this idea based on [71].
3. Proportional integral (PI) control approach was used to provide voltage and current regulation. There are some inherent issues associated with PI such as Pulse Width Modulation (PWM), PID parameter tuning, cascading scheme delayed response issue, complex coordinate transformation, etc. Keeping in view above-mentioned issues, the implementation of PI control becomes intricate when attempting to address complex grid behaviors.

4. MPC is used to operate PV & BESS in GSGFE modes [72-73]. MPC can be used to operate PV in both GSGFM and GSGFE modes but it will need to devise multiple control objective in MPC cost function. MPC provides a framework for multiple control objectives in a cost function by associating weighing factor with each objective. It is worth pointing out that, the performance of MPC is deeply influenced by the weighing factors, the tuning of which is still a challenge to be undertaken [74-75].

4.3 Proposed Technique

In this chapter, MPC based variable weighing factor has been proposed for bidirectional DC/DC converter connected to battery energy storage system (BESS). MPC based control algorithm is proposed for bidirectional DC/DC converter to regulate the highest deviated parameter (DC voltage regulation as GSGFMD or DC current regulation as GSGFED) in all non-linear conditions by performing multi-variable control using variable weighing factor algorithm. The proposed algorithm enables bidirectional DC/DC converter to act as a GSGFMD or GSGFED. The proposed algorithm can work in islanded mode and grid-connected mode. In grid-connected mode, references for current and voltage will be coming from grid. In islanded mode, references will be coming from AC DG-1. Irrespective of source of the references coming from, the proposed algorithm will work as discussed below.

4.4 Model Predictive Control (MPC) Based Variable Weighing Factor Algorithm for Bidirectional DC/DC Converter

4.4.1 Variable weighing factor algorithm for Bidirectional DC/DC converter

Following principles will be followed by variable weighing factor algorithm:

- Every MPC controller have the capability to control two variables i.e., voltage and current.
- Either voltage or current have to be controlled, is to be decided by weighing factor of MPC cost function.
- Weighing factor would be calculated by evaluating grid condition.

- Weighing factor would be decided such that bidirectional DC/DC converter would control the variable that will have most deviation from its reference value. Voltage would be regulated by acting as GSGFMD and current would be regulated by acting as GSGFED. As that variable with most deviation comes close to reference value, then bidirectional DC/DC converter then will then control other variable having most deviation from its reference value, thus operating in flip flop manner.

4.4.2 MPC cost function

MPC cost function in equation 4.1 shows that each DC-DC converter in DC microgrid is able to regulate current and voltage in DC grid by acting either as GSGFMR or as GSGFER.

$$Cost(DC - DC) = \lambda_{VDC}\left(V_{refDC} - V_{outDC}\right)^2 + \lambda_{IDC}\left(I_{refDC} - I_{outDC}\right)^2 \tag{4.1}$$

4.4.3 Bidirectional DC/DC converter circuit

In this chapter, Buck-Boost GSGFMD and GSGFED topologies have been used. Buck-Boost topology allows the bidirectional DC/DC converter topology used to transfer power from battery to DC grid and vice versa as shown in Fig. 4.1. Bidirectional DC/DC converter acts as bidirectional converter through two IGBT switches (S1-S2) connected to DC grid through series inductance (Ls) and filter capacitance (Cs). Bidirectional Buck-Boost topology used for DC/DC converter is shown in Fig. 4.2. Buck topology is used for charging the battery and boost topology is used for discharging the battery.

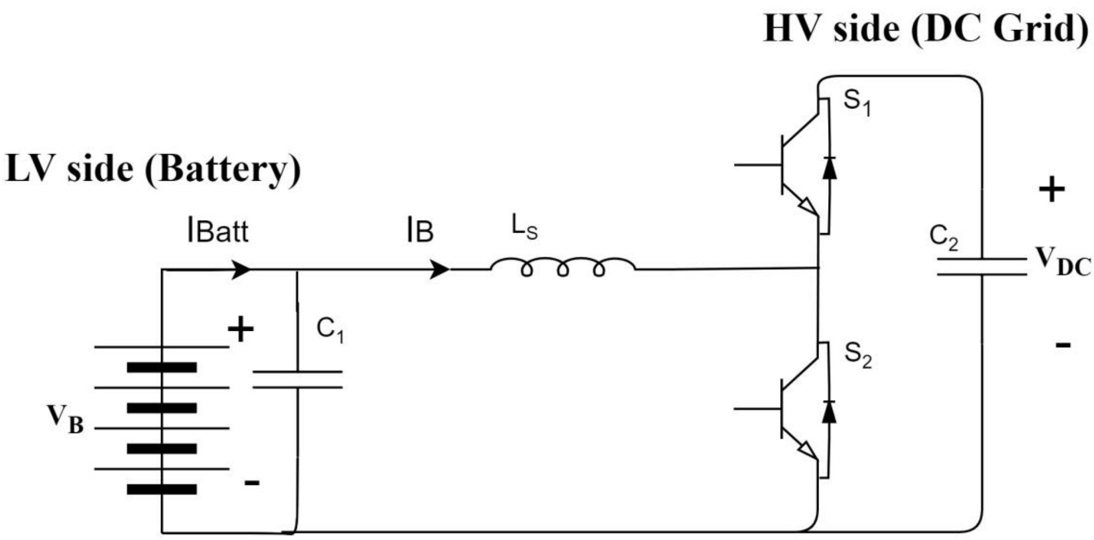


Figure 4.1 Bidirectional DC/DC converter for Battery

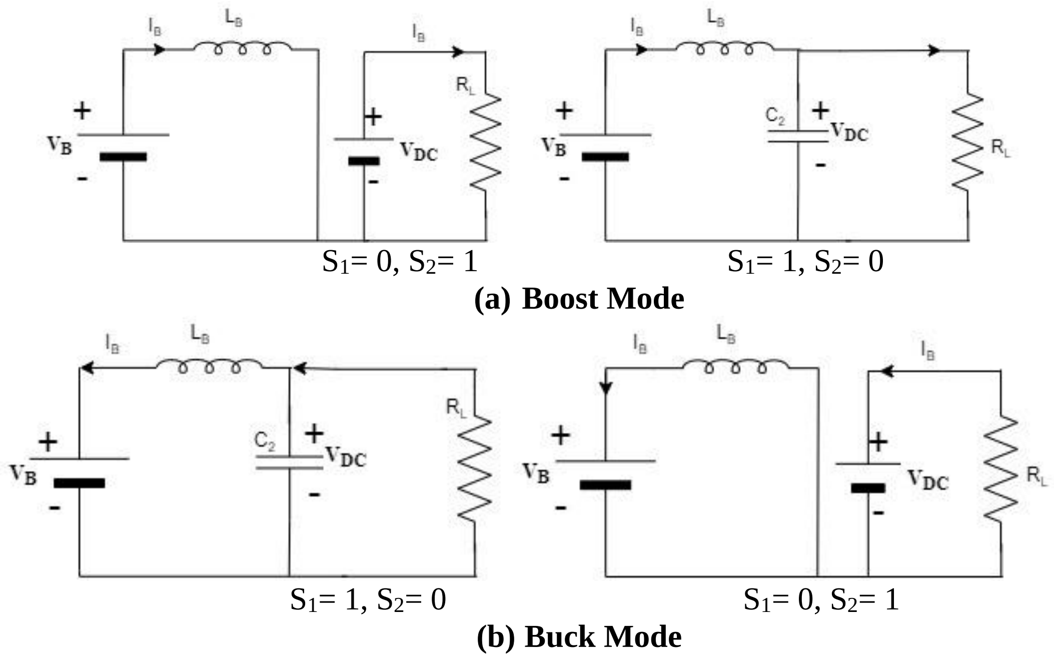


Figure 4.2 Topologies of Bidirectional DC/DC converter (Buck/Boost) for Battery

Voltage Control (GSGFM DG)

Battery regulates DC grid voltage through a bidirectional DC/DC converter and will be described in this section. Current dc grid voltage and reference dc grid voltage is used to calculate the required power output required for the battery converter to regulate the dc grid voltage as GSGFMD has been shown in Fig. 4.3. Figure 4.5(b) shows the proposed MPC based GSGFMD control algorithm.

When battery discharges to supply power, the BESS operates in boost mode (Fig. 4.2 (a)). On the contrary, when battery is charged to absorb power, the BESS operates in buck mode (Fig. 4.2(b)).

The battery voltage, current, and dc grid voltage will be used to calculate $I_{Batt}(k+1)$, leading us to calculate $P_{Batt}(k+1)$.

$$V_{dc}(k+1) = V_{dc}(k) + \frac{1}{N}(V_{dc}^{*} - V_{dc}(k)) \tag{4.2}$$

Euler approximation equation will be

$$I_C(k+1) = \frac{C_2}{T_S}(V_{dc}(k+1) - V_{dc}(k))$$

$$= \frac{C_2}{NT_S}(V_{dc}^{*} - V_{dc}(k)) \tag{4.3}$$

Where N is an integer coefficient used to limit the capacitor's current.

Battery current is predicted as

$$I_{Batt}(k+1) = I_{RDG}(k) - I_C(k+1) - I_{load}(k) \tag{4.4}$$

So, the battery output power can be predicted as

$$P_{Batt}(k+1) = |I_{Batt}(k+1).V_B(k)| \quad (4.5)$$

Reference power output required by battery converter is

$$P^*_{Batt}(k+1) = |I_{Batt}(k+1).V^*_{dc}| \quad (4.6)$$

So, cost function for regulating dc grid voltage is

$$g = |P^*_{Batt}(k+1) - P_{Batt}(k+1)| \quad (4.7)$$

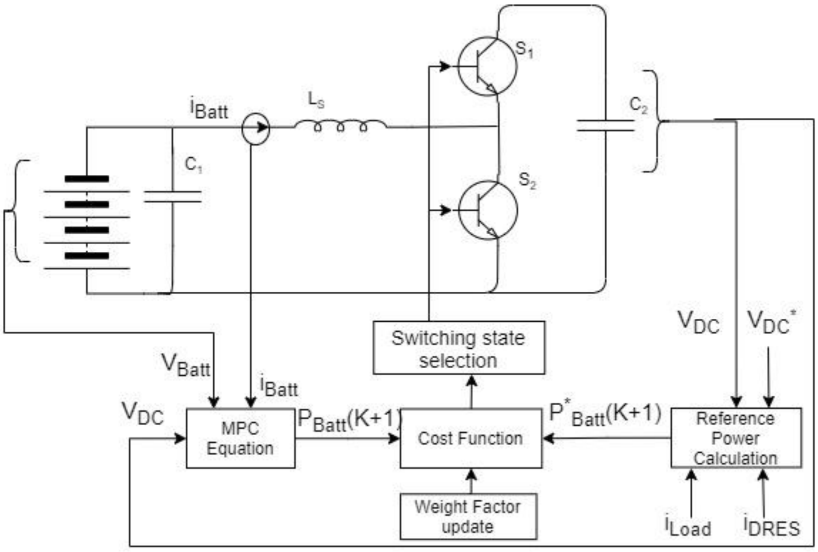


Figure 4.3 MPC for bidirectional DC/DC converter acting as GSGFMD

Current Control (GSGFE DG)

Battery regulates DC grid current by acting as GSGFED through MPC as shown in Fig. 4.4. Figure 4.5(a) shows the proposed MPC based GSGFED control algorithm. Two states of switches used in Fig. 4.2 are:

$$\begin{cases} S_1 = 0, S_2 = 1: \frac{dI_B}{dt} L_B = V_B \\ S_1 = 1, S_2 = 0: \frac{dI_B}{dt} L_B = V_B - V_{DC} \end{cases} \quad (4.8)$$

So now discrete-time equation with sampling time can be written as:

$$\begin{cases} S_1 = 0, S_2 = 1: I_{Batt}(k+1) = \frac{T_S}{L_B} V_B(k) + I_B(k) \\ S_1 = 1, S_2 = 0: I_{Batt}(k+1) = \frac{T_S}{L_B}\left(-V_{DC}(k) + V_B(k)\right) \\ \qquad +I_B(k) \end{cases} \quad (4.9)$$

Following current based cost function will be used to control charging or discharging of battery:

$$g = |I_{refDC} - I_{Batt}(k+1)| \quad (4.10)$$

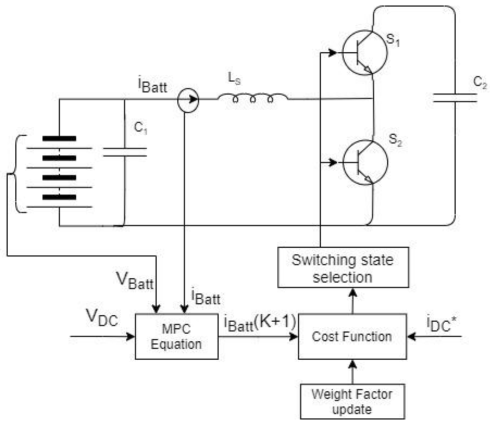


Figure 4.4 MPC for bidirectional DC/DC converter acting as GSGFED

4.5 Hybrid cost function with an auto-tuning weighing factor

MPC cost function will enable BESS to switch between GSGFMD and GSGFED control modes. The cost function for BESS with weighing functions tuning in different modes are as follows:

$$\min g = \lambda_{IDC} g_{IDC} + \lambda_{VDC} g_{VDC} \tag{4.11}$$

Where cost function is:

$$g_{VDC} = \frac{1}{V_{Rated}} |V_{Ref}(k+1) - V_{Out}(k+1)|$$
$$g_{IDC} = \frac{1}{I_{Rated}} |I_{Ref}(k+1) - I_{Out}(k+1)| \tag{4.12}$$

The above cost function consists of two penalty terms to regulate voltage (V_{Out}) and power (I_{Out}). The weighing factor (λ_{VDC},λ_{IDC})is multiplied by the penalty term for prioritizing the multi-objective cost function. MPC controller auto-tunes the weighing factors keeping in view the quantized tracking errors of all the variables. The basic aim of this auto-tuning method is to minimize the penalty terms in both grid-connected and standalone modes.

For a reliable operation of a DC microgrid, one DG must assume the role of regulating DC grid voltage by acting as GSGFM DG. BESS will be charged or discharged, keeping in view the unbalance between generated and consumed power [75]. So BESS will act as GSGFM DG since battery current will be limited due to power unbalance, and other converter may act as GSGFE DG. As soon as BESS is almost fully charged and reaches the voltage threshold, battery voltage should be constant [71]. So, BESS will now act as GSGFE DG to regulate power, and other converter will act as GSGFM DG to regulate voltage. For instance,

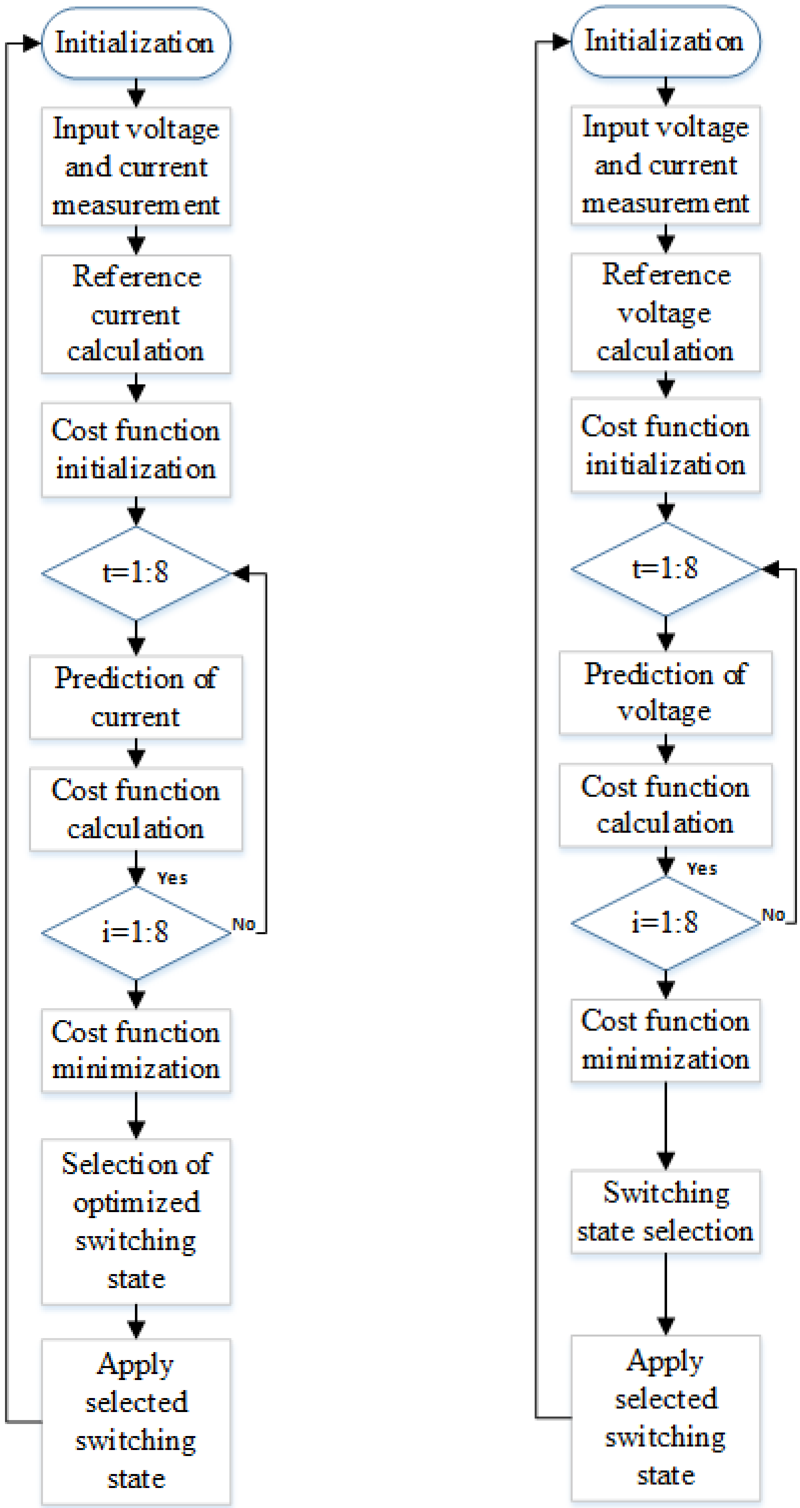


Figure 4.5 (a) GSGFED control algorithm (b) GSGFMD control algorithm

BESS will operate as GSGFM DG as long as V_{batt} is less than the threshold voltage V_{th}. When V_{batt} achieves threshold value, BESS changes its operation mode from GSGFM to GSGFE mode. At this moment, other converter acting in GSGFE mode should change its mode to GSGFM mode to regulate DC microgrid voltage. Thus, other converter will continue acting as GSGFM DG as long as it has enough power to supply power to the DC microgrid. Otherwise, BESS DG will re-assume the role of GSGFM DG. So, BESS DG has single cost function with an variable weighing factor algorithm for switching between GSGFM and GSGFE control modes.

4.6 Setting up variable weighing factor

An auto-tuning method to select the value of weighing factor (λ_{VDC} & λ_{IDC}) has been proposed in this section. This method directly affects the robustness and overall performance of the proposed MPC controller in abnormal or fault conditions. In this method, calculations to select optimal weighing factors are performed in every sampling interval. The weighing factors are calculated dynamically, such that highest priority is assigned to a given objective which has large error that should be corrected. So, weighing factor represents the urgency of correcting the largest error. In Fig. 4.6, (ε) represents the amplitude of the error which is to be corrected by increasing or decreasing converter output. If a large fixed error (Kε) exists, it is essential to apply appropriate switching state of the converter using MPC to reduce the error.

On the other hand, if a small error (ε) exists, a correction is not as important and higher priority can be given to other objectives. Since ξ provides a good measure of the existing error and, because of the "urgency" of correcting it, the weighing factor could be defined proportionally to ξ. However, this would mean that the weighing factor would be almost zero whenever the error is small, which would increase the error. To avoid this, a minimum value of the weighing factor is taken as 1 in this chapter. This value is used whenever the error is lower than a predefined boundary of ε, as shown in figure 4.6. The limit ε represents the maximum admissible error in normal operation. Once the error surpasses ε, the weighing factor increases linearly with the error. The selection of optimal weighing factors involves predicting errors of all the controllers' objectives which are current & voltage in both operational modes. For every controller, controller objective may vary in both modes, i.e., for AC-DC converter, controller objective is to predict error for voltage and current in grid-connected mode, for Solar, wind & battery DG's controller objective is to predict error for voltage & power in standalone mode and power in grid-connected mode.

Traditionally in MPC Controllers, the cost function is minimized, and a corresponding switching vector is applied. The proposed algorithm performs auto-tuning of the weighing factor and then minimizes the cost function for the next sampling period as shown in figure 4.9. So, the cost function is being split into two parts with each part affecting individual control objectives:

$$g_V = \frac{1}{V_{rated}} |V_{ref}(k+1) - V_{out}(k+1)| \leq \psi_V \tag{4.13}$$

$$g_I = \frac{1}{I_{rated}} |I_{ref}(k+1) - I_{out}(k+1)| \leq \psi_I \tag{4.14}$$

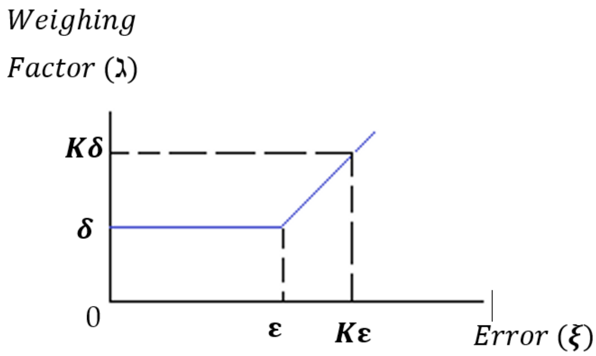


Figure 4.6 Weighing factor as a function of the error

Ψ_V and Ψ_I are the tracking errors for voltage and current regulation objectives. A minimum value of cost function (g_V & g_I) and their corresponding possible switching states have been selected as follows:

$$\xi_V = \min g_V \tag{4.15}$$

$$\xi_I = \min g_I \tag{4.16}$$

Now above-mentioned minimum values are compared with a small number (ε):

$$\xi_V \leq \varepsilon \rightarrow \lambda_{VDC} = \delta \tag{4.17}$$

$$\xi_I \leq \varepsilon \rightarrow \lambda_{IDC} = \delta \tag{4.18}$$

The above equations state that if cost functions (g_V & g_I) are smaller than ε, then weighing factors (λ_{VDC}& λ_{IDC}) are assigned a small number δ initially. However, if the condition in the above equations is not satisfied, then weighing factors (λ_{VDC}& λ_{IDC}) are assigned high values to set the highest priority in their relevant cost function for (k+1) sampling interval minimization cycle as follows:

$$\xi_V \leq K\varepsilon \rightarrow \lambda_{VDC} = K\delta \tag{4.19}$$

$$\xi_I \leq K\varepsilon \rightarrow \lambda_{IDC} = K\delta \tag{4.20}$$

Where $K \in \{2,3, \ldots, N\}$.

The algorithm for weighing factor selection based on absolute errors ξ_V and ξ_I is shown in Figure 4.7. Above equation quantized $\boldsymbol{\xi_V}$ & $\boldsymbol{\xi_I}$ through which weighing factors are determined by comparing $\boldsymbol{K}$ multiples of $\boldsymbol{\varepsilon}$ until equation (4.19) & (4.20) is satisfied for each variable objective. Simple values of weighing factors (λ_{VDC}& λ_{IDC}) are multiplication of $\boldsymbol{K}$

by **ε**. Three weights $\boldsymbol{K3}, \boldsymbol{K2}$ & $\boldsymbol{K1}$ have been shown with K3 being assigned to the variable having more ξ shown in Fig. 4.8. This algorithm will be run every cycle of sampling time, so weighing factors will be tuned online to minimize the cost function (4.13) & (4.14) for the next cycle.

For assigning weighing factors (λ_{VDC} and λ_{IDC}), δ is assumed as an initial value by using the branch and bound algorithm. The algorithm is applied to get the exact value of the weighing factor in one significant figure for which quantized error (ξ_V and ξ_I) is equal to zero. In the branch and bound algorithm, exploration of the best possible weighing factor that minimizes the cost function is conducted for different values of "*K*", and that value of *K* with one significant figure is selected for which quantized error is equal to zero. A flow diagram of the branch and bound algorithm is shown in Figure 4.8.

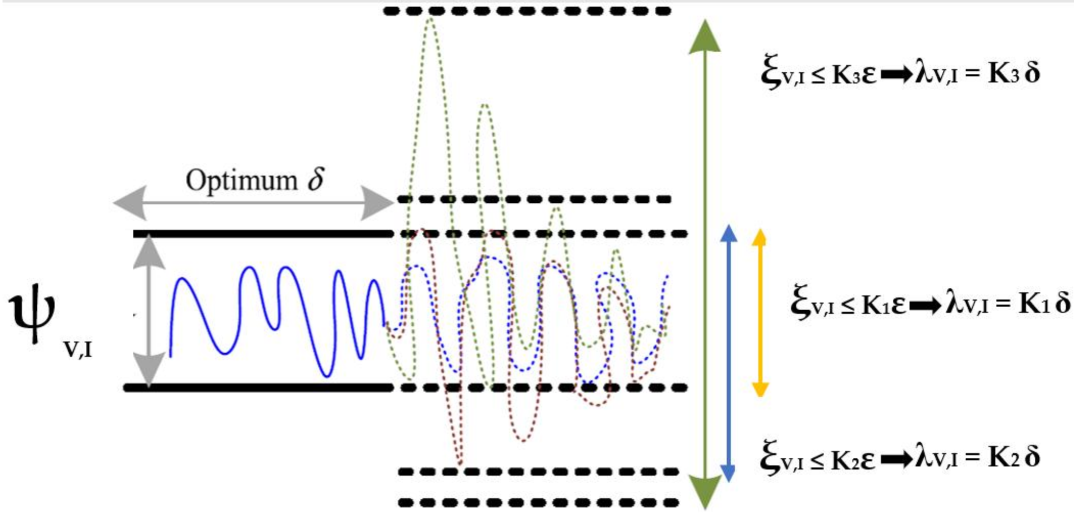


Figure 4.7 Tuning of weighing factors with respect to tracking error.

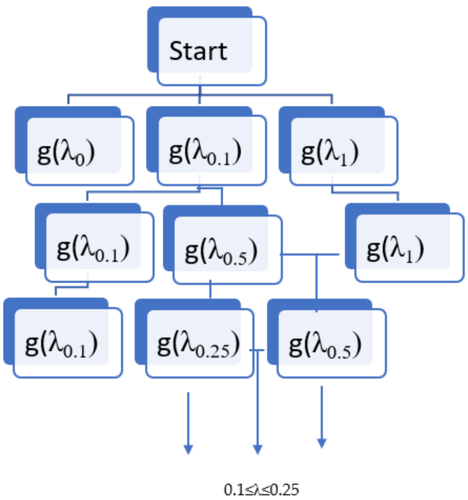


Figure 4.8 Flow diagram of branch and bound algorithm

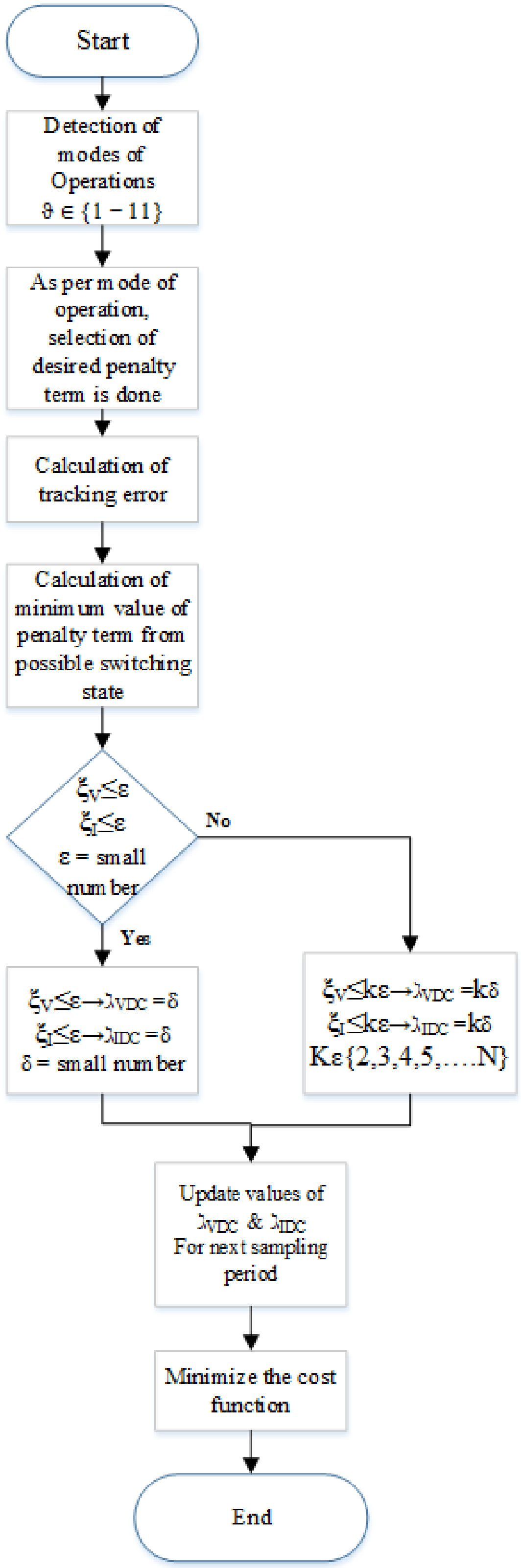


Figure 4.9 Setting up weight factor for variable weighing factor algorithm

4.8 Sensitivity Analysis

Sensitivity Analysis on DC/DC converter has been done with respect to the variation of parameters (Filtering inductor (L_s) and Capacitor (C_2)) on system response. Parameters have been changed from -50% to +50% of their values. Seven testing points are taken into consideration. For simplicity one parameter will be varied at a time. Performance parameters of Capacitor Voltage (V) and Grid Current THD have been chosen. Practically variation in L and C are within ±10% range. As shown in figure 4.10 and figure 4.11, these variations do not have considerable effect on capacitor voltage and grid current THD. These results show that proposed MPC algorithm is less sensitive to parameter change.

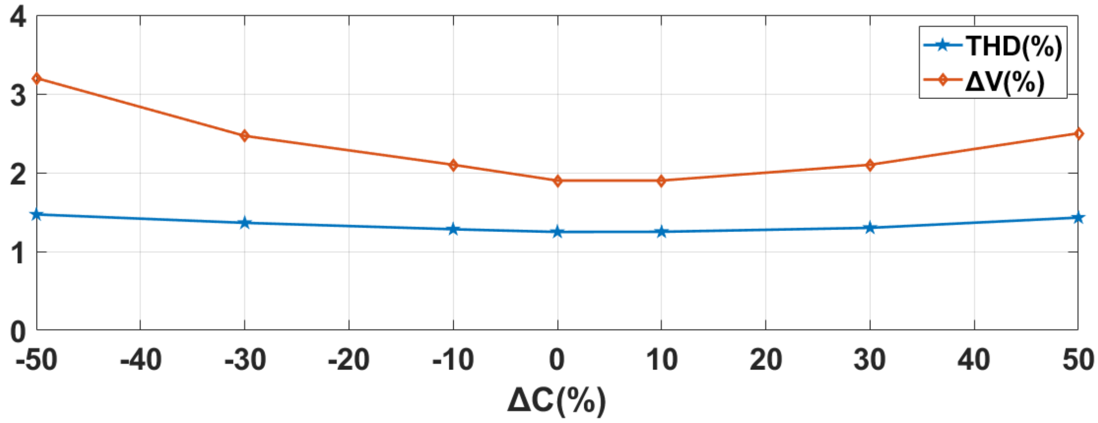


Figure 4.10 Sensitivity of proposed MPC controller to variation of capacitor value

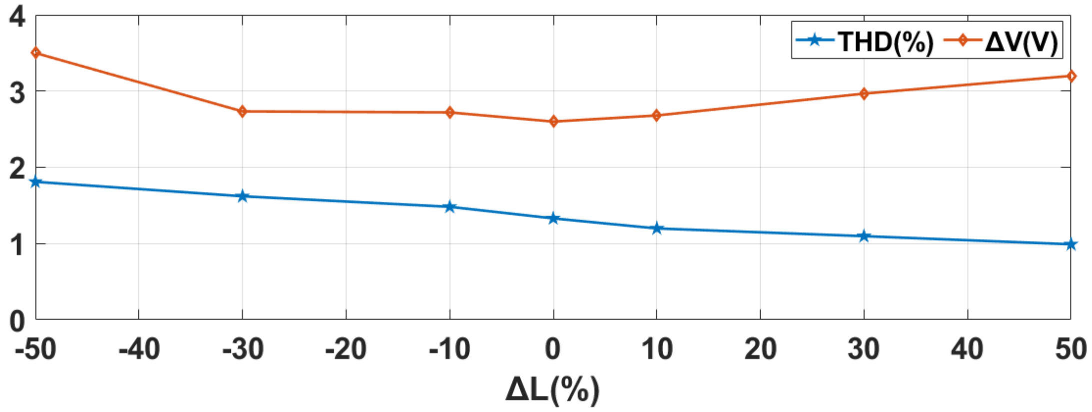


Figure 4.11 Sensitivity of proposed MPC controller to variation of inductor value

Sensitivity Analysis of DC/DC converter:

Sensitivity Analysis on DC/DC converter has been done with respect to the variation of parameters of Filtering inductor (L_s) on system response. Value have been changed from -50% to +50% of their values. Seven testing points are taken into consideration. Performance parameters of Duty Ratio (D) have been chosen. Practically variation in L is within ±10% range. Duty ratio for the buck boost converter [216] can be calculated as:

$$\boldsymbol{D} = \frac{(\mathbf{R_o}+\mathbf{R_L})}{(\mathbf{R_o}-\mathbf{R_S})}\left[\mathbf{1}-\sqrt{\frac{(\mathbf{R_S}+\mathbf{R_L})}{(\mathbf{R_o}+\mathbf{R_L})}}\right] \tag{4.21}$$

(4.22)

As evident from (5.83) duty cycle depends on inductor ESR (R_L). It does not depend on filter capacitor ESR (R_c). As shown in figure 4.12 the variation in filter inductor value do not have considerable effect on duty ratio. These results show that proposed MPC algorithm is less sensitive to parameter change.

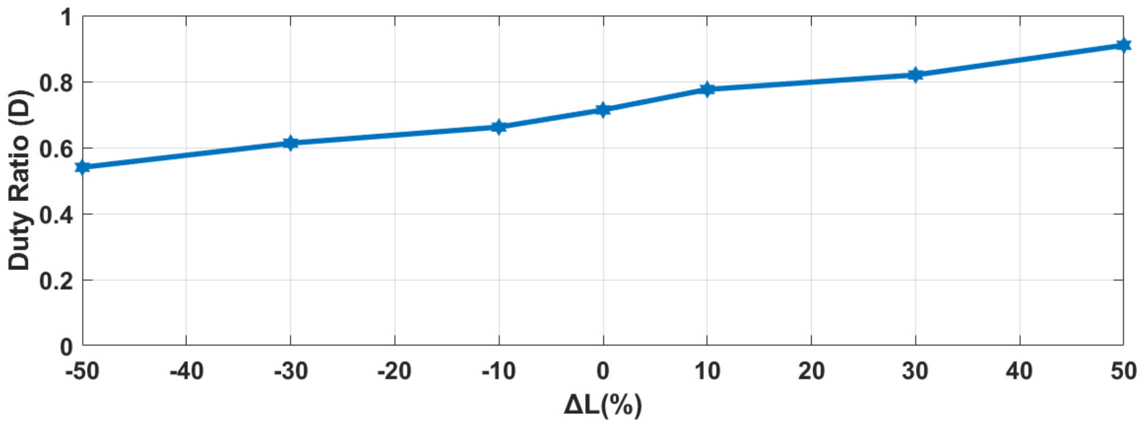


Figure 4.12. Sensitivity of proposed MPC controller to variation of inductor value

4.9 Results

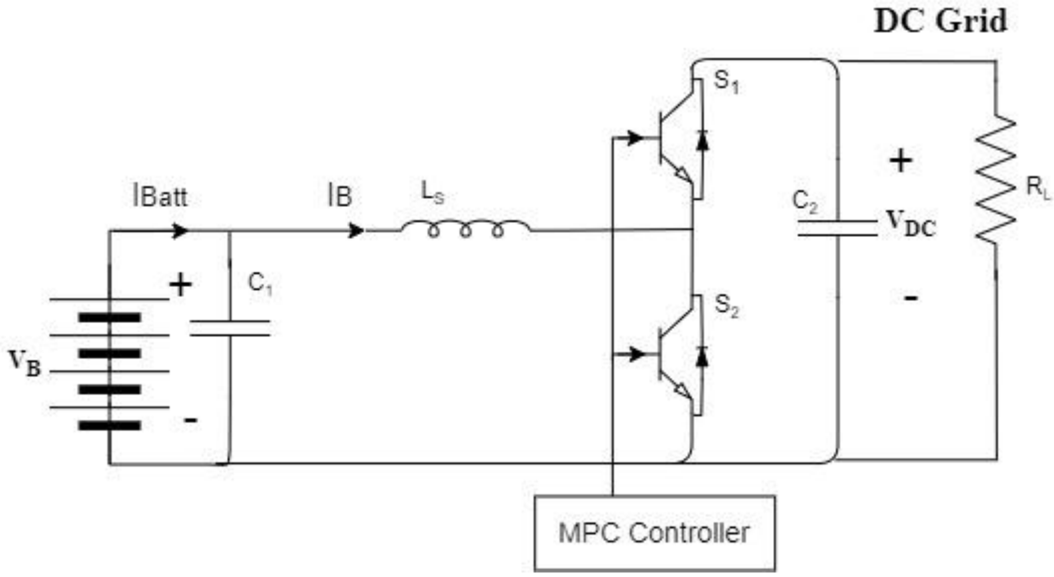
The performance of the proposed MPC algorithm for BESS in DC microgrid is being tested in MATLAB/Simulink. Parameters used in the simulation are shown in Table 4.1. Loads 1 and 2 are constant power loads represented by using constant resistances in MATLAB/Simulink.

Table 4.1 Simulation Parameters [161]

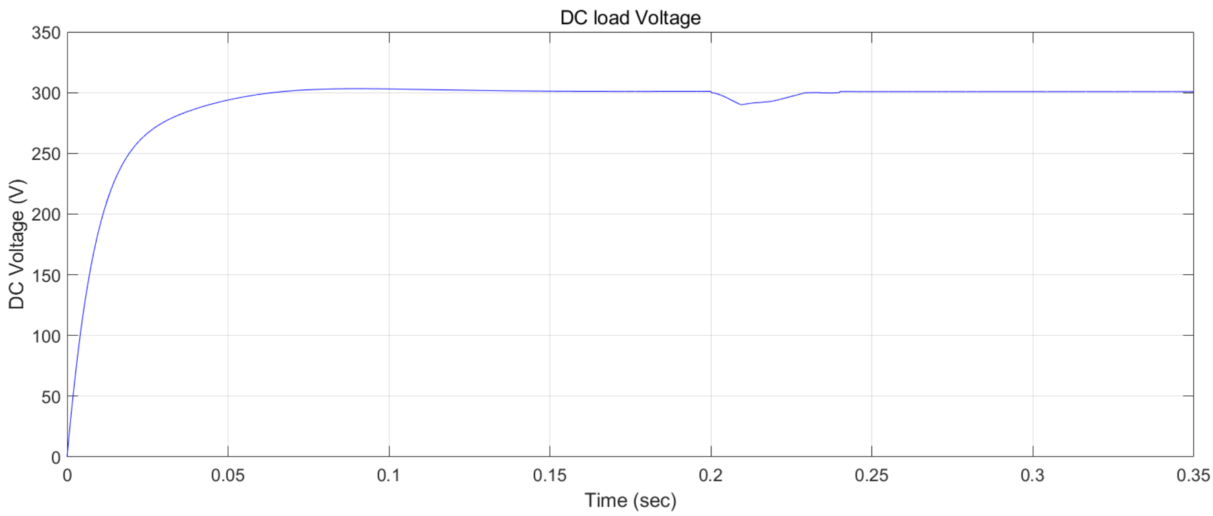
Parameters	Values
DC grid voltage	300 V
Inductance	5 mH
Battery internal resistance	0.1 Ω
Sampling time (Ts)	50 μsec
DC Load 1	3 KW
DC Load 2	4.5 KW
Capacitor	1000 uF
Battery	290V 20AH

A. BESS as GSGFMD:

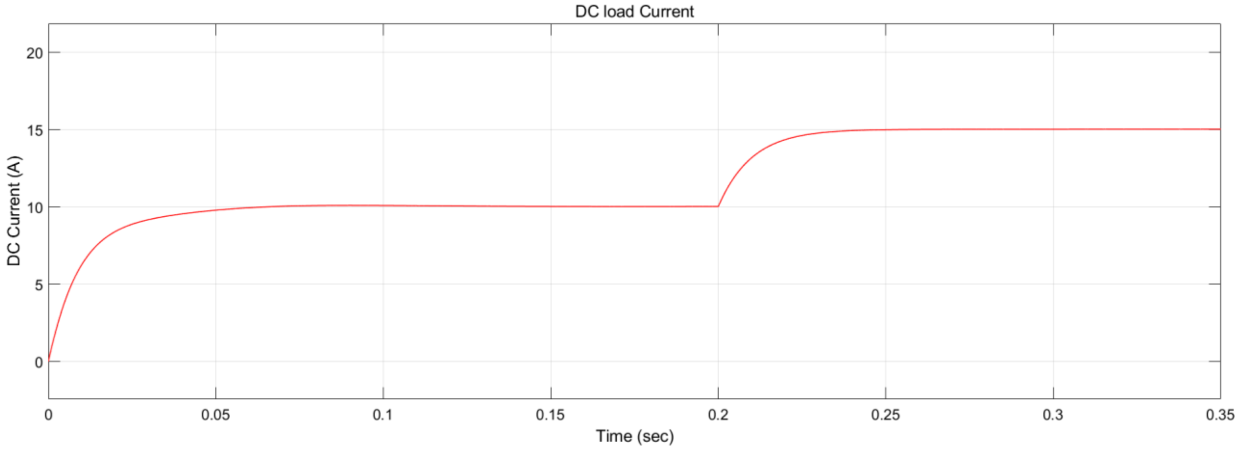
In this case, bidirectional DC-DC converter acting as GSGFM DG to regulate DC voltage in standalone mode is simulated. First, load 1 is connected. After the initial transients, bidirectional DC-DC converter stabilizes the DC voltage at 300V at 0.06 sec as shown in Fig. 4.13 (b) and at that point, weighing factor achieves zero value as shown in Fig. 4.13 (d). After that, BIC response to DC voltage fluctuation has been tested. In Figure 4.13 (c), at t = 0.2sec, small voltage fluctuation was introduced by adding load 2. Due to addition of DC load, DC voltage reduces to 290V and weighing factor achieves value of 10. BIC acts as GSGFMD, restores the voltage to 300V in 0.04sec. At that point weighing factor again achieves zero value.



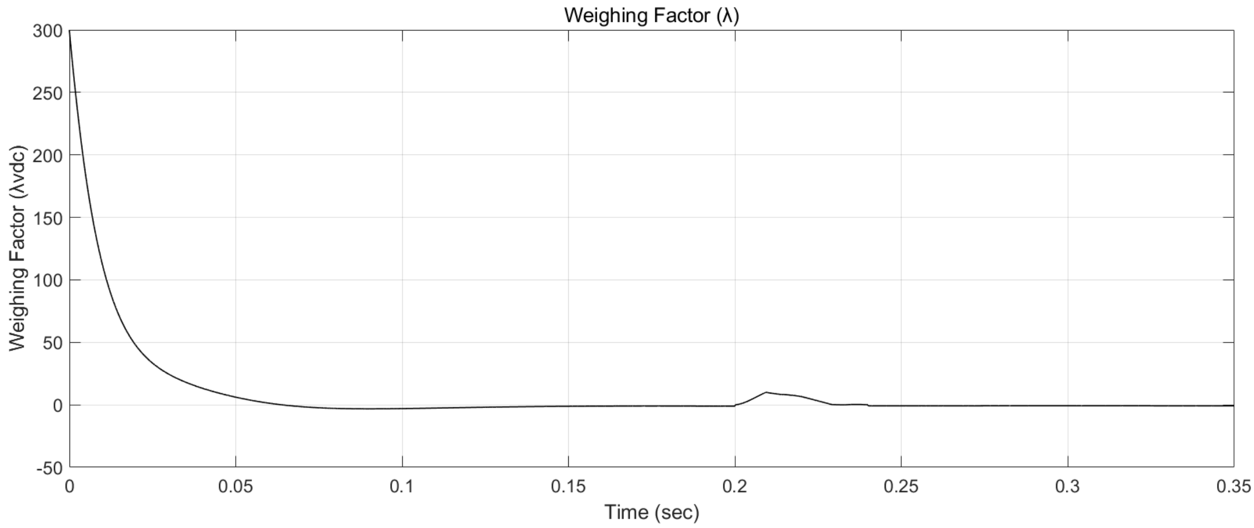
(a) Bidirectional DC-DC converter circuit acting as GSGFMD



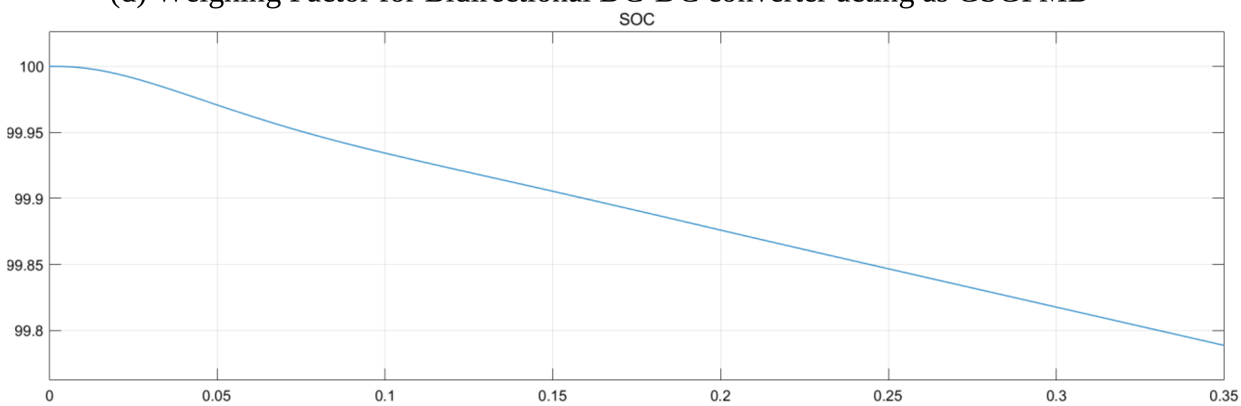
(b) DC voltage with Bidirectional DC-DC converter acting as GSGFMD



(c) DC current with Bidirectional DC-DC converter acting as GSGFMD



(d) Weighing Factor for Bidirectional DC-DC converter acting as GSGFMD



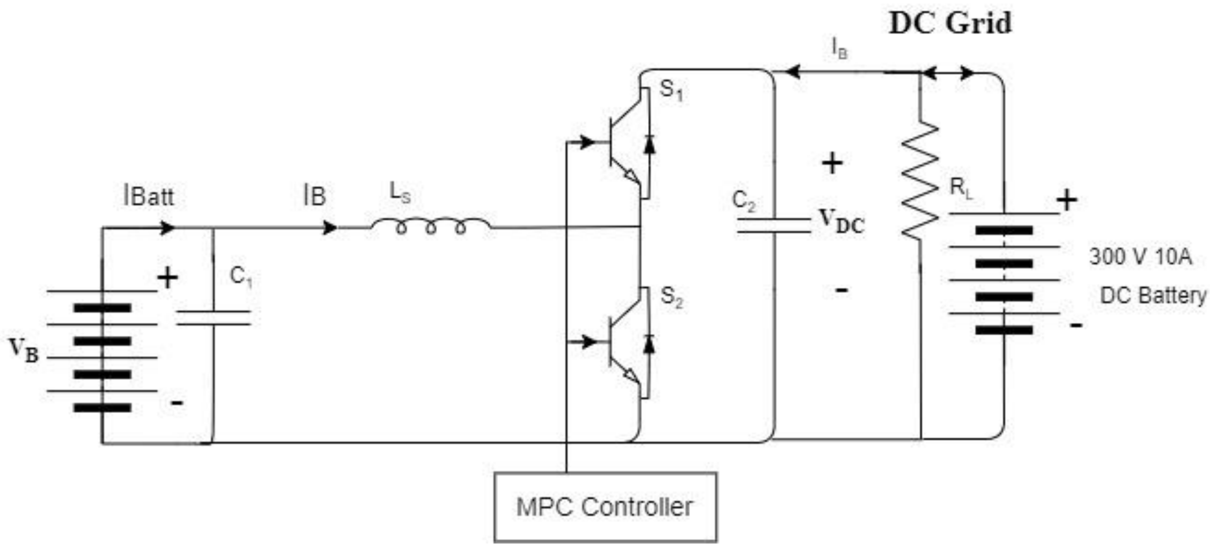
(e) SOC for BESS acting as GSGFMD

Figure 4.13 “DC voltage and current waveforms with Bidirectional DC-DC converter acting as GSGFMD”

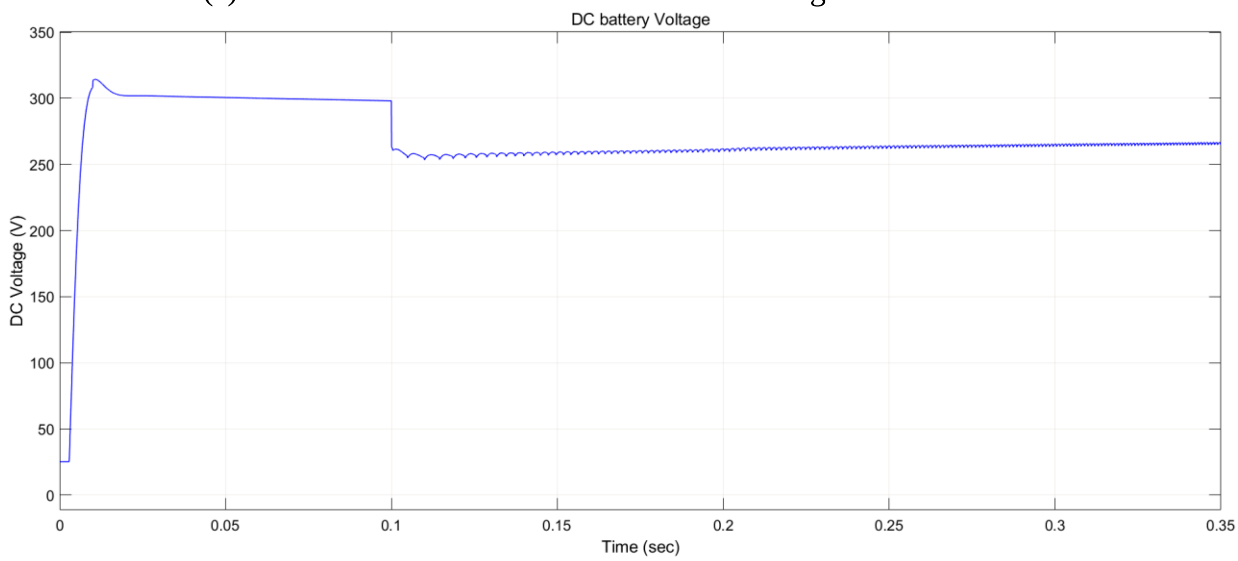
B. BESS as GSGFED:

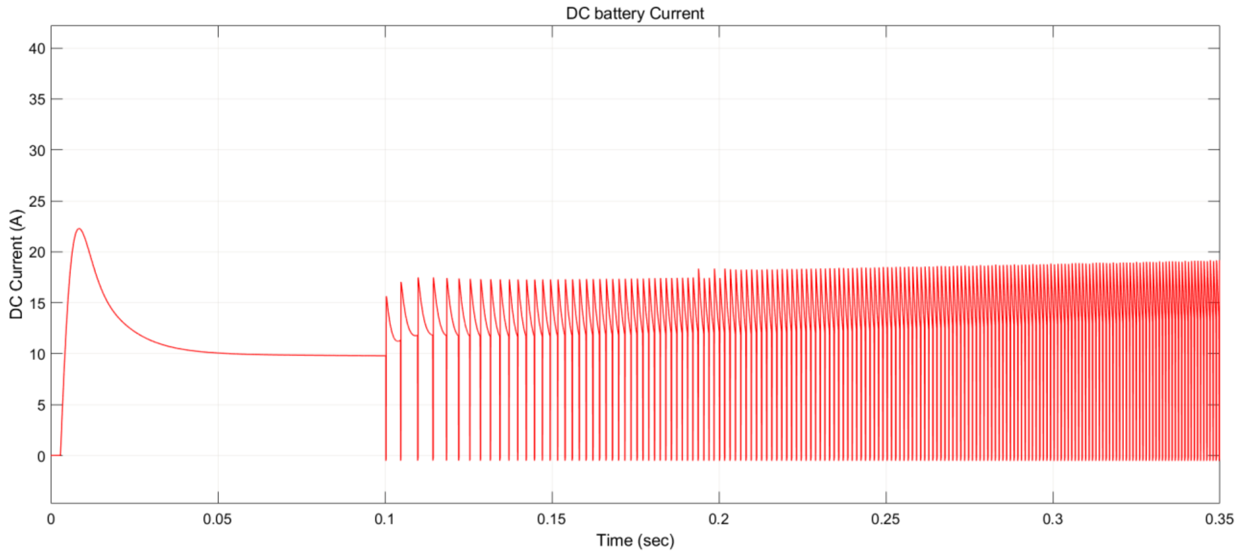
In this case, bidirectional DC-DC converter acting as GSGFED to regulate DC current is simulated as shown in Fig. 4.14 (a). First of all, DC load 1 is connected. After the initial transients, DC Voltage Source stabilizes the DC voltage to 300V and DC current to 10A at

0.04 sec as shown in Fig. 4.14 (b). At 0.1sec, DC load 2 is connected and voltage and current waveforms of DC voltage source is distorted, as it cannot support DC load 2 as shown in Fig. 4.14 (b). After that, bidirectional DC-DC converter response to DC voltage fluctuation has been tested. At this point, bidirectional DC-DC converter start acting as GSGFED and start injecting 5A current to support DC load 2 as shown in Fig. 4.14 (c). DC current stabilizes to 15A at 0.14sec thus; GSGFED stabilizes DC current in 0.04 sec. Initially bidirectional DC-DC converter is not acting as GSGFED so weighing factor is zero but at 0.1 sec with bidirectional DC-DC converter acting as GSGFED, weighing factor achieves value of 5 and ultimately it achieves zero value at 0.14sec as shown in Fig. 4.14 (d). Fig. 4.14 (e) shows voltage and current waveforms of DC load showing current regulation achieved successfully by bidirectional DC-DC converter acting as GSGFED within 0.04 sec.

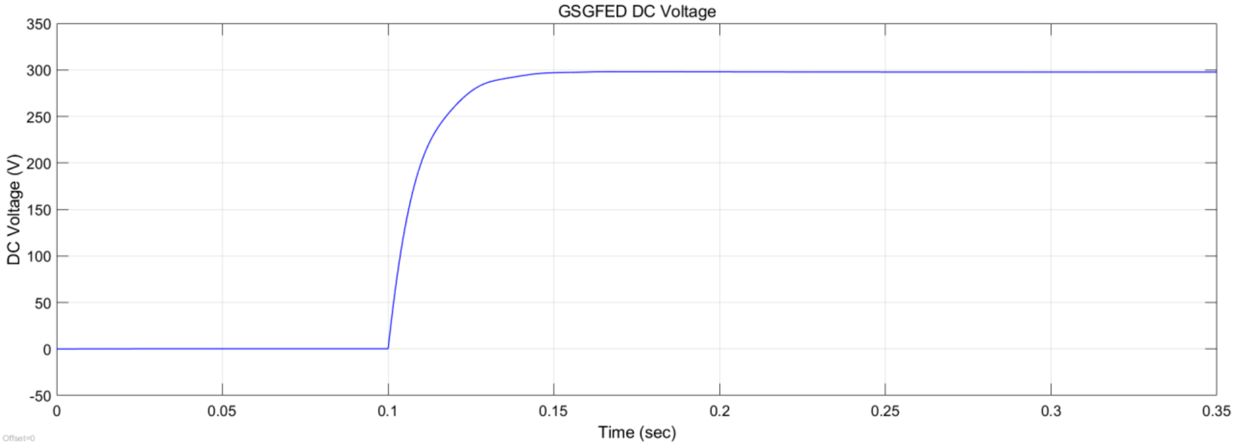


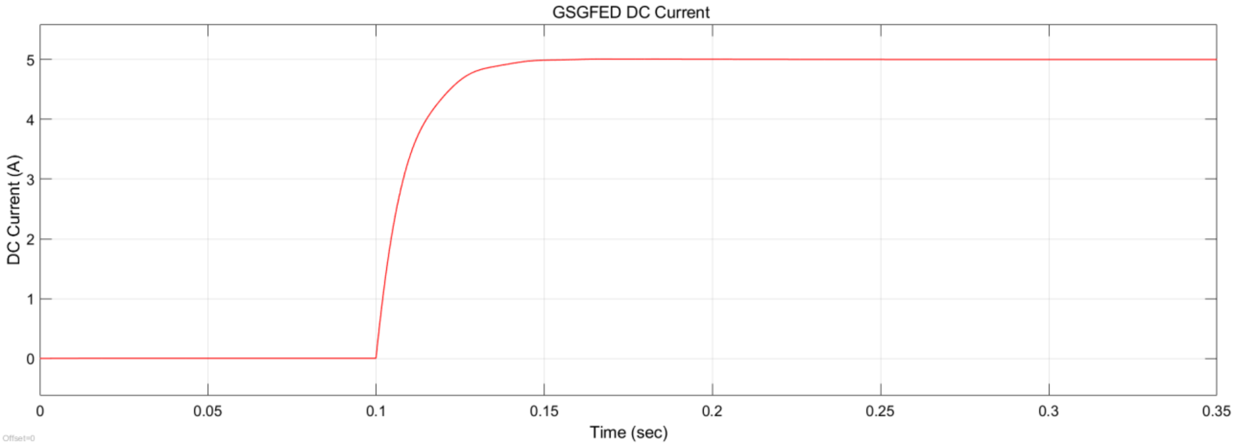
(a) Bidirectional DC-DC converter circuit acting as GSGFED



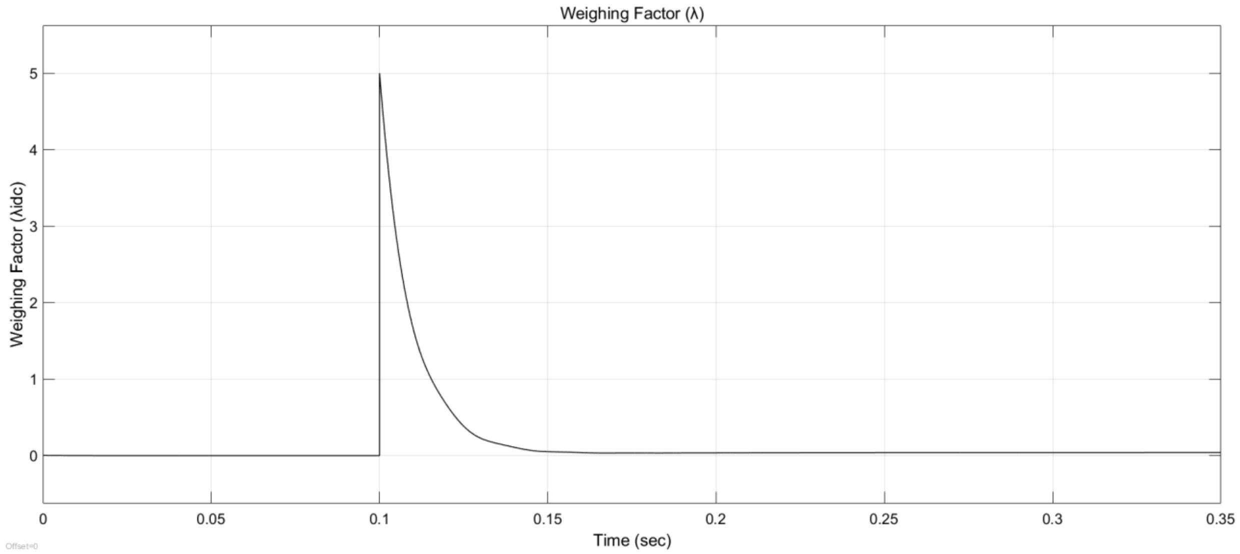


(b) DC voltage & Current of DC voltage Source

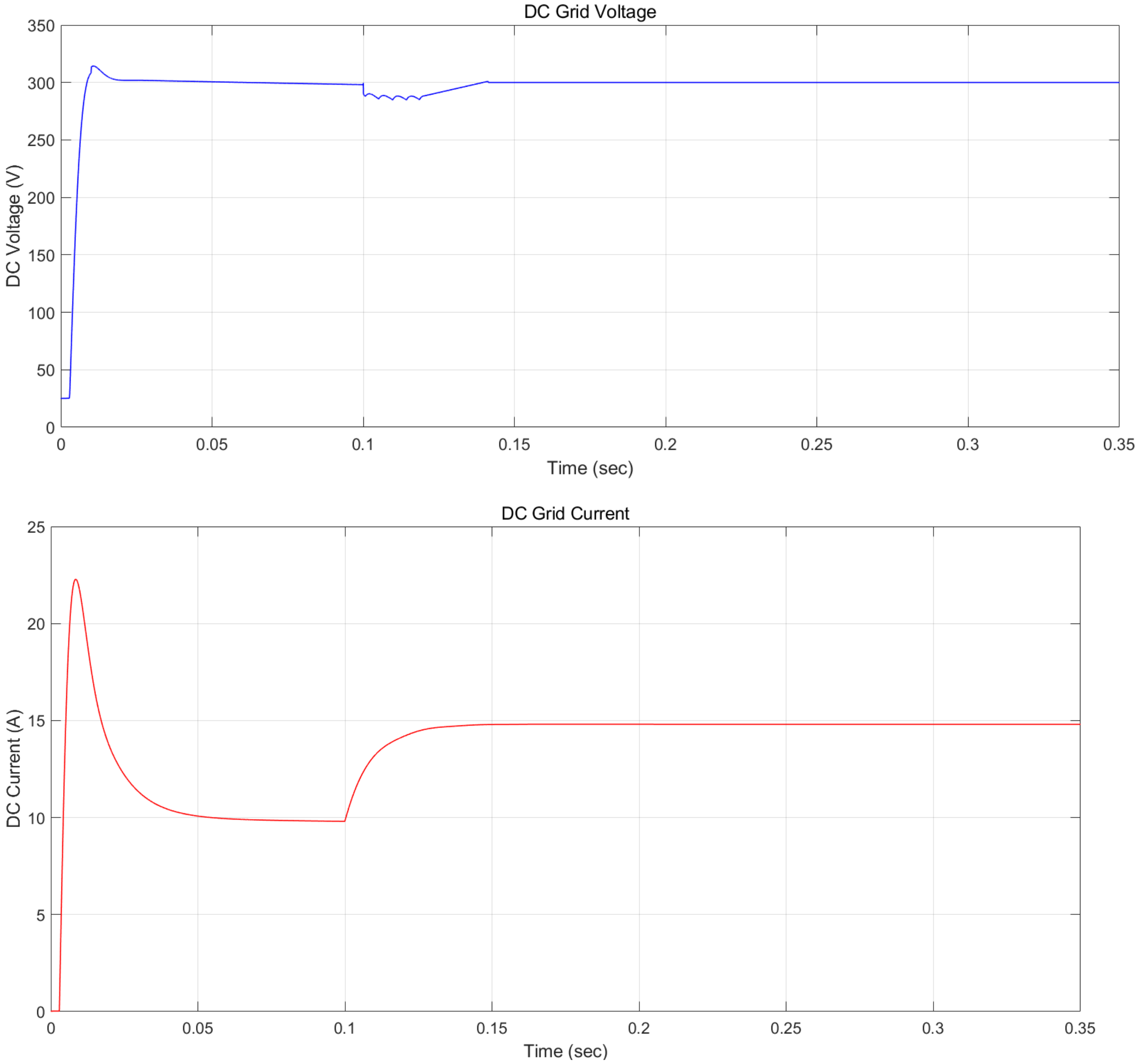




(c) DC voltage & current with bidirectional DC-DC converter acting as GSGFED



(d) Weighing Factor for bidirectional DC-DC converter acting as GSGFED



(e) DC load voltage & current

Figure 4.14 “DC voltage and current waveforms with Bidirectional DC-DC converter acting as GSGFED”

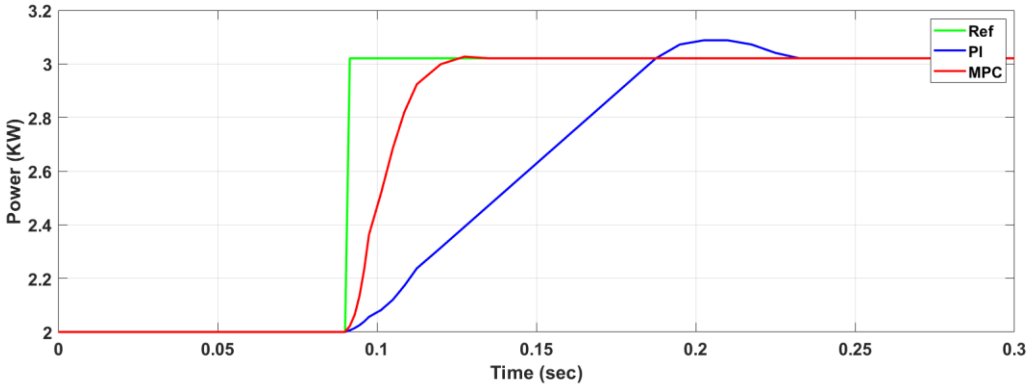


Figure 4.15: DC bus voltage regulation using (a) PI (b) MPC

A comparison of current regulation through MPC and PI is shown in Fig. 4.15. 3 KHz switching frequencies for the converters have been used to compare both PI and MPC techniques [217]. Moreover, MPC can increase the switching frequency resulting in less losses. Both MPC and PI-based VSC track the reference power with zero steady-state error. However, the PI controller exhibits overshoot during a transient and larger settling time than MPC. On the other hand, MPC tracks the reference with faster dynamic response and less over-shoot.

4.10 Summary

- MPC based variable weighing factor algorithm is proposed for Bidirectional DC/DC converter to regulate DC voltage by acting as GSGFMD or DC current by acting as GSGFED in all non-linear conditions by performing multi-variable control using variable weighing factor in the hybrid cost function. The control objectives are to regulate DC voltage & DC current to their reference values in steady state.
- It has been seen that the MPC based control methods are robust and they ensure fast dynamic response and mode changing capability.
- The results reveal that the proposed MPC based variable weighing factor algorithm effectively regulate the highest deviated parameter while increasing the efficiency of DC/DC converter with settling time of less than 0.06sec.

Chapter 5

Control of Hybrid Microgrid

5.1 Introduction

In this chapter control of hybrid MG is presented with AC source & load and BESS & PV based DGs & load. BESS based DG is connected to DC microgrid through bidirectional DC-DC converter already discussed in chapter 4. Moreover, PV based DG is connected to DC microgrid through DC-DC converter working as buck converter already discussed in chapter 4. Both AC and DC microgrid are connected to each other through BIC with control topology already discussed in chapter 3. The proposed hybrid MG is assumed to be in the building where sensors are nearby so that sensors readings are updated at the same time.

5.2 Proposed Technique

In this chapter, MPC based variable weighing factor has been proposed for both bidirectional interlinking converter and bidirectional DC/DC converter. Bidirectional DC/DC converter is connected to battery energy storage system (BESS) while DC/DC converter is connected to solar as shown in Fig. 5.1. MPC based control algorithm is proposed for both bidirectional interlinking converter and bidirectional DC/DC converter to regulate the highest deviated parameter in all operational modes by performing multi-variable control using variable weighing factor algorithm. The proposed algorithm enables bidirectional interlinking converter to act as a GSGFMR or GSGFMI or GSGFER or GSGFEI. The proposed algorithm enables bidirectional DC/DC converter and DC/DC converter to act as a GSGFMD or GSGFED.

5.3 Proposed EMS for Hybrid Microgrid

Energy Management System (EMS) has been proposed to explain power flow modes in hybrid MG. In the proposed hybrid MG, AC power coming through the AC source is supplied to the DC through BIC and same is the case with reverse flow of power. The ` BIC in rectifier or inverter mode will depend on the surplus/deficit power in AC and DC microgrid.

If surplus power is available in DC microgrid then BIC will operate in inverter mode to transfer power to AC microgrid. On the contrary, if surplus power is available in AC microgrid then BIC will operate in rectifier mode to transfer power to DC microgrid. So, BIC will either act as a GSGFMR to regulate DC voltage or GSGFER to regulate DC current or GSGFMI to regulate AC voltage or GSGFEI to regulate AC current. For a reliable operation of a hybrid AC-DC microgrid, one DG must assume the role of regulating DC grid voltage by acting as GSGFM DG. In AC microgrid AC source will act as GSGFM DG but if surplus power is available to fulfil rated load then BIC can also act as GSGFM DG to regulate AC voltage that is also demonstrated in result section as well. In DC microgrid, Solar DG, BESS DG and BIC will act as GSGFM or GSGFE DG which will be decided on the basis of power output of BESS DG (dependent on SOC), solar RDG (dependent on solar irradiance) and BIC (dependent on surplus AC power). All of above mentioned scenarios have been tested through modes 1-6.

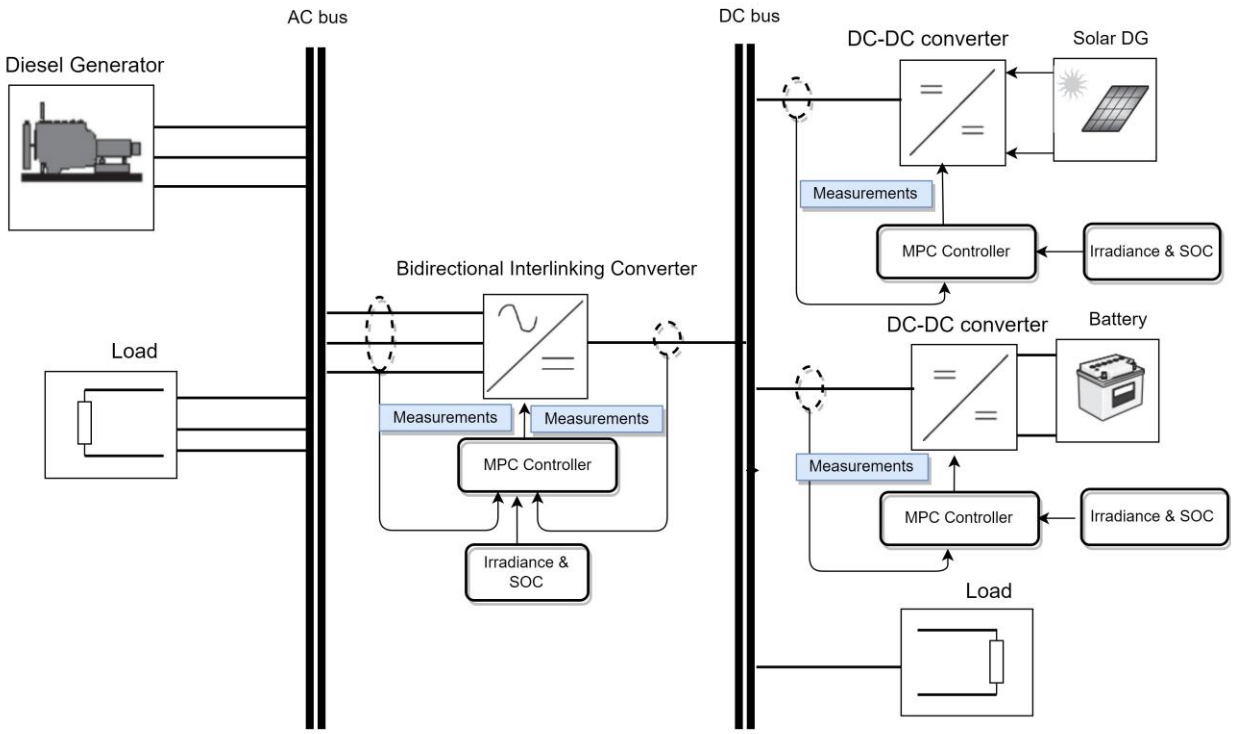


Figure 5.1 “Hybrid microgrid with MPC control”

In our proposed EMS, hybrid AC-DC microgrid operating mode will be determined based on generated and load power of Solar RDG, BESS DG, AC source and BIC. The power flow of DC microgrid is controlled by calculating the load and generated power of Solar RDG and BESS. The generated power is calculated from Solar RDG and BESS respectively as shown below:

$$P_{GEN} = P_{Solar} + P_{BESS} \quad (5.1)$$

$$P_{Load} = P_{Load} \quad (5.2)$$

Figure 5.2 shows the flow chart of EMS for hybrid AC-DC microgrid. In this mode, the generated power is compared with the load power. If generated power is greater than load power ($P_{Gen}>P_{load}$), then either Mode 1,2,3 (surplus power) will be chosen depending on battery SOC, rated power of BESS DG (P_{BESS_rated}), and amount of available charging power (P_{GEN}-P_{Load}). If generated power is less than load power ($P_{Gen}<P_{load}$), then either Mode 4,5,6 (deficit power) will be chosen depending on battery SOC, rated power of BESS DG (P_{BESS_rated}), and amount of available discharging power (P_{Load}-P_{Gen})

Mode 1

If power is surplus and battery SOC is less than the maximum allowable SOC, EMS will determine that battery needs charging, so mode 1 will be adopted. Surplus power ($P_{SURPLUS}$) is determined by comparing the difference between generated and load power (P_{GEN}-P_{Load}):

$$P_{SURPLUS} = P_{GEN} - P_{Load} \quad (5.3)$$

Surplus power must be less than or equal to the rated power of the battery:

$$P_{SURPLUS} \leq P_{BESS\_rated} \quad (5.4)$$

The amount of charging power is calculated by the equation:

$$P_{Char} = P_{GEN} - P_{Load} = [P_{Solar} - P_{Load}] > 0 \quad (5.5)$$

In this mode, Solar RDG will act as GSGFMD to regulate DC microgrid voltage, BESS is in charging mode and BIC will be sitting idle, so cost functions for all converters will be:

$$BIC = 0 \quad (5.6)$$

$$Solar = \lambda_{VDC}(V_{refDC} - V_{outDC})^2 \quad (5.7)$$

$$Battery = \lambda_{IDC}(I_{refDC} - I_{outDC})^2 \quad (5.8)$$

Mode 2

If Surplus power is more than the rated power of the battery, then EMS will operate the DC microgrid in mode 2:

$$P_{SURPLUS} \geq P_{BESS\_rated} \quad (5.9)$$

So, the battery charging current must be limited, and the remaining surplus power flows to the AC microgrid. So, battery power will be:

$$P_{Char} = P_{BESS\_rated} \quad (5.10)$$

The remaining surplus power flows to the AC microgrid through BIC. Here, BIC will act as GSGFEI to perform voltage regulation of AC microgrid:

$$P_{BIC} = P_{GEN} - P_{Load} - P_{BESS\_rated} > 0 \quad (5.11)$$

In this mode, Solar RDG is acting as GSGFMD to regulate DC voltage, and BESS is in charging mode, so cost functions for all converters will be:

$$BIC = \lambda_{IAC}(I_{refAC} - I_{outAC})^2 \quad (5.12)$$

$$Solar = \lambda_{VDC}(V_{refDC} - V_{outDC})^2 \quad (5.13)$$

$$Battery = \lambda_{IDC}(I_{refDC} - I_{outDC})^2 \quad (5.14)$$

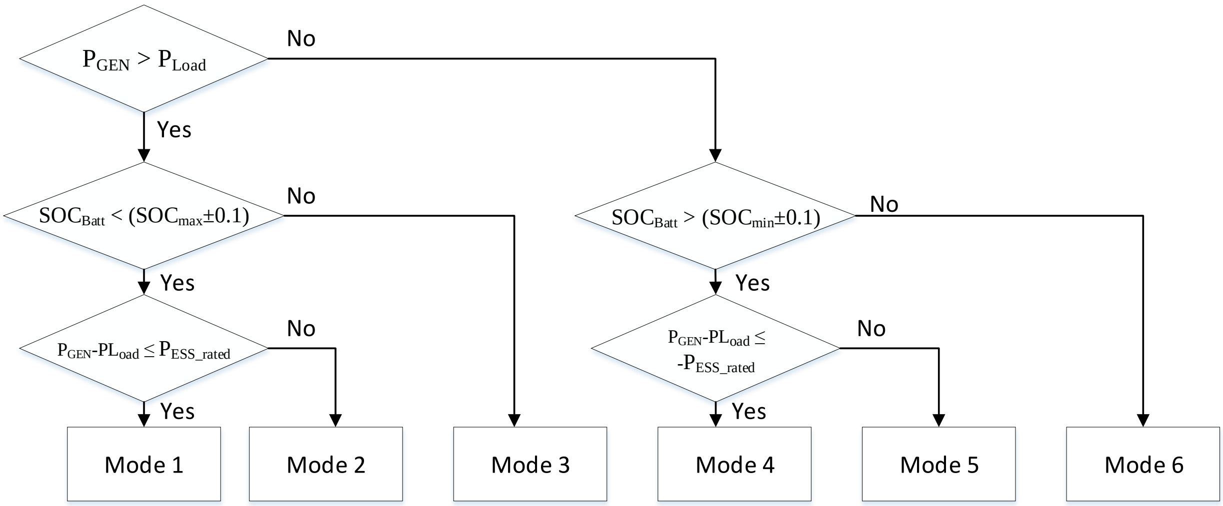


Figure 5.2 Flow chart of EMS for hybrid AC-DC microgrid

Mode 3

If battery SOC is greater than maximum SOC, no charging will be required. So, EMS will operate in this mode, and all the surplus power flows to the AC grid through BIC:

$$P_{BIC} = P_{GEN} - P_{Load} > 0 \quad (5.15)$$

So, when generated power is greater than load power, Mode 1,2 or 3 will be selected depending on SOC of the battery. BIC will act as GSGFMI to perform voltage regulation of AC microgrid and exports surplus power to the AC microgrid. Solar RDG will act as GSGFMD to regulate DC voltage & BESS is sitting idle, so cost functions for all converters will be:

$$BIC = \lambda_{VAC}(V_{refAC} - V_{outAC})^2 \quad (5.16)$$

$$Solar = \lambda_{VDC}(V_{refDC} - V_{outDC})^2 \quad (5.17)$$

$$Battery = 0 \quad (5.18)$$

Mode 4

When generated power is less than load power, the battery is discharged to fulfil the load power requirement provided battery SOC is greater than the minimum threshold SOC.

Then required discharge power is compared with the BESS converter rated capacity (P_{ESS_rated}). If the required discharge power is less than P_{ESS_rated}, then this mode is adopted by EMS. In this mode battery discharges the power to fulfil load requirement:

$$P_{BESS} = P_{GEN} - P_{Load} < 0 \quad (5.19)$$

In this mode, BESS will act as GSGFMD to perform voltage regulation of DC microgrid & Solar RDG will act as GSGFED to perform power regulation of DC microgrid and BIC will be idle, so cost functions for all converters will be:

$$BIC = 0 \quad (5.20)$$

$$Battery = \lambda_{VDC}(V_{refDC} - V_{outDC})^2 \quad (5.21)$$

$$Solar = \lambda_{IDC}(I_{refDC} - I_{outDC})^2 \quad (5.22)$$

Mode 5

If the required discharge power is greater than P_{ESS_rated}, then mode 5 is adopted by EMS. In this mode, the discharge power by the battery will be:

$$P_{BESS} = -P_{BESS\_rated} \quad (5.23)$$

Additional required power will be imported from AC microgrid through BIC:

$$P_{BIC} = P_{GEN} - P_{Load} - P_{BESS_{rated}} < 0 \quad (5.24)$$

In this mode, BIC along with BESS will act as GSGFED to perform power regulation of DC microgrid and Solar RDG will act as GSGFMD to perform voltage regulation of DC microgrid, so cost functions for all converters will be:

$$BIC = \lambda_{IDC}(I_{refDC} - I_{outDC})^2 \quad (5.25)$$

$$Solar = \lambda_{VDC}(V_{refDC} - V_{outDC})^2 \quad (5.26)$$

$$Battery = \lambda_{IDC}(I_{refDC} - I_{outDC})^2 \quad (5.27)$$

Mode 6

If battery SOC is at the minimum level, then discharge through the battery is not possible and mode 6 is adopted by EMS in which required power is imported from AC microgrid through BIC:

$$P_{AC-DC\,converter} = P_{GEN} - P_{Load} < 0 \quad (5.28)$$

In this mode, BIC will act as GSGFMR to perform voltage regulation of DC microgrid with Solar RDG & BESS acting as GSGFED to perform power regulation of DC microgrid, so cost functions for all converters will be:

$$BIC = \lambda_{VDC}(V_{refDC} - V_{outDC})^2 \quad (5.29)$$

$$Solar = \lambda_{IDC}(I_{refDC} - I_{outDC})^2 \quad (5.30)$$

$$Battery = 0$$

(5.31)

In grid-connected mode, when Solar RDG generated power is less than load power, EMS will select mode 4 to let the battery discharge the required power to fulfil load power. If battery discharge power is not enough to fulfil all the load power requirement, then mode 5 is selected to let the battery discharge and import the remaining required power from the AC grid. If battery discharge power is not possible, mode 6 is selected to import power from the AC grid. Following cost functions have been implemented for above mentioned modes:

$$\mathrm{Cost(BESS\ or\ Solar)} = \lambda_{\mathrm{IDC}}(\mathrm{I_{refDC}} - \mathrm{I_{outDC}})^2 + \lambda_{\mathrm{VDC}}(\mathrm{V_{refDC}} - \mathrm{V_{outDC}})^2 \quad (5.32)$$

$$Cost(BIC) = \lambda_{\mathrm{VAC}}(\mathrm{V_{refAC}} - \mathrm{V_{outAC}})^2 + \lambda_{\mathrm{IAC}}(\mathrm{I_{refAC}} - \mathrm{I_{outAC}})^2 + \lambda_{\mathrm{VDC}}(\mathrm{V_{refDC}} - \mathrm{V_{outDC}})^2 + \lambda_{\mathrm{IDC}}(\mathrm{I_{refDC}} - \mathrm{I_{outDC}})^2 \quad (5.33)$$

Following limits for λ are being tested: $0 \leq \lambda_{Vac} \leq 5$, $0 \leq \lambda_{Vdc} \leq 3$, $0 \leq \lambda_{Iac} \leq 1$ & $0 \leq \lambda_{Idc} \leq 3$.

Table 5.1 Roles of power converters in all cases

Mode	Solar DG	Battery DG	BIC	AC Source
1	GSGFMD	Charging	Idle	GSGFMI
2	GSGFMD	Charging	GSGFEI	GSGFMI
3	GSGFMD	Idle	GSGFMI	GSGFEI
4	GSGFED	GSGFMD	Idle	GSGFMI
5	GSGFMD	GSGFED	GSGFED	GSGFMI
6	GSGFED	Idle	GSGFMD	GSGFMI

5.4 Results

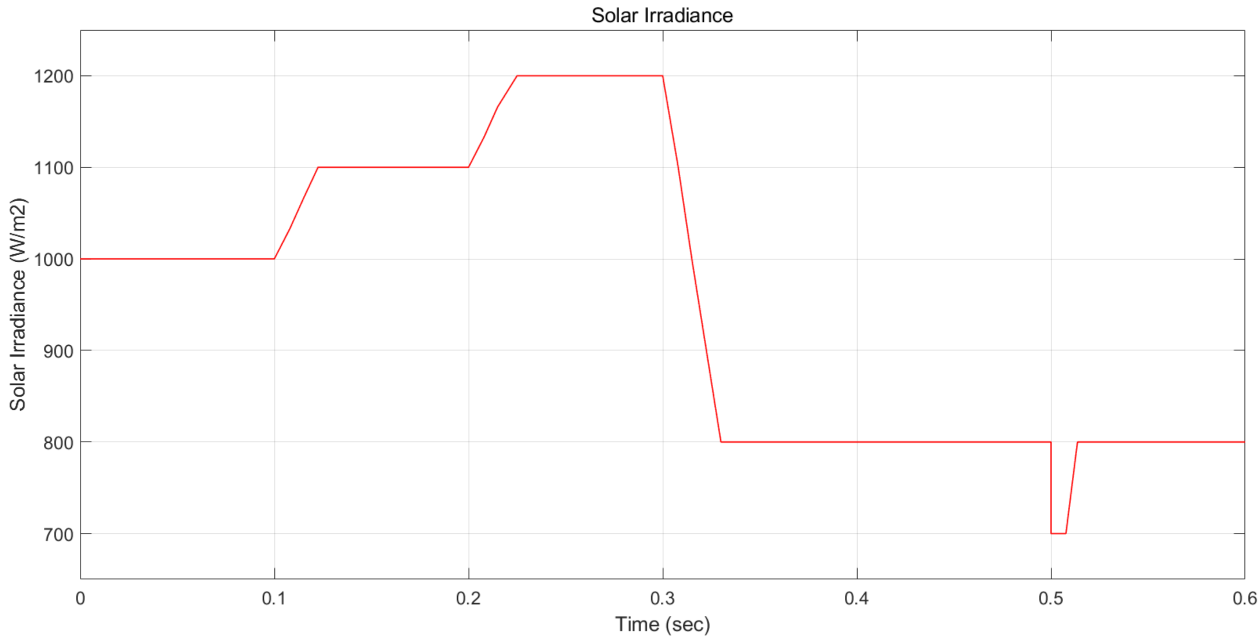
The performance of the proposed MPC algorithm for EMS of Hybrid AC-DC microgrid is being tested in MATLAB/Simulink. Parameters used in the simulation are shown in Table 5.2. To verify the efficiency of the proposed method, real time solar irradiation data of Karachi [218] has been used to generate PV output plotted in Fig. 5.3(a).

Table 5.2 Simulation Parameters [161]

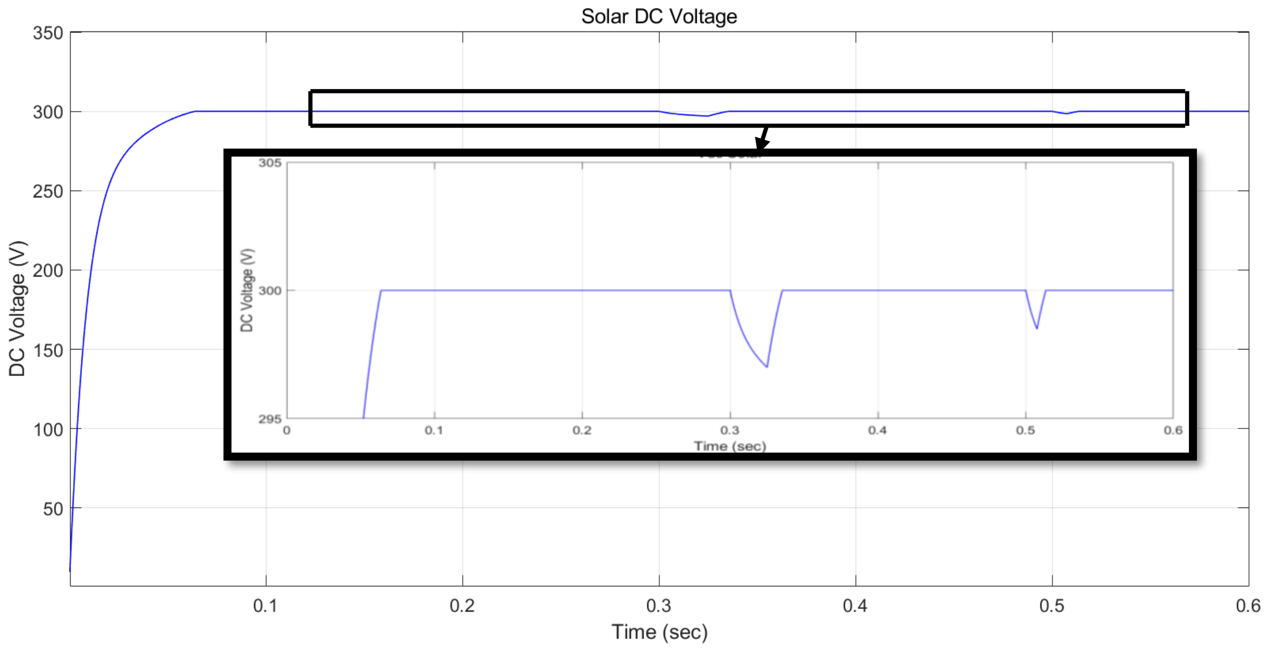
Description	Values
Solar Plant	Trina Solar TSM-250PA05.08, 2.7KW.
Battery	290V 4.1AH
Diesel Generator	110V 6A
DC grid voltage	300 V
AC grid voltage	110V
Sampling time (Ts)	50 µsec
DC Load	2.4 KW

Figures 5.3 to 5.8 shows the simulation waveform for hybrid AC-DC microgrid. In AC microgrid load of 0.3KW and in DC microgrid, load of 2.4KW is connected to the microgrid initially. From t=0 to t=0.1sec, solar DG power output is 2.7KW with the solar

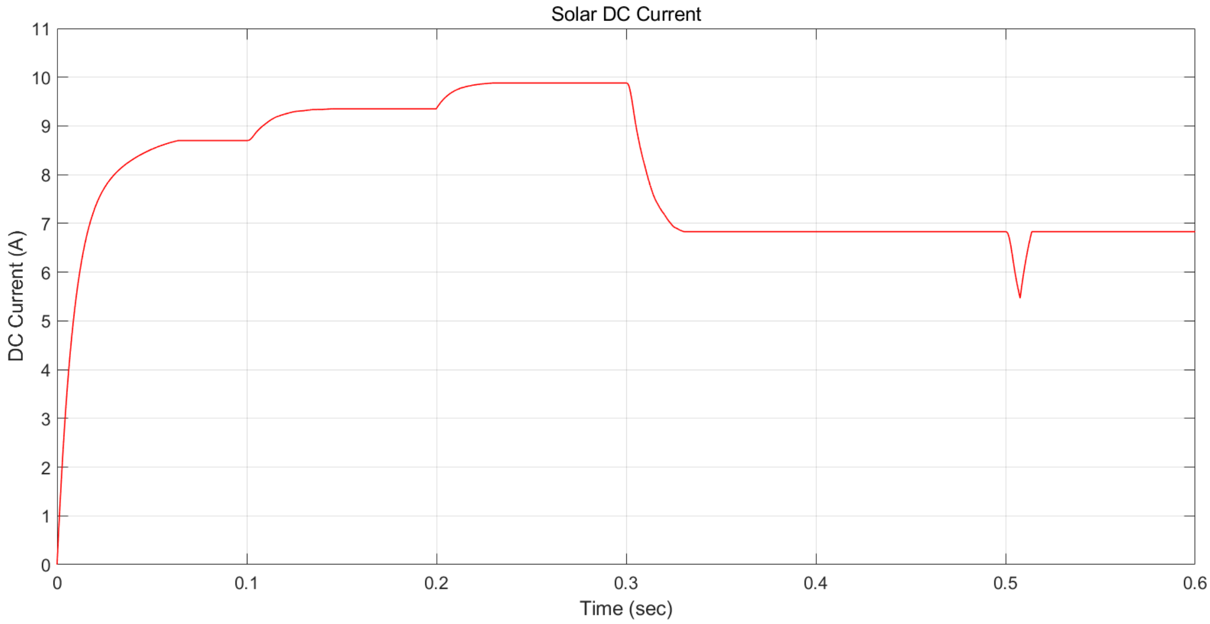
irradiance of 1000W/m^2. So solar DG power output is greater than the load power so surplus power equal to the rated charging power of BESS, is used to charge the battery as explained in mode 1. From t= 0.1sec to t= 0.2sec, solar irradiance increases due to which solar DG power output is greater than load power so surplus power greater than the rated charging power of BESS, is used to charge the battery as well as exported to AC microgrid with BIC acting as GSGFEI to regulate AC current as explained in mode 2. From t=0.2 to 0.3 sec, battery SOC has reached maximum SOC value (here it is set at 30%) so the battery does not require charging current anymore and solar DG power output is greater than load power which means that surplus power is fed to AC microgrid with BIC acting as GSGFMI to regulate AC voltage greater as explained in mode 3. From t=0.3 to 0.4 sec, solar DG output power decreases due to decrease in solar irradiance and it cannot fulfil complete load power requirement so BESS DG start acting as GSGFMD to give required power to fulfil deficient load power requirement provided that deficient load power requirement is less than the rated discharge power of BESS as explained in mode 4. From t=0.4 to 0.5 sec, solar DG output power stabilizes due to which it start acting as GSGFMD to regulate DC voltage but still it cannot fulfil complete load power requirement. So, BESS DG keep on giving deficient load power but as its SOC is near to minimum threshold SOC value (here, it is set at (30.00%), so BESS DG power output is curtailed and remaining required output power is given by BIC which start acting as GSGFED as explained in mode 5. From t=0.5 to 0.6 sec, BESS DG SOC is equal to minimum threshold SOC value so no power putout can be given by BESS so remaining load output power is given by BIC which start acting as GSGFMD to regulate DC voltage as explained in mode 6.



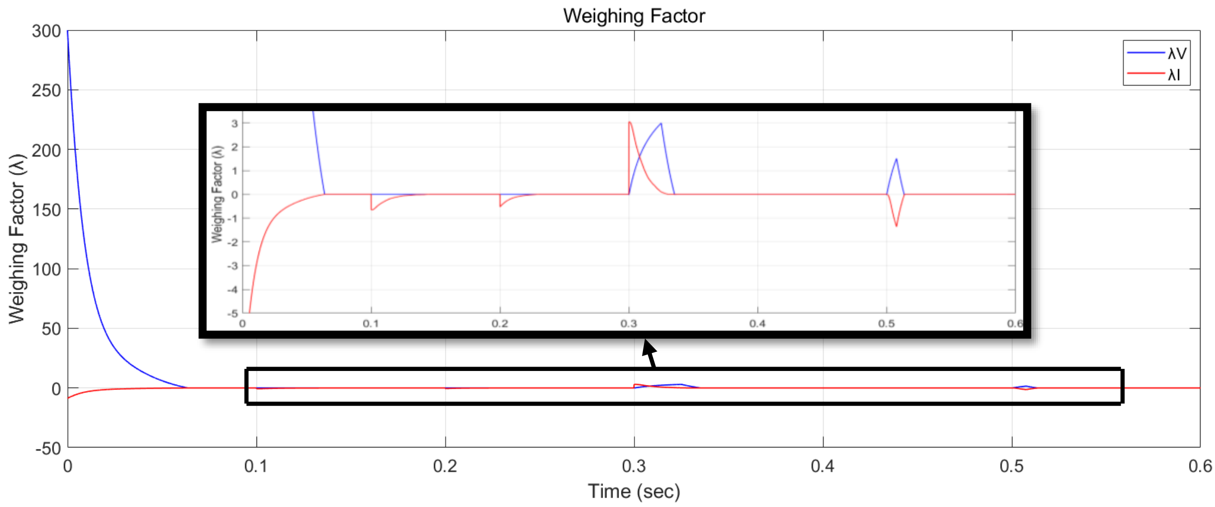
(a) Solar irradiance



(b) Solar DC voltage

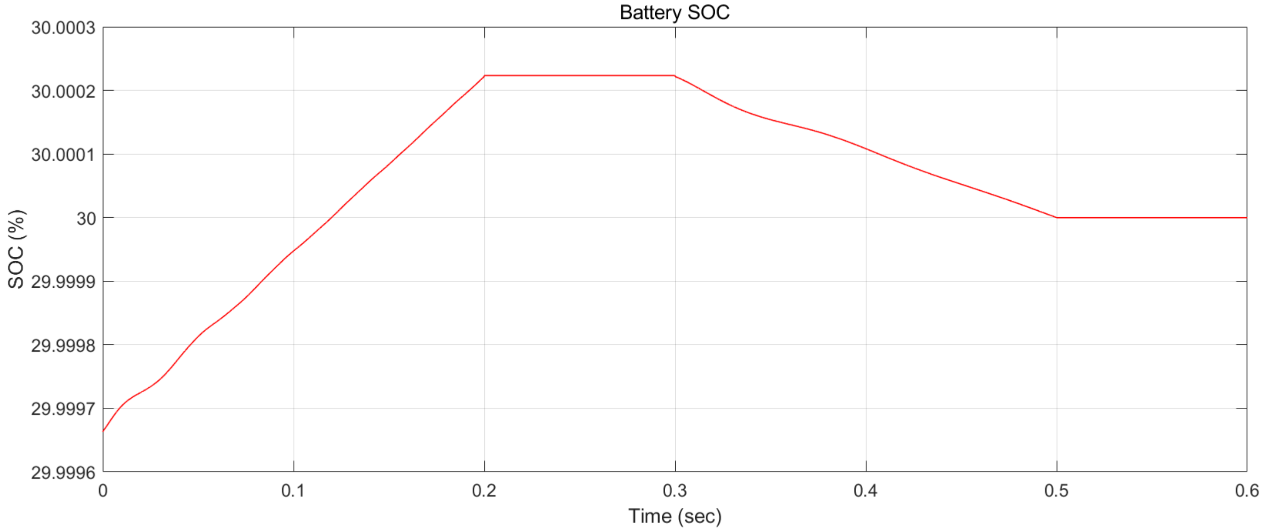


(c) Solar DC current

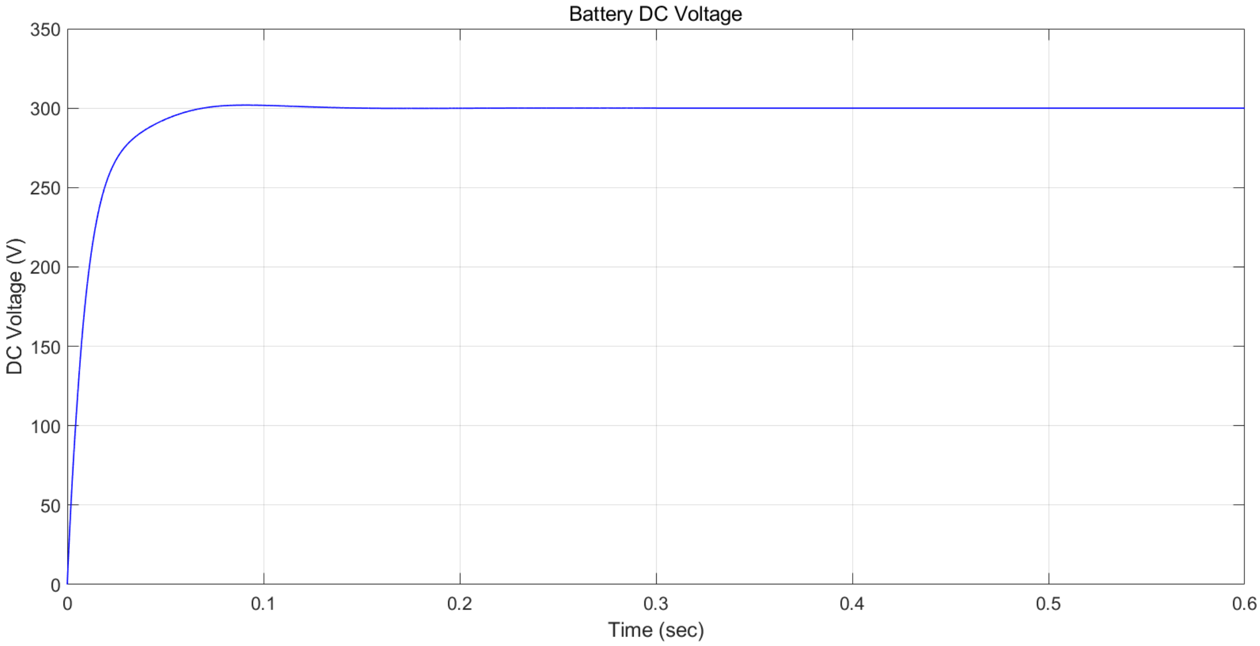


(d) Weighing Factor of Solar DG

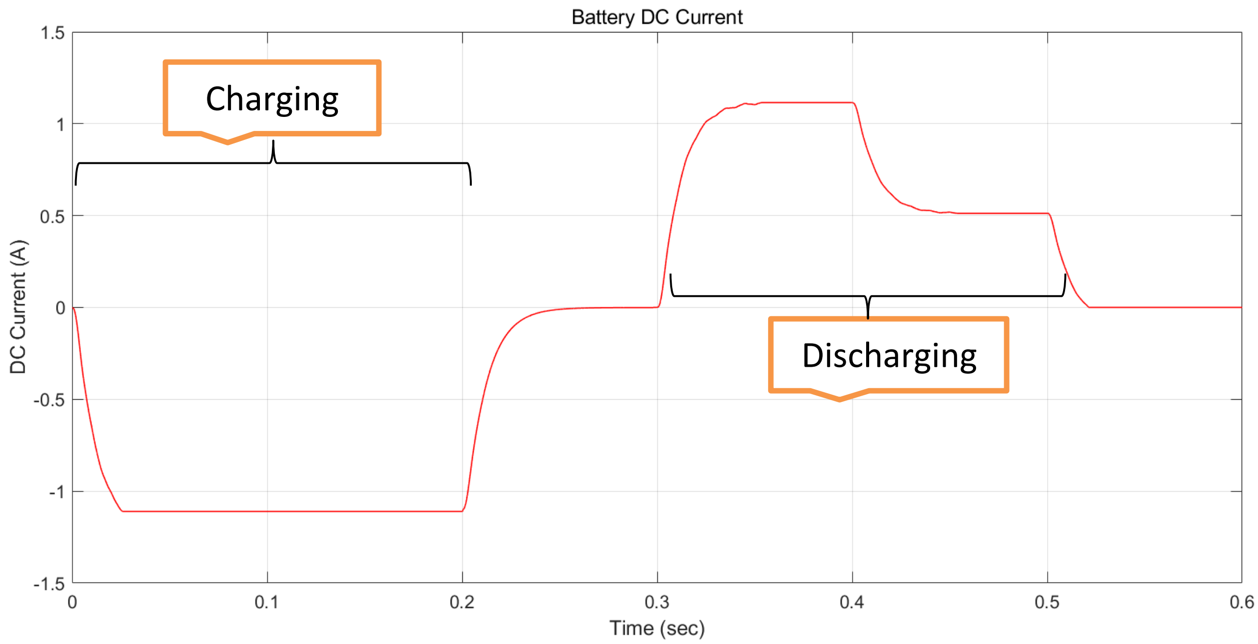
Figure 5.3 “DC voltage, current, weighing factor and solar irradiance waveforms of Solar DG”



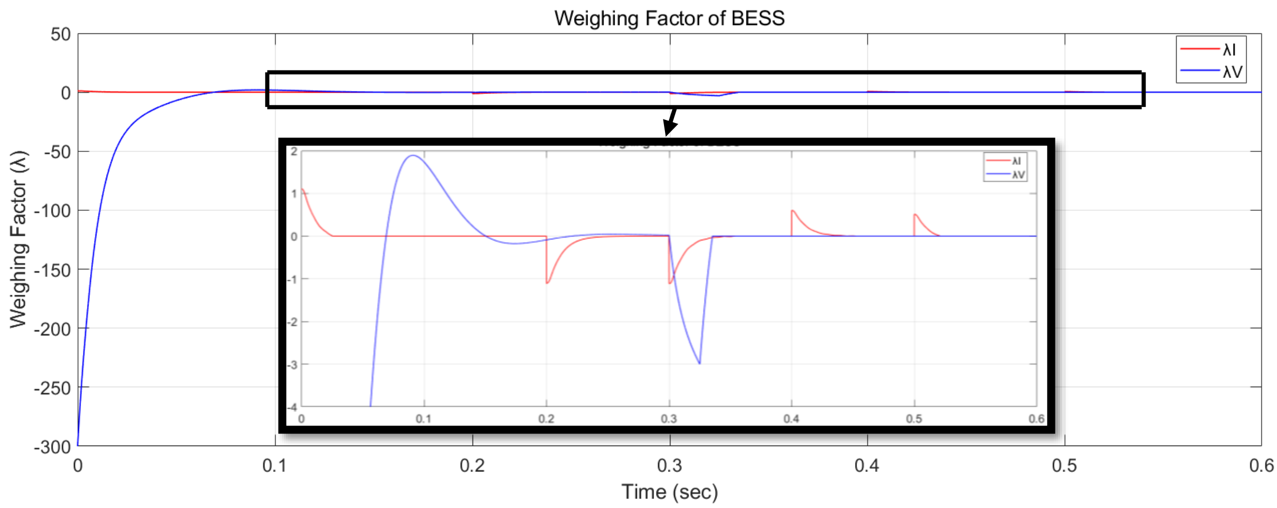
(a) BESS SOC graph



(b) BESS DC voltage

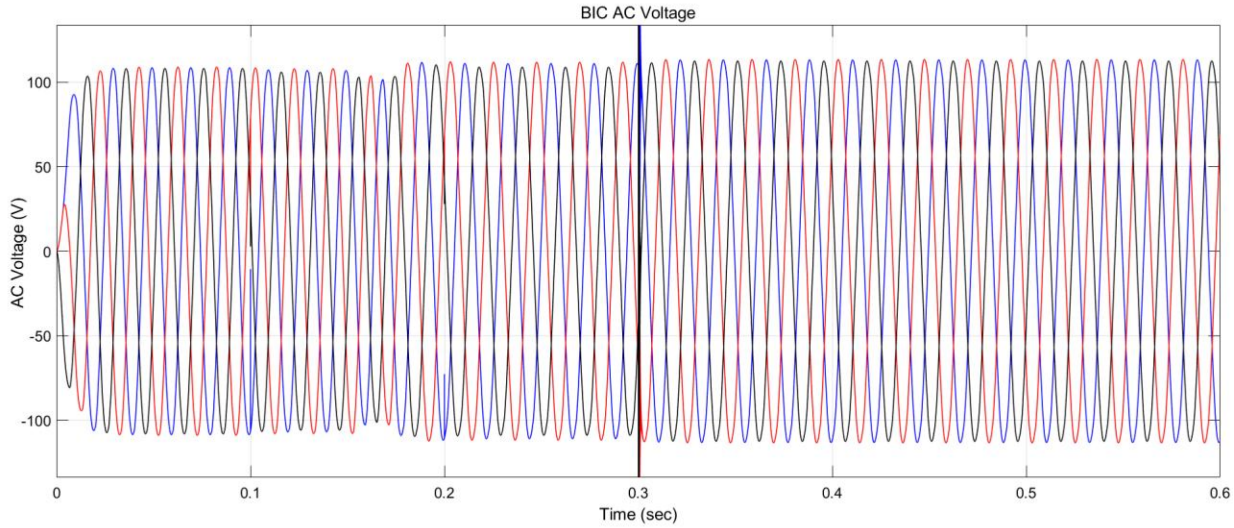


(c) BESS DC current

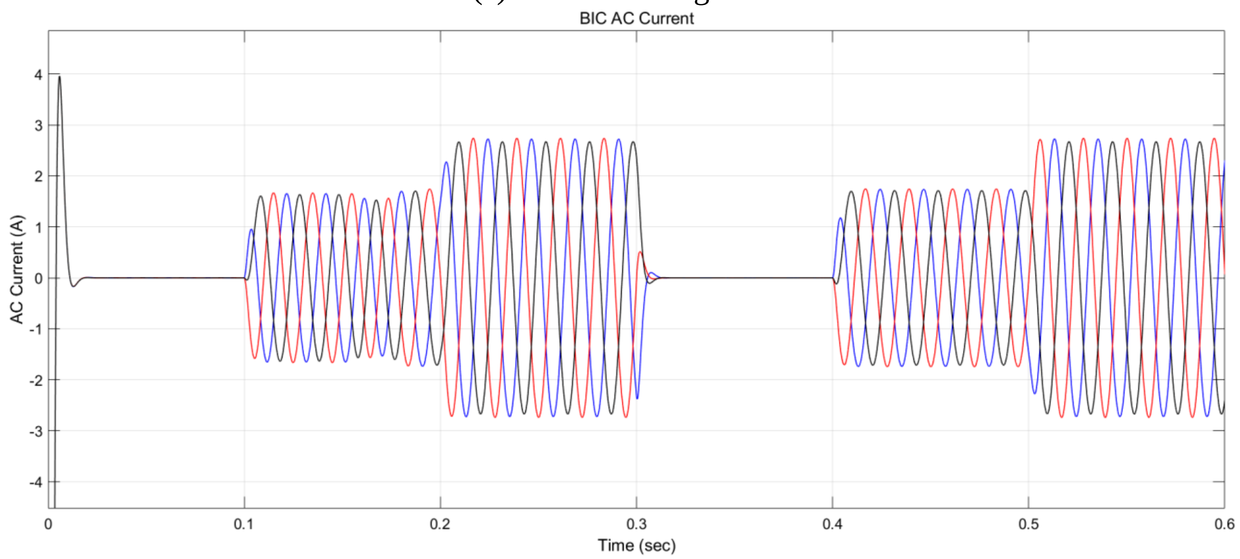


(d) Weighing Factor of BESS

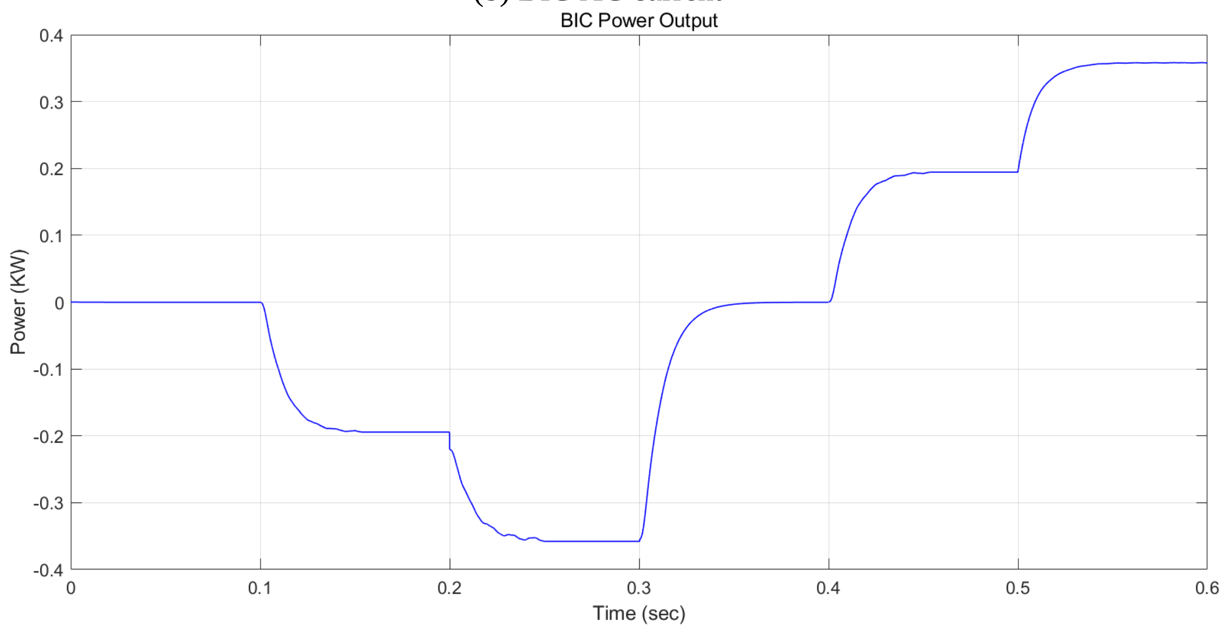
Figure 5.4 “DC voltage, current and battery SOC waveforms of BESS DG”



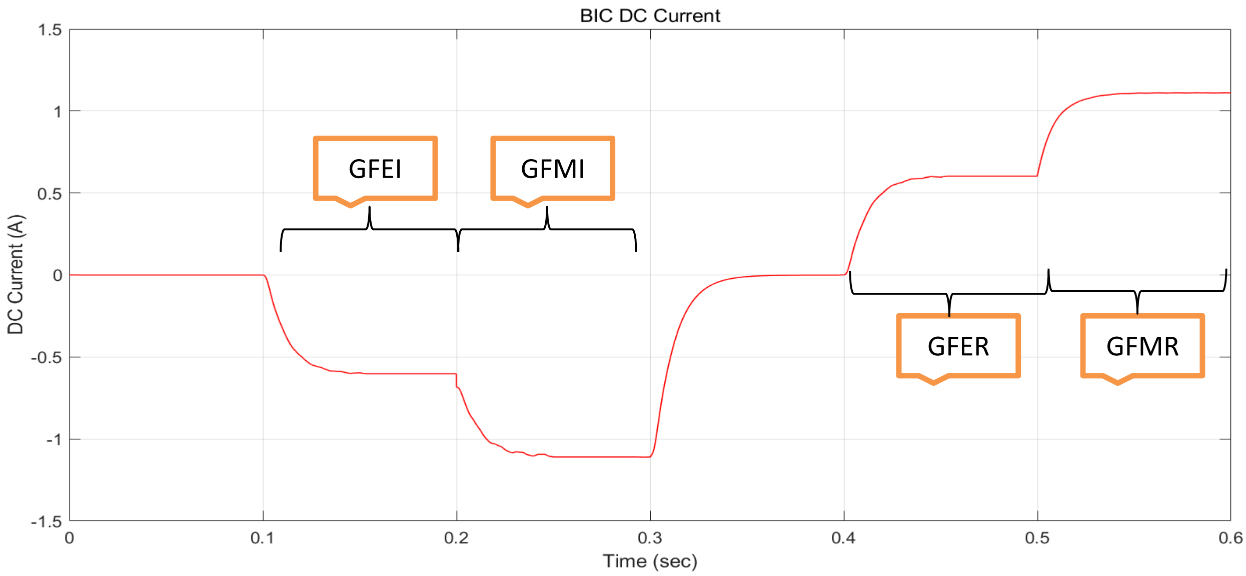
(a) BIC AC voltage



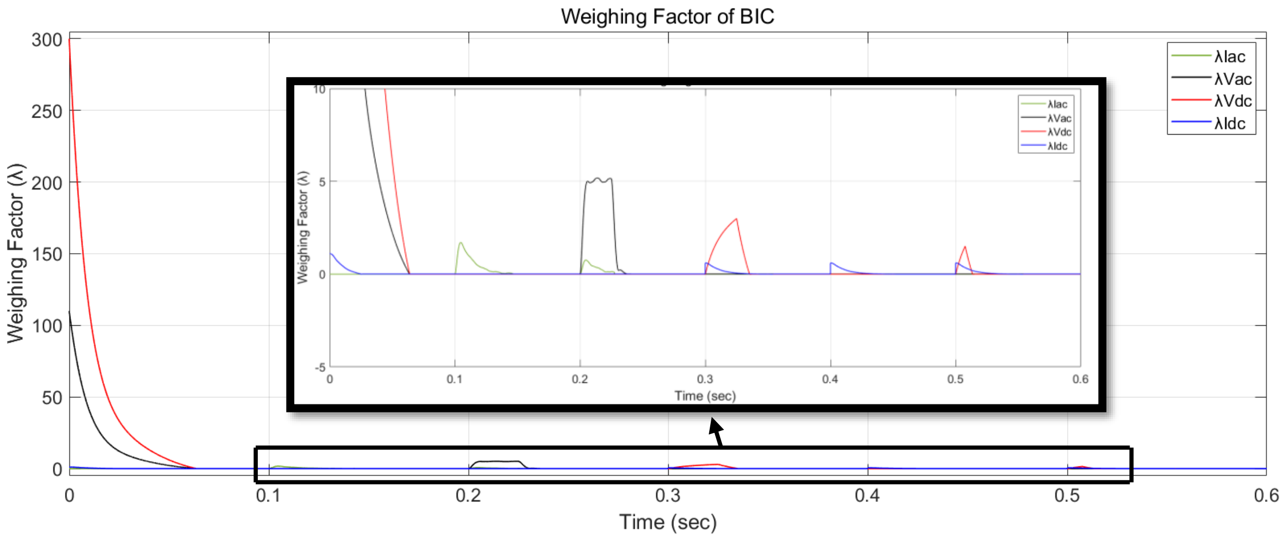
(b) BIC AC current



(c) BIC power output



(d) BIC DC current



(e) Weighing Factor of BIC

Figure 5.5 “Voltage and Current waveforms of BIC”

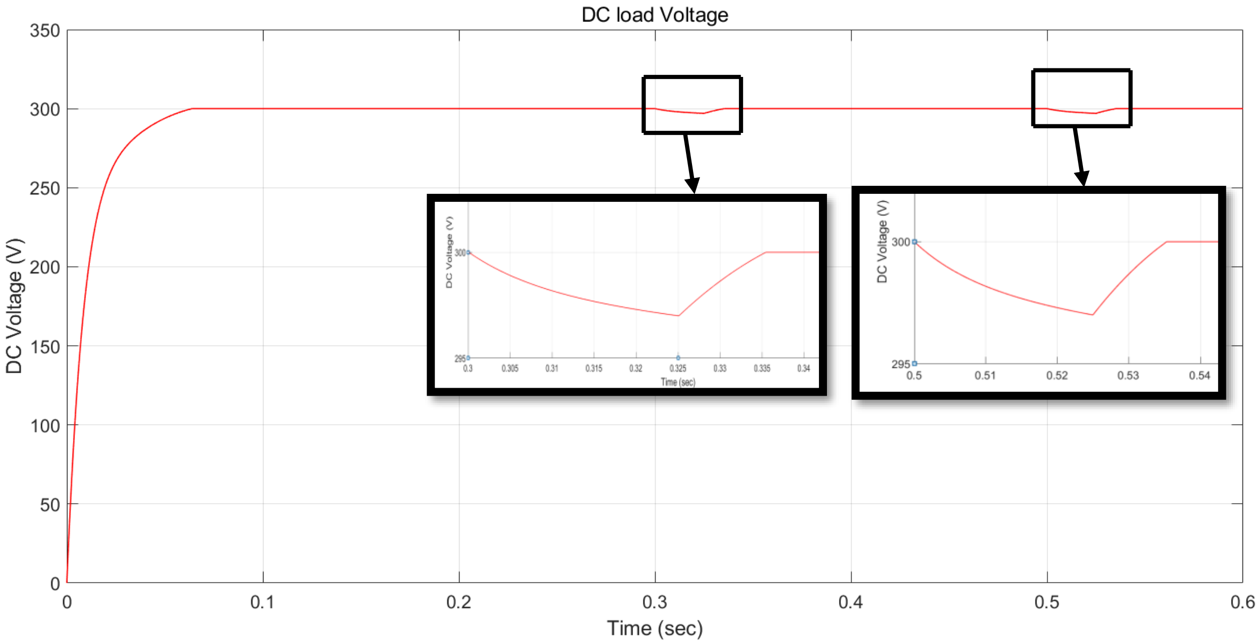
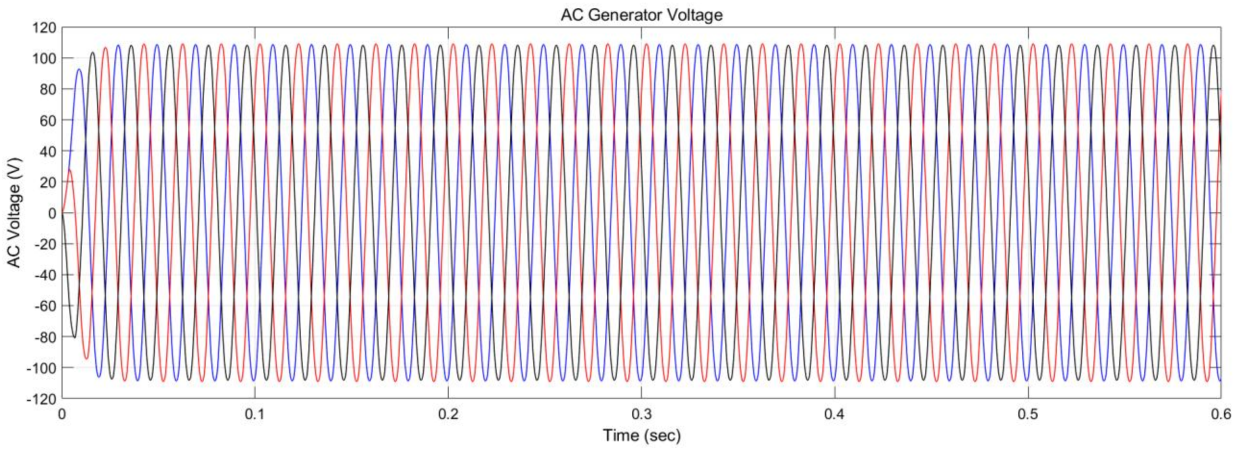
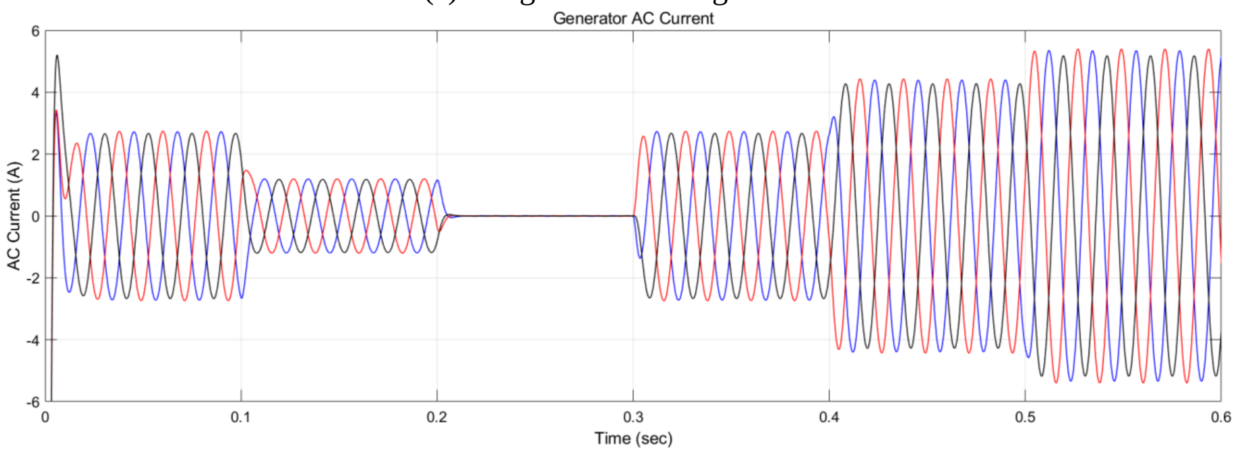


Figure 5.6 “DC voltage waveform of DC load”



(a) AC generator voltage



(b) AC generator current

Figure 5.7 “Voltage and Current waveforms of AC Generator”

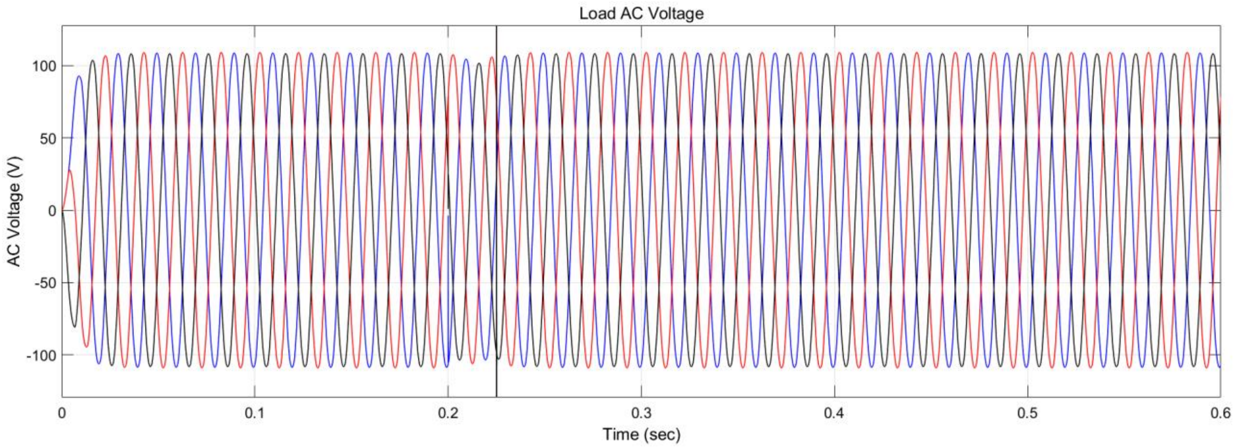


Figure 5.8 “AC voltage waveform of AC load”

5.3 Summary

This chapter proposes an MPC based variable weighing factor algorithm for RDG and BESS individual controllers to regulate voltage as GSGFM or regulate current as GSGFE. Their roles are determined based on the basis of DGs power output with respect to solar irradiance, wind speed, SOC of BESS and load power. Based on above mentioned parameters, capability of RDG and BESS BDDC’s respectively to act as GSGFM or GSGFE units is decided. A single cost function coupled to MPC based variable weighing factor algorithm leverages RDG and BESS to act as GSGFM or GSGFE. It has been noted that MPC technique exhibits settling time and no overshoot. The results confirm that the proposed MPC-based energy management system ensures good steady state operation and dynamic response of all DGs in hybrid microgrid. The results are very encouraging and will play an important part in improving the performance of the energy management system for the hybrid AC-DC microgrid using AI techniques with MPC and its testing in hardware in loop setup.

Chapter 6

Summary, Conclusion and Future Work

This chapter discusses the summary, conclusion and future work related to hybrid AC-DC microgrids.

6.1 Summary

Control of hybrid MG to ensure optimal power flow is a promising research area but still there is a lot to learn about it. This thesis comprises of five chapters. First chapter consists of motivation, problem statement and research objectives being achieved in this thesis. Second chapter consists of the introduction of the hybrid MG followed by the literature review on hybrid MG control and MPC application on it. In this chapter literature review with respect to hybrid MG control, MPC and its application on power electronics converters and DC microgrid control is explained. Third chapter consists of details of the proposed variable weighing factor based MPC framework for BIC in hybrid AC-DC microgrids followed by the technical details and results of our proposed methodology. Fourth chapter consists of control of RDG and BESS in hybrid AC-DC microgrids using proposed variable weighing factor based MPC framework followed by the technical details and results of our proposed methodology.

6.2 Conclusion

- This thesis proposes the architecture of a MPC based variable weighing factor algorithm for RDG, BESS and BIC to act as GSGFM or GSGFE DG for all operational modes of hybrid AC-DC microgrid.
- The basic design principal of this algorithm is to maximize the usage of controllers of all the DG units of microgrid by assigning them the role of GSGFM DG or GSGFE DG as per their power handling capacity and grid loading conditions; thus, achieving the good steady-state performance and quick dynamic response.
- MPC based variable weighing factor algorithm determine the role on the basis of DGs power output with respect to solar irradiance, wind speed, SOC of BESS and load power. The

proposed algorithm is used to ensure optimal power flow in both grid-connected and standalone operation modes.

- Based on above mentioned parameters, capability of RDG and BESS BDDC's respectively to act as GSGFM or GSGFE units is decided. A single cost function coupled to MPC based variable weighing factor algorithm leverages RDG and BESS to act as GSGFM or GSGFE.
- In this thesis, a single cost function coupled with MPC based variable weighing factor algorithm has been proposed for both GSGFM and GSGFE.
- Results are compared with traditional Proportional Integral (PI) based control technique. Comparison shows that low THD and less settling time has been achieved. These results will help in achieving the reliable and stable operation of hybrid MG with multiple DGs.
- Pakistan is the sixth largest nation in the world with around 51 million people (20% of the population) living off grid with no access to electricity*. The proposed algorithm will aid in offering the off-grid solution to those areas, which are not grid connected.

6.3 Future Work

The future outlook of this study can be described in the following main headings:

1. In our research, auto tuning method to tune weighing factors has been proposed according to the maximum admissible error. Thus, this study can be extended to auto tuning of weighing factor using Artificial Intelligence (AI), Machine Learning (ML) or Artificial Neural Network (ANN). Online optimization techniques can also be used keeping in view the real-time grid and operational conditions as well. It consists of AI-based and non-AI based techniques. Various AI-based techniques such as fuzzy logic, genetic algorithm etc. can be used to optimize the tuning process of weighing factor in different type of power converters such as 2L-VSC, 3L-NPC etc. Biological process in metaheuristic techniques such as particle swarm optimization (PSO), genetic algorithm (GA), support vector regression coupled with multi objective particle swarm optimization (SVR-MOPSO), Brain Emotional Learning (BEL) may be used for optimization of switching frequency, total harmonic distortion (THD), flux, torque, mode switching etc. in model predictive control of power electronics converters. Machine learning techniques may be used with respect to supervised approach or unsupervised approach using labelled or unlabeled dataset for auto tuning of weighing factor in MPC. Another variant of machine learning is reinforcement learning which does not require dataset. It can also be used for auto tuning of weighing factor

in MPC. Another variant of supervised approach is neural network which can also be applied for auto tuning of weighing factor in MPC. Above mentioned methods are offline methods which have an effect on the efficiency of controller and controller response to the disturbances. Online methods to auto tune the weighing factor in MPC includes neural network technique comprising of PSO algorithm coupled with Lyapunov stability method that ensures control stability. Summarizing the above discussion, it can be concluded that artificial intelligence and machine learning techniques can be employed for auto tuning of weighing factor to further improve MPC efficiency without needing significant computational resources. As far as non-AI-based Online Optimization methods are concerned, methods such as tracking error optimization, torque ripple optimization, coefficient of variation, algebraic etc. can also be used to tune the weighing factors. Moreover, effect of cable resistances on tuning methods for weighing factors can be studied to further improve MPC efficiency.

2. In our research, Finite Control Set Model Predictive Control (FCS-MPC) for is used for predicting the output. Thus, this study can be extended to field implementation of prediction of output using modulated MPC with fixed switching frequency for multilevel converters such as neutral point clamped (NPC) converters, matrix converters etc. Another variant of MPC called as sequential MPC can also be employed where multiple objectives are sequentially cascaded in a cost function to perform multi objective controllability.

3. The limitations of this research is the unavailability of hardware in loop (HIL) setup in Pakistan to validate the performance of proposed algorithm in control hierarchy of hybrid microgrid.

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Appendix

A.1

In Lyapunov's direct method, value for derivative of the Lyapunov function shown in (3.27) should be negative which shows that the considered system is stable [211]. Below table shows the derivative of the Lyapunov function ΔL(k) found out against error in current (i_{error}):

S.No.	Error in current (i_{error})	ΔL(k)
1.	1	-0.05
2.	2	-0.010
3.	3	-0.015
4.	4	-0.020
5.	5	-0.025

A.2

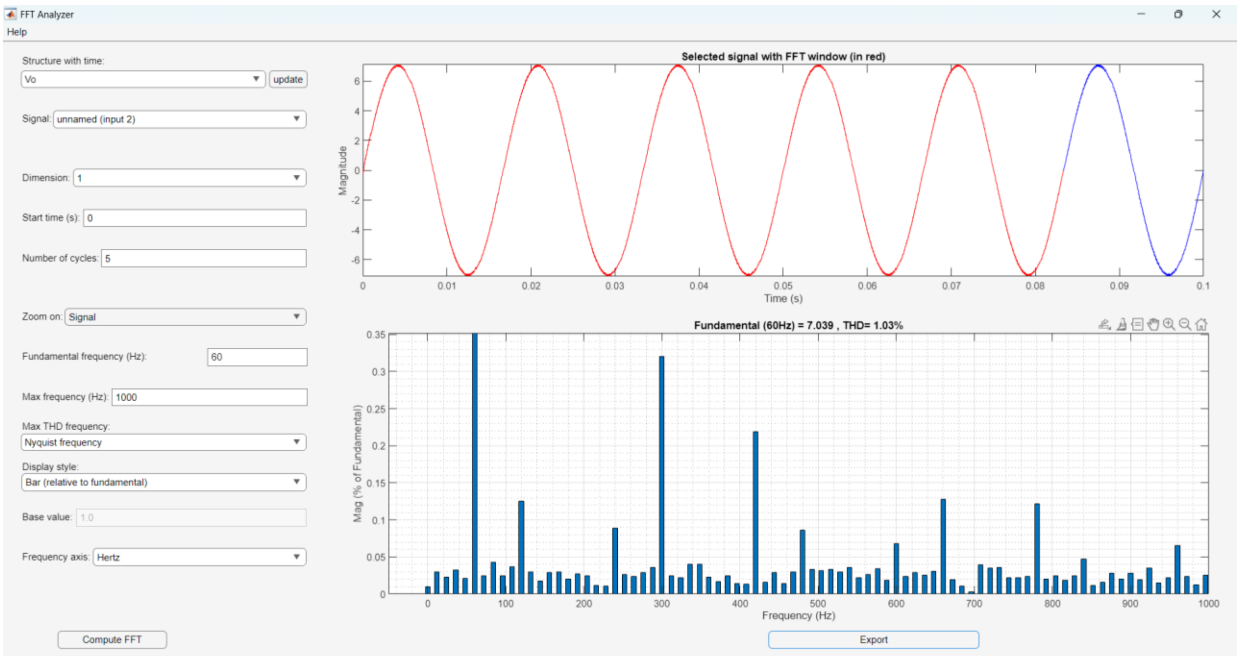

Figure 3.16 THD achieved in MATLAB

A.3

Filter design has been designed on the formula:

$$L = \frac{V_{DC}}{4*F_{SW}*\Delta I_{pmax}} = \frac{300V}{4*3KHz*(\frac{1500W}{110V}*\sqrt{2}*0.3)} = 4.7\text{mH}$$