

# Parallel Operation Of 2x Mobile DG's With Different Ratings

By

Mahad Imtiaz Lodhi

Enrollment No. 01-133222-034

Ayesha Aqeel

Enrollment No. 01-133222-013

**Supervised By**

Dr. Syed Umaid Ali



Session 2022-2026


A Report is submitted to the Department of Electrical Engineering, Bahria University, Islamabad. In partial fulfillment of requirement for the degree of BS(EE).

-

## Certificate

We accept the work contained in this report as a confirmation to the required standard for the partial fulfillment of the degree of BS(EE).

\_\_\_\_\_  
Head of Department

  
\_\_\_\_\_  
Supervisor

\_\_\_\_\_  
Internal Examiner

\_\_\_\_\_  
External Examiner

# Dedication

I dedicate this degree to my parents and my respected teachers who have supported me throughout my academic journey. Your guidance, sacrifices, and encouragement have made me who I am today. Thank you for believing in me and helping me achieve my dreams.

## Acknowledgments

I would like to express my sincere gratitude to Dr Syed Umaid Ali for their invaluable guidance and support throughout this project. I also appreciate the assistance provided by Sir Imran in setting up the experimental setup. Additionally, I acknowledge the contributions of Bahria University for providing the necessary resources and facilities.

## Abstract

Mobile diesel generators (DGs) are widely used in industries such as construction, mining, disaster recovery, and remote operations to provide immediate power where grid access is unavailable. In many cases a single generator cannot meet the required load, making parallel operation necessary. Operating generators in parallel offers benefits like increase capacity, improved reliability, and better fuel efficiency. Parallel operation of DGs with different ratings presents challenges, particularly in synchronization and load sharing. Synchronization ensures that voltage, frequency and phase angle match before interconnection. Load sharing between unequal generators requires precise control to prevent overloading smaller units and underutilizing larger ones. Traditional methods often assume identical ratings, making them unsuitable for mixed setups. This project develops a system for parallel operation of two DGs with different ratings advanced synchronization and load sharing strategies. The design includes synchronization panels, controllers and measurements instruments. Testing under various load conditions confirmed smooth synchronization, accurate load sharing and improved fuel efficiency. In conclusion this project provides a practical solution for industries relying on mobile power sources. Future enhancements may include renewable integration, intelligent controllers for dynamic load management, and grid tied hybrid systems.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Introduction . . . . .	2
1.2	Project Background . . . . .	2
1.3	Project Objectives . . . . .	3
1.4	Importance of Parallel Operation of Mobile Diesel Generators	3
1.4.1	Increased Power Capacity . . . . .	3
1.4.2	Improved Reliability and Redundancy . . . . .	3
1.4.3	Enhanced Fuel Efficiency . . . . .	4
1.4.4	Reduced Maintenance Stress . . . . .	4
1.5	Challenges of Parallel operation with Different Ratings . . .	4
1.5.1	Unequal Load Distribution . . . . .	4
1.5.2	Dynamic Stability Issues . . . . .	4
1.6	Project Description . . . . .	5
1.7	Project Scope . . . . .	5
1.7.1	Limitations . . . . .	5
<b>2</b>	<b>Literature Review</b>	<b>6</b>
2.1	Distributed Generation Overview . . . . .	7
2.2	Need For Parallel Operation . . . . .	8
2.3	Role of Diesel Generators in Islanded and Mobile Power Systems . . . . .	8
2.4	Synchronization Techniques . . . . .	9
2.5	Load Sharing Methods . . . . .	9
2.6	Load Sharing Principles in Parallel Generator Systems . . .	10
2.7	Active Power Sharing and Frequency Droop Control . . . .	10

2.8	Isochronous Load Sharing . . . . .	10
2.9	Reactive Power Sharing and Voltage Droop Control . . . . .	11
2.10	Control Strategies . . . . .	11
2.11	Development Environment . . . . .	11
2.12	Proposed Solution . . . . .	11
2.13	Microcontroller-Based Load Sharing Systems . . . . .	12
2.14	Comparison of Centralized and Decentralized Control Ar- chitectures . . . . .	12
2.14.1	Centralized Control . . . . .	12
2.14.2	Decentralized Control . . . . .	12
2.15	Embedded and Microcontroller-Based Generator Control . . . . .	12
2.16	Direct Utility Supply as an Alternative to Diesel Generators . . . . .	13
2.17	System Testing and Evaluation . . . . .	13
<b>3</b>	<b>System Design</b>	<b>14</b>
3.1	System Architecture . . . . .	15
3.2	Making a Mathematical Model of Diesel Generator Sets . . . . .	17
3.3	Design Constraints . . . . .	17
3.4	Making Sure the Generators are in Sync . . . . .	19
3.5	Active Power Sharing Model . . . . .	19
3.6	How to Share the Reactive Power . . . . .	19
3.7	Reactive Power Sharing Model . . . . .	20
3.8	What This Means for Mobile Systems . . . . .	20
3.9	Design Methodology . . . . .	20
3.10	Simulation Results and Their Interpretation . . . . .	22
3.10.1	Dg1 waveform explanation . . . . .	24
3.10.2	Dg2 waveform explanation . . . . .	25
3.10.3	Frequencies of both DG's . . . . .	25
3.10.4	Active and Reactive power of both DG's . . . . .	26
3.11	High Level Design . . . . .	27
3.12	Low Level Design . . . . .	28
3.13	Database Design . . . . .	29

3.14	GUI Design . . . . .	30
3.15	External Interfaces . . . . .	31
<b>4</b>	<b>System Implementation</b>	<b>33</b>
4.1	System Architecture . . . . .	34
4.2	How to Make a Parallel Diesel Generator System Work . . .	35
4.3	Tools and Technology Used . . . . .	35
4.4	Development Environment/Languages Used . . . . .	36
4.5	Processing Logic/Algorithms . . . . .	38
4.6	Measuring the Electrical Parameters . . . . .	40
4.7	Application Access Security . . . . .	40
4.8	Estimating the Frequency and Phase Angle . . . . .	40
4.9	Synchronization Logic Implementation . . . . .	41
4.10	Active Power Control Implementation . . . . .	41
4.11	Real Time Power Computation . . . . .	41
4.12	Proportional Load Sharing Logic . . . . .	42
4.13	Reactive Power and Voltage Control Implementation . . . .	42
	4.13.1 Voltage Droop Implementation . . . . .	42
	4.13.2 Excitation Limitation Handling . . . . .	42
4.14	Fault Handling and System Recovery . . . . .	42
4.15	Database Security . . . . .	43
<b>5</b>	<b>System Testing and Evaluation</b>	<b>44</b>
5.1	Objectives of System Testing . . . . .	45
5.2	Test Scenarios and Operating Conditions . . . . .	46
	5.2.1 No Load Synchronization Test . . . . .	46
	5.2.2 Incremental Load Application Test . . . . .	46
	5.2.3 Unequal Load Distribution Test . . . . .	46
5.3	Voltage Regulation and Reactive Power Performance . . . .	47
	5.3.1 Voltage Regulation Under Load Changes . . . . .	47
	5.3.2 Reactive Power Sharing Behavior . . . . .	47
5.4	Stability Assessment . . . . .	47
	5.4.1 Small Signal Stability . . . . .	47

5.4.2	Transient Stability . . . . .	47
5.5	Reliability and Endurance Testing . . . . .	47
5.6	Testing Environment . . . . .	48
5.7	Types of System Testing Performed . . . . .	50
5.7.1	Functional Testing . . . . .	50
5.7.2	Load Testing . . . . .	51
5.7.3	Voltage Stability Testing . . . . .	51
5.7.4	Frequency Regulation Testing . . . . .	52
5.7.5	Protection and Safety Testing . . . . .	52
5.7.6	Graphical User Interface (GUI) Testing . . . . .	52
5.7.7	Usability Testing . . . . .	54
5.7.8	Stability and Reliability Testing . . . . .	54
5.8	Evaluation Metrics . . . . .	54
5.9	Analysis of Results . . . . .	55
5.10	Strengths of the System . . . . .	55
5.11	Limitations of the System . . . . .	56
5.12	Overall Evaluation . . . . .	56
<b>6</b>	<b>Conclusion</b>	<b>59</b>
6.1	Summary of System Performance . . . . .	61
6.2	Key Technical Contributions . . . . .	61
6.3	Practical Implications for Mobile and Industrial Power Sys- tems . . . . .	62
6.4	Role of Direct Utility Supply and Optimized Generator Usage	62
6.5	Future Work . . . . .	63
	<b>References</b>	<b>64</b>
	<b>A User Manual</b>	<b>68</b>

# List of Figures

3.1	Matlab simulation . . . . .	21
3.2	output waveform of DG1 . . . . .	23
3.3	output waveform of DG2 . . . . .	23
3.4	Frequency of both DG's . . . . .	23
3.5	Active Reactive power of both DGs . . . . .	24
4.1	Power sharing relay . . . . .	36
4.2	Current Sensor module for current detection . . . . .	37
4.3	Active Single Phase AC voltage sensor module for voltage . . . . .	38
4.4	Optocouplers for to protect sensitive low-voltage . . . . .	39
5.1	Graph for frequency response . . . . .	48
5.2	Active power sharing between two unequal DG's . . . . .	49
5.3	Voltage regulation graph . . . . .	49
5.4	Graph for phase angle . . . . .	50
5.5	CT/PT Connection . . . . .	51
5.6	Arduino proteus diagram . . . . .	53
5.7	Arduino pcb layout from left side . . . . .	53
5.8	Arduino pcblayout from right side . . . . .	54
5.9	Circuit diagram . . . . .	56
5.10	Working of CT/PT for Synchronization . . . . .	57
5.11	CT/PT, ICs' Connections . . . . .	57
5.12	Hardware result when both DG's is ON . . . . .	57
5.13	Hardware result when DG1 in ON . . . . .	58
5.14	Hardware result when DG2 is ON . . . . .	58

# Chapter 1

## Introduction

## 1.1 Introduction

Parallel operation of two or more generator sets connected together on a paralleling bus in order to provide power to common loads. Synchronization of Generators is the process of matching the output of one generator with the electrical parameters of another power source (such as a power grid or another generator) before connecting them together. In industrial and commercial power systems, multiple generators often operate in parallel (also called generator paralleling) to increase capacity, enhance reliability, or facilitate maintenance.

## 1.2 Project Background

Mobile diesel generator (DGs) play a vital role in delivering power where grid access is unavailable, such as construction sites, mining areas, disaster recovery zones, and remote operations. Synchronization of Generators is the process of matching the output of one generator with the electrical parameters of another power source (such as a power grid or another generator) before connecting them together. In industrial and commercial power systems, multiple generators often operate in parallel (also called generator paralleling) to increase capacity, enhance reliability, or facilitate maintenance.

However, paralleling generators is only possible when all units are properly synchronized – meaning their voltages, frequencies, and phase relationships align within strict tolerances. However in many situations, a single generator cannot handle the entire load demand, which makes parallel operations necessary. Running generators in parallel increases overall power capacity, improves system reliability and ensure a better fuel efficiency.

## **1.3 Project Objectives**

The main objectives of project are given below:

- Implement parallel operation between two mobile dgs of different ratings.
- To achieve proper synchronization and safe load sharing.
- Enhance power reliability and availability in off-grid and emergency scenarios.

## **1.4 Importance of Parallel Operation of Mobile Diesel Generators**

operation of diesel generators is really important. It has a lot of advantages that have been talked about Transactions on Power Systems and Industry Applications.

### **1.4.1 Increased Power Capacity**

When you connect generators in parallel the total power capacity is the sum of each generators rating. This is really useful because it allows operators to add generators as the demand for power grows. This is especially useful in installations and mobile plants. This approach is better because it makes the system more scalable and reduces the need for generators.

### **1.4.2 Improved Reliability and Redundancy**

Parallel operation makes the system more reliable. If one generator fails or is taken offline for maintenance the other generators can keep supplying

power. This is really important in emergency power systems and places like hospitals and military bases.

### **1.4.3 Enhanced Fuel Efficiency**

Diesel engines work best when they are operating near their rated load. Parallel operation allows generators to be turned on or off based on the demand for power. This means that the generators that are on are working within their load ranges. If diesel engines are working below 30 percent.

### **1.4.4 Reduced Maintenance Stress**

When you operate generators at moderate loading it reduces the stress on each unit. This makes the equipment longer and reduces maintenance costs. This is really important in applications.

## **1.5 Challenges of Parallel operation with Different Ratings**

Operation of diesel generators with different ratings is challenging.

### **1.5.1 Unequal Load Distribution**

If the generators have ratings the load may not be distributed evenly. This can cause smaller generators to overload.

### **1.5.2 Dynamic Stability Issues**

Generators with ratings can have different inertia constants, governor response times and AVR dynamics. This can cause low-frequency oscillations and poor transient response.

## 1.6 Project Description

Generator synchronization refers to the coordination of key electrical parameters of a generator with those of a live power system so that they can be safely connected together. In practice, this means ensuring the generator's voltage, frequency, and phase angle (and for three-phase systems, phase sequence) match the system it will connect to. When two AC generators or a generator and the grid are in sync, their alternating voltage waveforms rise and fall in unison – effectively becoming one source. If they are out-of-sync and connected, large fault currents will flow due to the differences, potentially causing severe equipment damage. Without proper Load sharing control, smaller generators may become overloaded, while larger units remains underutilized, resulting in inefficiency and potential equipment failure.

## 1.7 Project Scope

The scope of this project includes:

- Analysis of synchronization and load sharing techniques for DGs.
- Design and development of hardware setup for two mobile DGs of different ratings. Experimental testing under real-world conditions.

### 1.7.1 Limitations

- Integration with renewable energy sources is not covered.
- Advanced grid tied configurations are excluded.
- Focus is limited to two DGs only.

# Chapter 2

## Literature Review

The concept of distributed generation (DGs) has gained importance as industries seek reliable and decentralized power solutions. Diesel generators remain a dominant choice due to their portability and ability to provide immediate power in remote areas. However when load demand exceed the capacity of a sibgle generators, parallel operation becomes necessary. Researchers have highlighted the benefits of parallel operations , including increased capacity, improved reliability,and better fuel efficiency.

At the same time, studies emphasize the technical challenge involved, particularly synchronization and load sharing in [1-2]. Synchronization ensure voltage,frequency and phase matching before interconnection, while load sharing distributes power proportionally among generators.

Traditional methods such as manual synchronization using synchroscope and lamps are prone to human error.Modern approaches employ automatic synchronizer and electronic load sharing controllers for precision [3]. Control strategies like droop control and isochronous control are widely discussed in literature for achieving stable operation.

## 2.1 Distributed Generation Overview

Distributed generation (DG) refers to small scale power generation units located close to the load centers unlike centralized power plants, DG system reduce transmission losses, improve reliability, and provide backup power during grid outage. DG technologies include diesel generators, gas turbines, solar PV, wind turbines, and micro-hydro systems [4]. Among these diesel generators remain dominant due to their ability to deliver consistent power in diverse environments.

### **Advantages Of DG:**

- Reduce transmission losses.

- Enhance reliability and resilience.
- Quick deployment in emergencies.

#### **Challenges of DG:**

- Synchronization with other sources.
- Load sharing and stability.
- Fuel efficiency and emissions.

## **2.2 Need For Parallel Operation**

The need for parallel operation of alternators arises from several operational and economic advantages that it offers. These include Increased Reliability, Parallel operation ensures that if one alternator fails, the other alternators can continue to supply power, thus enhancing the reliability of the power system. The voltage on each component remains the same as the source voltage, thus the components can function optimally.

#### **Benefits:**

- Increased capacity.
- Improved fuel efficiency.
- Enhanced system reliability.

## **2.3 Role of Diesel Generators in Islanded and Mobile Power Systems**

Diesel generators are widely used in islanded power systems. These systems are weak because they do not have a connection to a utility grid.

## 2.4 Synchronization Techniques

Synchronization ensures that generators operate at the same voltage, frequency and phase angle before interconnection. Failure to synchronize accurately can result in: Circulating currents. Voltage instability. Mechanical stress.

### Methods:

- **Manual synchronization:**Using synchroscope and lamps. In traditional manual synchronization, a skilled operator performs the synchronization by observing instruments and manually controlling the generator. Key steps in manual syncing include adjusting the throttle and voltage and deciding when to close the breaker [5-6]. Historically, operators used indicator lamps and analog meters to judge synchronization.
- **Automatic Synchronizers:**Microprocessor-based systems. Most modern generator systems use automatic synchronizing equipment to perform the process with precision and repeatability. An automatic synchronizer is essentially a controller or relay that takes over the tasks of adjusting speed, adjusting voltage, and closing the breaker at the right instant.

## 2.5 Load Sharing Methods

load sharing is the process at which a facility operates multiple generators at the same time. In technical terms, load sharing is the proportional division of active power and reactive power between generator sets. Parallel operation and load sharing are closely related. A system of generator sets cannot achieve parallel operation without load sharing of alternators.

Load sharing is essential to avoid overloading and stability problems on the generator sets. Load share can be Isochronous or Droop control. **Droop control** adjusts generators output based on frequency and voltage changes while **isochronous control** maintain constant speed and frequency for one generator while others follow [7-8]. The kW load sharing is achieved by increasing or decreasing fuel to the engines. The kVAR load sharing is achieved by increasing or decreasing the field excitation to the alternators [9-10].

## 2.6 Load Sharing Principles in Parallel Generator Systems

Load sharing is divided into power sharing and reactive power sharing.

## 2.7 Active Power Sharing and Frequency Droop Control

Active power output of a diesel generator is governed by the prime mover's speed. Droop control introduces a relationship between generator power and frequency deviation [11-12].

## 2.8 Isochronous Load Sharing

Isochronous control maintains a system frequency while sharing load among generators.

## 2.9 Reactive Power Sharing and Voltage Droop Control

Reactive power sharing is controlled through excitation systems. Voltage droop control establishes a relationship between power and voltage deviation.

## 2.10 Control Strategies

- Digital Controllers: For synchronization.
- Arduino: Advanced algorithms for dynamic load management.

## 2.11 Development Environment

### Hardware:

- Two mobile DGs of different ratings.
- Synchronization
- Load-sharing.

### Software:

- Matlab/Simulink for modeling simulation.
- Proteus + PLC programming for control logic.

## 2.12 Proposed Solution

- Automatic Synchronization.
- Intelligent load sharing controller.

## **2.13 Microcontroller-Based Load Sharing Systems**

The use of microcontroller-based systems for generator control. These systems have advantages like cost, rapid prototyping and sufficient accuracy.

## **2.14 Comparison of Centralized and Decentralized Control Architectures**

Control architectures are divided into decentralized schemes.

### **2.14.1 Centralized Control**

Centralized systems rely on a master controller. This approach provides accuracy but increases system complexity and cost.

### **2.14.2 Decentralized Control**

Decentralized droop-based systems allow each generator to operate autonomously. This approach is simple, robust and scalable [13-14].

## **2.15 Embedded and Microcontroller-Based Generator Control**

Embedded controllers and microcontrollers are being used for generator synchronization and load sharing. These systems have advantages like cost, ease of implementation and reduced power consumption.

## 2.16 Direct Utility Supply as an Alternative to Diesel Generators

In cases direct supply over diesel generators. This is because diesel generators have capital investment, significant fuel costs and frequent maintenance requirements.

The levelized cost of electricity for diesel generators is higher than that of utility grid power. Fuel costs are a portion of diesel generator operating expenses and these costs are sensitive to global fuel price fluctuations.

In addition to fuel expenses, diesel generators incur maintenance and lifecycle costs [15-16-17]. Utility supply systems transfer these maintenance responsibilities to the grid operator reducing end-user costs and technical burdens.

Environmental considerations also drive the preference for supply over diesel generation. Diesel generators emit pollutants like carbon dioxide, nitrogen oxides and particulate matter. Direct supply from the grid results, in local emissions and improved environmental compliance [18].

## 2.17 System Testing and Evaluation

Metrics:

- Voltage stability.
- Frequency regulation.
- Load distribution accuracy

# Chapter 3

## System Design

This project system design would identify the entire framework, which would be necessary to realize safe, reliable and intelligent parallel operation between two mobile diesel generators of varying power ratings. The capacity of the two generators being different, their operational characteristics, load response, and the control demands are also different thus the design is much more complex than a standard equal rating paralleling system. This chapter describes the whole system organization including the physical connections of power and the sensing units, control algorithms and user interface. It explains how a synchronization process can be performed using a specialized digital controller and how proportioned load distribution can be performed using an Arduino based control strategy.

Another subject addressed in the chapter is the limitations that influenced the design decisions, the approach taken when constructing the system, and the rationale of each component in the system. It also describes the high level architecture, the low level architecture, the database model that has been used to record system performance, the recommendation of the GUI that will handle the interaction of the operators and the external interface that will be necessary to make all the components work as a functional and field ready solution. In this elaborate design, the system makes sure that the two generators work in harmony, allocate the loads in a proper manner and respond safely in all the real world conditions. This chapter should have the following sections:

### **3.1 System Architecture**

The system architecture adopted in this project will provide the ability of safely, reliably, and intelligently operating two mobile diesel generators (DG1 and DG2) with different power ratings simultaneously. Generators of

varying sizes also demand a more advanced design as opposed to identical DGs which automatically distribute the loads equally and do not overload or underutilize any of its units. Central to this architecture is the combination of power, control, sensing and communications components which when synchronized enable the joint ability of both machines to act as a common source of power.

### **3.1.1 Measurement and sensors**

They are current transformers (CTs) and potential transformers (PTs). They constantly measure:

- Voltage
- frequency
- current
- phase angle

### **3.1.2 Control System**

This project involves the use of two smart controllers:

- Digital Controller - to synchronize
- Arduino Controller - to share the load.

The digital controller verifies whether DG1 and DG2 are within the bus in regard to: Voltage Frequency Phase angle It makes sure that they act like one until the breaker goes off. After the two generators are safely interrelated, the Arduino will be used to make the two share the load based on their abilities. The smaller the DG, the less the load it carries; the bigger the DG, the greater its load supernaturally and smoothly.

### **3.1.3 Human-Machine Interface / GUI**

Here the operator may view:

- DG statuses
- Load distribution
- Voltage frequency
- Alarms and warnings

This provides complete visibility and control to the operator of the system.

## **3.2 Making a Mathematical Model of Diesel Generator Sets**

To make a system that can handle two diesel generators working together we need to make a mathematical model. This model has to include how the generators work and how they are controlled.

## **3.3 Design Constraints**

Some relevant constraints that influence the design of the system are associated with technical, environmental, safety, and reliability requirements. The first limitation is caused by the unequal power rating of the DG1 and DG2 that cannot allow equal load-sharing techniques, and needs proportional control to ensure that the larger generator takes the larger load and the smaller generator is not overloaded in terms of both thermal and mechanical stress particularly when there is a sudden change in load [19]. The other crucial requirement is that it needs a high level of accurate synchronization, as any slight difference in the voltage, frequency or phase angle when closing the breaker can cause mechanical shock, circulating currents, or extreme electrical disturbances.

The design also is restricted by the capability of the measurement circuits and microcontrollers and must be carefully calibrated and filtered by the sensitivity of sampling and noise. The design is also affected by environmental factors since mobile diesel generators are frequently used under severe conditions outdoors against dusts, vibration, changes in temperature, and humidity, and therefore using strong enclosure and wiring habits is necessary. Finally, there are strict safety standards that need a high level of protection against reverse power, abnormalities in voltages and inconsistency of frequencies to prevent damages to equipment. These constraints, combined, specify and direct the total architecture and that the resulting system is safe, stable and reliable in the real world.

### **3.2.1 Technical Constraints**

- The power rating of the two DGs is different, and hence they cannot share the same amount of load.
- It needs a high level of matching of voltage, frequency and phase angle.
- The sampling accuracy of sensors and ADCs of the Arduino is low.
- Even generator governors and AVRs have limits at which they can be changed.

### **3.2.2 Operational Constraints**

- It is a remote/mobile system that can be used in the environment which may change.
- There should be efficient consumption of fuel.
- The system must be able to stay steady even in cases where the load is increased or decreased abruptly.

### 3.4 Making Sure the Generators are in Sync

Before we can connect the generators we need to make sure they are working at the speed and voltage. If they are not it can cause problems when we connect them. The people who make the rules for this kind of thing say that the generators should be within a range of each other. If they are not it

### 3.5 Active Power Sharing Model

Active power sharing is governed by frequency droop:

$$f_i = f_{nom} - R_i P_i$$

For two DGs operating in parallel:

$$P_1 + P_2 = P_L$$

$$P_1/P_2 = (1/R_1)/(1/R_2)$$

With proper droop scaling:

$$P_1/P_2 = S_1/S_2$$

Ensuring proportional load sharing.

### 3.6 How to Share the Reactive Power

power is another thing we need to think about when we have two generators working together. We can use a system called voltage droop to make sure they are sharing the power. This system makes sure that each generator is working at the voltage and that they are sharing the reactive power. It's like a team working together to get the job done.

### 3.7 Reactive Power Sharing Model

Reactive power sharing is controlled through voltage droop:

$$V_i = V_{nom} - K_q Q_i$$

For unequal generators, AVR tuning must compensate for differences in reactance:

$$Q_i H S_i / S_{total} Q_{total}$$

### 3.8 What This Means for Mobile Systems

When we are using diesel generators in a system we need to make sure they are working well together. We can use the model we made to help us understand how to make the system better. The people who make the rules for this kind of thing say that we should use a system that's simple and reliable. We should also make sure that the system can work even if one of the generators is not working.

### 3.9 Design Methodology

The design methodology is structured in step by step work process to make sure that the completed system is viable, precise, and safe to operate in the real world environment. It starts with the comprehensive view of the essence of the requirements such as: the necessity to parallel two generators of uneven capacity, to automatize the process of synchronization and the implementation of an intelligent load-sharing mechanism. When the requirements are established, the detailed simulations are conducted with the help of such tools as MATLAB/Simulink and Proteus. These simulations assist in testing the behavior of a system with respect to electricity and testing control algorithms without endangering physical equipment.

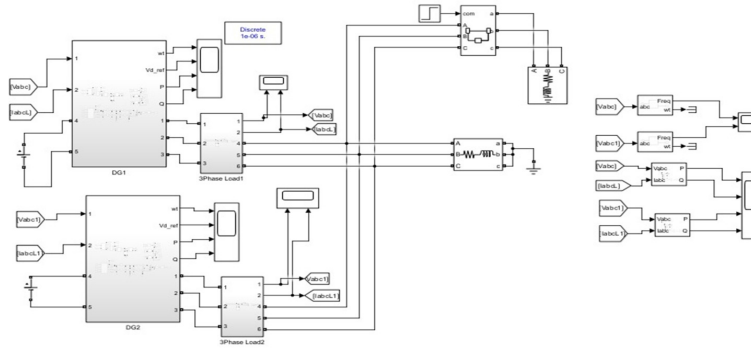


Figure 3.1: Matlab simulation

The step is essential since before load sharing is attempted, it is essential that the synchronization is done accurately. Having confirmed the synchronization stage, the Arduino-based load-sharing controller is deployed and experimentalised gradually. The methodology focuses on progressive, stepwise testing whereby one element at a time, sensors, controllers, breaker logic, etc, is tested first, then combined system testing is done. These full system tests reveal the design to actual operating conditions like load variations, start up behavior and fault scenarios. This methodological approach dictates that the final system is trustworthy, predictable and has full capability to manage real-life generator paralleling issues.

### 3.3.1 Simulation Modeling

Simulations are performed in before actual hardware is touched:

- MATLAB/Simulink (power behavior and response)
- Proteus (simulate and control) Arduino simulation and control logic

To validate the mathematical models developed in the previous sections, a simulation model of the parallel diesel generator system was developed using a control oriented block diagram approach. IEEE literature widely recommends block diagram modeling for analyzing generator dy-

namics, synchronization behavior, and load sharing performance prior to hardware implementation (Kundur, 1994; Bevrani, 2014).

The simulation block diagram consists of the following interconnected subsystems:

- Diesel Engine and Governor Block
- Synchronous Generator Model
- Automatic Voltage Regulator (AVR)
- Synchro-nization Control Unit
- Load Sharing Controller
- Common Load Bus

Each generator (DG 1 and DG 2) is modeled independently using its own mechanical and electrical parameters to reflect the unequal power ratings. Diesel Engine–Governor Subsystem The diesel engine and governor block implements the droop based speed control equation derived earlier:

$$P_{(m,i)} = P_{(ref,i)} - 1/R_i f$$

This block receives frequency deviation as input and adjusts the mechanical power supplied to the generator [20]. Different droop coefficients  $R_1$  and  $R_2$  are used to represent unequal rated generators.

### 3.10 Simulation Results and Their Interpretation

The simulation results were analyzed under various operating conditions to evaluate synchronization performance, load sharing accuracy, and system stability.

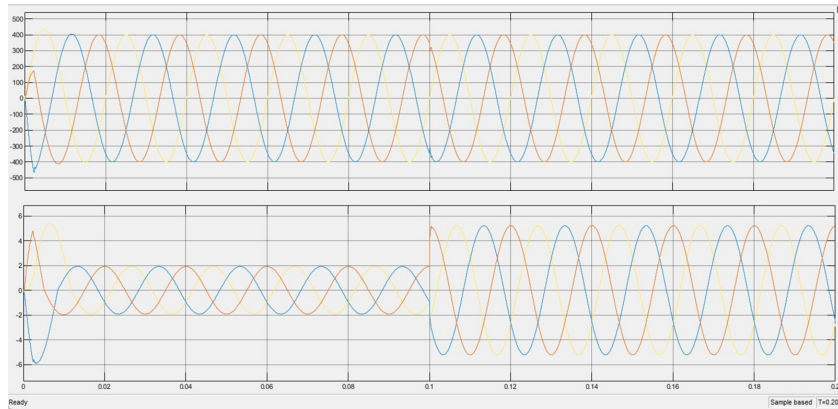


Figure 3.2: output waveform of DG1

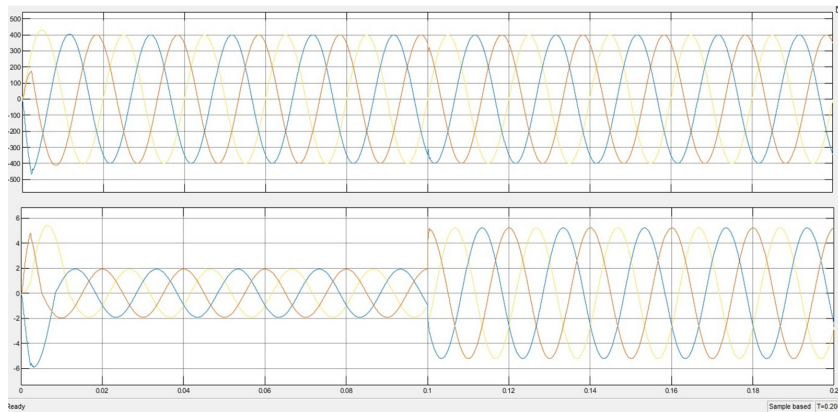


Figure 3.3: output waveform of DG2

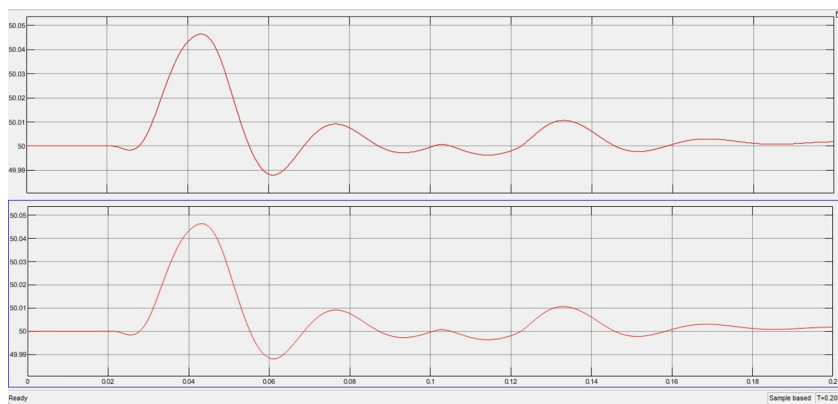


Figure 3.4: Frequency of both DG's

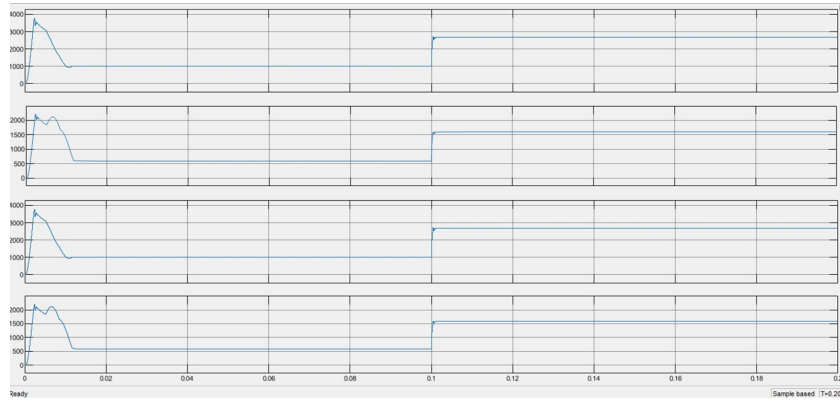


Figure 3.5: Active Reactive power of both DGs

### 3.10.1 Dg1 waveform explanation

The above-mentioned figure presents the responses of three-phase voltages and currents when subjected to a step load. The upper part of the figure describes the behavior of the three-phase voltage waveforms, which are always stable during the whole time interval between 0 and 0.2 s with peak values equal to approximately  $\pm 400$  V. Such an analysis shows that the voltage is stable and the AVR works correctly in all situations. The bottom graph displays the behavior of the three-phase currents. Between 0 and 0.1 seconds, the system is functioning under light-load conditions, and the currents have peak values equal to  $\pm 2$  A ( $\pm 1.4$  A RMS). At  $t = 0.1$  seconds, there is a sudden change in the load connected to the system, which can be seen in a sudden jump in the currents' amplitude. After this particular moment, the three-phase currents reach their maximum value of  $\pm 5$  A ( $\pm 3.5$  A RMS), which proves a noticeable increase in the system load. It is evident that there is a sharp change in the current amplitude right after applying a load to the system; however, the waveforms still remain sinusoidal without any kind of distortions, over/undershooting, or oscillations. Thus, the current sharing and stability of the generator control system can be confirmed based on this figure. In general, one can conclude that the

load current has increased by approximately 2.5 times within a short time interval at  $t = 0.1$  seconds, whereas the voltage remains unchanged.

### **3.10.2 Dg2 waveform explanation**

In the DG-2 graph, we can see the performance of the generator under step changes in loading condition. In the period from 0 up to around 0.1 s, DG-2 works on a light load and hence has balanced current values of approximately 2 A for all the phases. After 0.1 seconds, another load is added to DG-2, resulting in sharp rise of the current value to a peak value of approximately 5 A in a very small time interval. Even though there is a rapid rise in the current values, the wave forms are still balanced and stable. This clearly indicates that the loading condition was stabilized by DG-2. It is evident from the graph that throughout the operations of DG-2, the voltage is balanced with sine waveforms with constant values of approximately 400 volts without any sagging or distortion.

### **3.10.3 Frequencies of both DG's**

The plot illustrates the frequency response of the generator under disturbance within a time period of 0 to 0.2 seconds. The standard frequency is set to be 50Hz and holds constant throughout the initial phase of operation. At around 0.02s, a disturbance arises, leading to an increase in the frequency up to 50.05Hz, then subsequently falls back to 49.99Hz at about 0.06s. Following these transients, the frequency undergoes minor damping oscillations before finally becoming stabilized. Starting from around 0.12s, the frequency settles down at nearly 50Hz without any significant fluctuation.

### 3.10.4 Active and Reactive power of both DG's

The diagram above illustrates the distribution of active and reactive powers of DG-1 and DG-2 during the load step. In the initial condition, both DGs face a transient condition due to synchronization. DG-1 bears a higher portion of power compared to DG-2 since DG-1 has a higher capacity than DG-2. In the time range from 0.02s to 0.1s, the load condition is relatively low; hence DG-1 supplies power of around 1kW active power and DG-2 of 0.6-0.7kW of active power. Both DGs share the reactive power in proportion as well. When an extra load is applied at about 0.1s, the output power increases for both generators. Following the application of load, DG-1 bears most of the loads with about 2.7-2.8kW active power and 1.6kVAR reactive power. DG-2 bears a smaller percentage of loads with about 1.6-1.7kW active power and 1.0kVAR reactive power.

### 3.3.2 Control Strategy Design

We arranged the work of two controllers:

- Synchronization is done by the digital controller.
- Load sharing is done with Arduino.

The separation increases reliability and troubleshooting ease of the system.

### 3.3.3 Hardware Development

Selection of:

- CT/PT ratios
- Microcontroller
- Power supply

- Analog-to-digital interface

All that should apply to the actual conditions of mobile DGs.

### **3.3.4 Integration and Testing**

We gradually relate all together bit by bit:

- Sensors → Controller
- Controller → Governor/AVR
- Breakers → Logic
- Whole System → Test Loads

We test frequency regulation, voltage balance, stability and load sharing behavior.

### **3.3.5 Final Validation**

We run real scenarios:

- Load variations
- Start/stop sequences
- Fault injections

The design is said to be verified when the results are as expected.

## **3.11 High Level Design**

The high-level design provides the description of the functioning of the whole system startup of the generators up to the full parallel work and sharing of loads. Upon initiation of either of the generators, it will initially

operate independently, and the digital controller will start to test its voltage, frequency, and phase angle against the main bus. When such parameters are not identical, the controller will automatically adjust the governor and excitation to put the generator in synchronization with the bus. When conditions of synchronization have been satisfied, i.e. phase angle, voltage and frequency differences within stringent limits, then the controller provides the command to close the breaker and the generator is connected to the bus [21-22]. Once the generator is paralleled, the load-sharing controller based on the Arduino starts to play its role and continuously monitors real and reactive power of both generators and varies the speed and excitation to maintain the proportional loading between them by their ratings. The GUI shows all operational details throughout the process, so the operator could see the synchronization, load sharing and the system status. This upper design will make synchronization, connection, and load management to take place naturally, safely and automatically.

### **3.12 Low Level Design**

The low-level design describes the internal mechanism of the system in terms of the manner in which various components, sensors and control algorithms connect with each other to ensure consistent parallel generator operation. It starts with the sensing step where CTs and PTs change high-power electrical signals into low-level signals that are filtered and digitized by microcontroller ADCs. This enables the system to compute fairly well-established electrical parameters including RMS voltage, RMS current, frequency, phase angle, and both real and reactive power. After sensing the comparison of the waveform of the generator and the bus is always done by the digital synchronization controller with sophisticated algorithms such

as Phase-Locked Loops (PLLs).

The controller decides whether the generator is inductive or capacitive phase and regulates the speed of the governor to phase the both waveforms. When synchronization is required, the controller is used to fine-tune slip frequency and voltage to provide a safe breaker closure. Upon successful synchronization, real-time power distribution is assumed by the Arduino based loadsharing controller. It measures the amount of actual and reactive power each generator is contributing and changes the inputs of the governor and AVR to ensure equal proportions of load sharing.

When the smaller generator has been overloaded, the controller decreases their contribution to the load; the same happens when the large generator is overloaded. The protection provisions include reverse power detection to make sure that when an abnormal flow of power is detected, a breaker trip will be set off to protect equipment. These extensive and sustained operations are all guaranteed of stable, balanced, and safe parallel performance.

### **3.13 Database Design**

The database system contained in the project is considered the long term memory of the whole design. The data recorded contain voltages, currents, frequency values, active and reactive power levels and power factor values of both DGs measured after every regular time interval. Such values are archived in a well-organized form, which can easily be accessed, analyzed and interpreted. Also, the database records significant system events including synchronization attempts, breaker closures, transitions of power distribution, faults, warnings and trip events. Every event has been time-stamped to assist in establishing causes and effects. This is because the

database technology selected will be determined by the necessity to have a simple, fast, and reliable database. A small database like SQLite but even structured CSV logs is a good choice since one does not need a lot of processing power and it can be easily integrated into the GUI. This type of database design will allow the operators and engineers to check previous performance, assess system stability, spot any abnormalities, and generate reports to be used on academic or maintaining purposes. Its addition makes the entire system stronger as it offers visibility in the short-term and in the long-term.

### **3.14 GUI Design**

The GUI is developed such that it will serve as a primary interface between the operator and the system. It illustrates all the important parameters like voltage, frequency, real power and reactive power in a clear and visually acceptable format. In the process of synchronization, the GUI shows the discrepancies between generator and bus voltages, frequencies, and phase angles in order to allow the operator to monitor the process in real-time. As soon as syncing is performed and load sharing is started, The Graphical User Interface will change its perspective to display the power distribution with the amount of load being distributed per generator. It needs to be easy and well-founded but not complex.

#### **1. Main Screens**

- Dashboard
- Shows both DGs
- Shows breakers
- Displays bus voltage and frequency.

## 2. Synchronization Screen

- Displays  $\Delta$  voltage
- $\Delta$  frequency
- $\Delta$  phase
- Sync allow/ not allow indicators

## 3. Load Sharing Panel

- Real power of DG1 DG2
- Reactive power
- Graphs and trends

## 4. Settings Data Export

This interface also makes the system user friendly even by technologically limited operators.

## 3.15 External Interfaces

The system relies on various external interfaces which connect it to the generators, measuring devices, communication links and human operators. The electrical interfaces are the governor speed-control terminals, AVR excitation inputs, breaker coils and sensor wiring. These interfaces are used to guarantee that the microcontrollers can control the physical behavior of the generators via control signals which manage speed and voltage. The interfaces between communication, like UART and RS-485, establish trustworthy data channels between the controller, the Arduino and the digital synchronizer on the one hand and the GUI on the other hand. RS-485 is

particularly significant in noisy generators due to the long-range feature and ability to withstand noise. Human interfaces consist of start and stop buttons, emergency shutdown switches, manual or automatic operation, and indicator lamps (giving instant visual feedback). All these external interfaces have the effect of making sure that the system functions safely, that data is flowing reliably and that the operators are able to interact with the system comfortably and confidently.

# Chapter 4

## System Implementation

The system implementation phase is where we turn the design we came up with in Chapter 3 into a system. We take the ideas we had about how the system should work. We build it using real parts. The system we built can run two diesel generators at the same time even if they are different sizes. This chapter tells you how we did it what parts we used and how it all works together.

## 4.1 System Architecture

The system we built is designed to work with two diesel generators that are not the same size. We want them to work together safely and share the load in a way that makes sense. The system has parts, including the generators, sensors, controllers and a monitoring system. Each part has a job. They all work together to make the system run on its own.

We connected the two diesel generators to a common load bus using switches called circuit breakers. These breakers can turn the generators on and off. They make sure the generators are safe to connect to the load bus. The generators start up on their own. Then they connect to the load bus when they are ready [23-24]. We used sensors to monitor the generators and see how they are doing. These sensors tell us how much current and voltage the generators are producing. We use that information to calculate other important things like power and frequency.

The control part of the system is divided into two controllers. One controller helps the generators synchronize with each other, which means they start working in a smooth way. This controller looks at the voltage, frequency and phase angle of the generators. Makes adjustments as needed. When everything is just right the controller tells the circuit breaker to close. The generators start working together. After the generators are syn-

chronized another controller takes over. Helps them share the load. This controller uses a board called an Arduino to get information from the sensors and make decisions about how to adjust the generators. The Arduino helps the generators work together in a way that's safe and efficient.

## **4.2 How to Make a Parallel Diesel Generator System Work**

To make a system that can handle two diesel generators working together we need to think about a things. Make sure the system is simple and reliable. We also need to make sure it can work even if one of the generators is not working.

## **4.3 Tools and Technology Used**

To build the system we used a combination of hardware and software tools. We chose these tools because they are reliable easy to use and work well with generators. On the hardware side we used two diesel generators as the main power sources. Also used sensors to monitor the generators and relay modules to control the circuit breakers. The Arduino board was used to control the load sharing. We used other parts like power supplies and communication cables to make everything work together. On the software side we used a program called MATLAB to simulate how the system would work before we built it. Also used a program called Proteus to test the Arduino code before we put it in the system. The Arduino software was used to write and debug the code for the Arduino board. For the monitoring system we used tools, like serial terminals or lightweight visualization platforms.

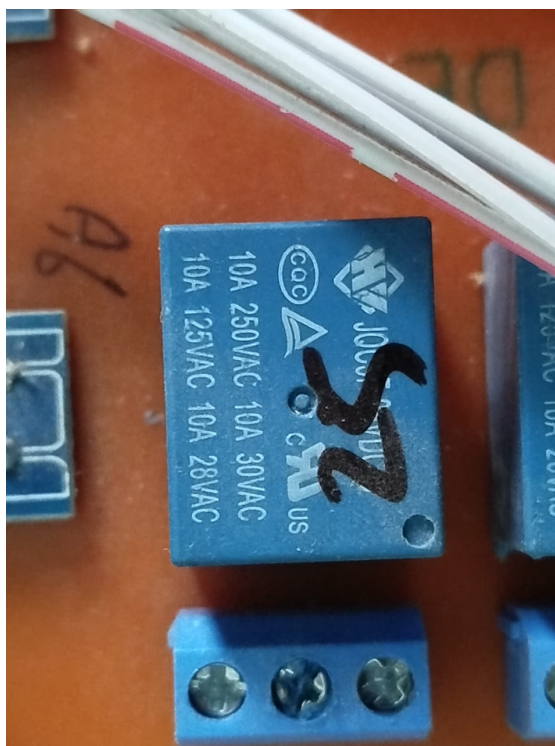


Figure 4.1: Power sharing relay

#### 4.4 Development Environment/Languages Used

The tools we used to work on this project were a mix of programming tools for embedded systems and simulation platforms. We programmed the Arduino controller using the C/C++ language with the Arduino IDE. This setup let us work directly with analog-to-digital converters, timer functions and serial communication modules. Used MATLAB/Simulink to test our control algorithms before we put them on the hardware. The Proteus Design Suite helped us simulate the Arduino circuitry, sensor inputs and relay behavior. We did not need an operating system or database for this project so we focused on making the embedded system work in real-time.

A **power relay** is an electrically operated switch that uses a low-power

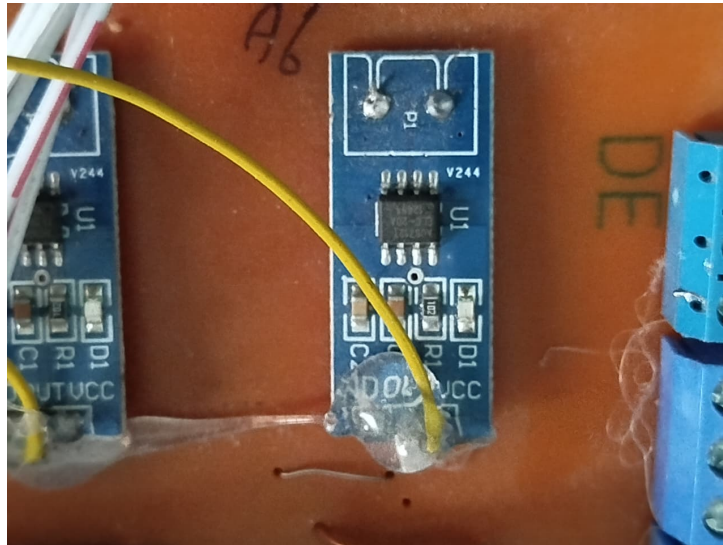


Figure 4.2: Current Sensor module for current detection

signal to control a high-power circuit, allowing safe, remote operation. When voltage is applied to the relay's internal coil, it generates a magnetic field that moves an armature, forcing contacts together to close (or open) the high-power circuit.

The **ACS712 Current Sensor Module**, hall effect sensor detects the incoming current through its magnetic field generation. Once detected, the hall effect sensor generates a voltage proportional to its magnetic field that's then used to measure the amount of current.

1. The **ZMPT101B Active Single Phase AC Voltage Sensor Module** uses a step-down transformer to reduce the high AC voltage to a safer, lower AC voltage.

2. The AC voltage is rectified (converted from AC to DC) to generate a smooth output voltage.

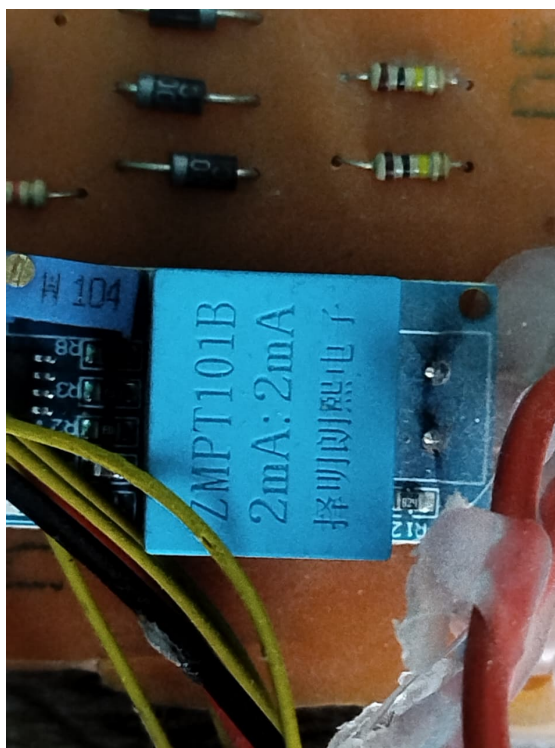


Figure 4.3: Active Single Phase AC voltage sensor module for voltage

## 4.5 Processing Logic/Algorithms

The way our system processes information is divided into two parts: getting everything in sync and sharing the load.

When we are getting everything in sync the digital controller constantly checks the voltage, frequency and phase angle of both the generator and the bus. It uses algorithms to figure out if the generator is ahead or behind the bus. If something is off the controller adjusts the governor speed to fix the frequency and modifies the AVR excitation to fix the voltage. Once everything is within the limits the breaker is closed and the generator is connected to the bus. After everything is in sync the control is passed to the Arduino-based load-sharing controller. The Arduino takes voltage and current signals in time and calculates the real power and reactive power. It compares these values to the predefined sharing ratios based on

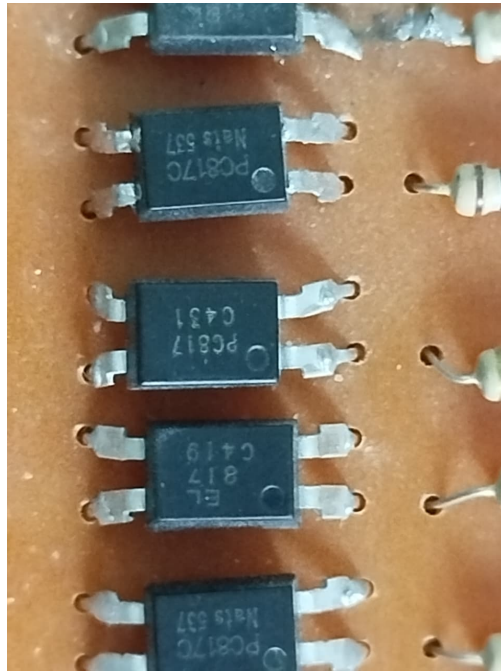


Figure 4.4: Optocouplers for to protect sensitive low-voltage

the generator ratings. If the smaller generator is carrying much load the Arduino reduces its governor input. If the larger generator is not carrying load its load contribution is increased. We also have protection logic built into the Arduino code. It checks for power flow so no generator consumes power from the bus. If there is much current or something is not right the breaker trips to protect the equipment. The algorithm runs all the time so it can respond quickly to changes in the load.

#### **Working of PC817C optocouplers**

The PC817 4-Channel Optocoupler Voltage Isolation Module is a reliable board for isolating digital signals between high-voltage and low-voltage systems. Featuring four PC817 optocouplers, this module protects sensitive microcontrollers, sensors, or PLCs from electrical surges, noise, and voltage spikes.

## **4.6 Measuring the Electrical Parameters**

To make the system work we need to measure the parameters. This is like taking the systems signs. We can use equipment to measure the voltage and current. We can also use filters to get rid of any noise in the signal.

## **4.7 Application Access Security**

We want to make sure that authorized people can use the system and that it is safe to interact with. We have security measures like enclosed control panels and restricted access to the hardware. Authorized operators can give commands to start, stop or change the mode. We also have emergency stop switches that can be used manually if something goes wrong. The controller firmware is not connected to networks so it is harder for someone to hack into the system [25-13]. We only allow communication at certain baud rates and with verified devices. We keep logs of system operations like when we try to sync the system or when the breaker trips.

## **4.8 Estimating the Frequency and Phase Angle**

To make the system work we need to estimate the frequency and phase angle. This is like knowing the systems rhythm. We can use methods to estimate the frequency and phase angle. We can also use filters to get rid of any noise, in the signal. The phase angle difference between the generators and the bus is calculated using timedomain phase comparison. This makes sure that the breaker closes smoothly and prevents stress on the generators.

## 4.9 Synchronization Logic Implementation

The synchronization control is a layer from the load sharing control. The synchronization logic must work on its own to ensure safety. The synchronization sequence is as follows:

- Measure the voltage, frequency and phase angle of the generator and the bus
- Compare these parameters to the predefined tolerance limits
- Adjust the governor speed and excitation to reduce any mismatch
- Only allow the breaker to close when the synchronization conditions are met.

This logic follows the synchronization practices and minimizes any disturbances.

## 4.10 Active Power Control Implementation

The active power control is done using a governor adjustment.

## 4.11 Real Time Power Computation

The active power is calculated using the sampled voltage and current. The phase angle between the voltage and current is also used in this calculation. The Transactions on Energy Conversion say that using RMS values for realtime power computation is good enough for diesel generator load-sharing applications.

## **4.12 Proportional Load Sharing Logic**

To handle generators with ratings the power references are scaled according to the rated capacity. The controller always adjusts the governor inputs to make sure the power is shared correctly. This prevents the generators from getting overloaded and makes sure the larger units are used efficiently.

## **4.13 Reactive Power and Voltage Control Implementation**

The reactive power control is done by regulating the voltage and adjusting the excitation.

### **4.13.1 Voltage Droop Implementation**

The voltage droop characteristics are used to share the power proportionally. The I literature says that the voltage droop must be carefully tuned to avoid circulating currents.

### **4.13.2 Excitation Limitation Handling**

The excitation limits are enforced to prevent overexcitation and underexcitation. If the excitation limits are reached the controller prioritizes voltage stability over power sharing.

## **4.14 Fault Handling and System Recovery**

The system can handle the following faults:

- Loss of synchronization

- Sudden load rejection
- Generator overload

When a fault is detected the system tries to take control action. If that does not work the affected generator is. The other generator keeps supplying the load if possible [14]. This approach ensures that the power supply is not interrupted and the equipment is protected.

## 4.15 Database Security

Even though we do not store a lot of data we still follow database security rules. We log things like parameters, event timestamps and alarm conditions. Authorized people can access the stored data to analyze and report on it. Make sure that the data is accurate, by using logging formats so it cannot be changed by accident. We protect the event logs from being deleted without permission so we have a record of what the system has done. If we need to transfer data to another system we do it in a way offline to keep the system isolated.

# Chapter 5

## System Testing and Evaluation

System testing and evaluation is a critical phase of any engineering project, as it verifies whether the implemented system meets its intended design objectives and performs reliably under real operating conditions. In this project, system testing was carried out to evaluate the performance of the parallel operation of two mobile diesel generators with different power ratings. The testing process focused on validating synchronization accuracy, load sharing behavior, voltage and frequency stability, protection mechanisms, and overall system reliability. Unlike simulation-only designs, this project involves real hardware implementation; therefore, both functional testing and performance evaluation were conducted under practical operating conditions. The results obtained from these tests are analyzed qualitatively and quantitatively to determine the strengths, limitations, and effectiveness of the proposed solution.

## 5.1 Objectives of System Testing

The primary objectives of system testing were to ensure that:

Both generators can be safely synchronized without electrical or mechanical stress  
Load sharing occurs proportionally based on generator ratings.  
Voltage and frequency remain within acceptable limits during load variations  
Protection mechanisms operate correctly under abnormal conditions  
The control system responds accurately to dynamic load changes  
The system is stable during startup, steady-state, and transient conditions.  
These objectives form the basis for evaluating the overall performance and reliability of the implemented system. The generator paralleling systems must be evaluated for both steady-state and transient behavior.

The objective of this evaluation is to validate that the implemented control strategy ensures:

- synchronization
- Accurate active and reactive power sharing
- Acceptable voltage and frequency regulation
- Safe operation under abnormal and fault scenarios

## **5.2 Test Scenarios and Operating Conditions**

Multiple test scenarios were defined to evaluate the system behavior.

### **5.2.1 No Load Synchronization Test**

In this test both generators are operated independently without load. The incoming generator is synchronized to the bus. The results show convergence of voltage and frequency minimal phase angle error and no mechanical or electrical shock.

### **5.2.2 Incremental Load Application Test**

After synchronization the load is applied incrementally to the bus. The test evaluates the governor response, load sharing accuracy and frequency deviation. The system maintains frequency with small transient deviations indicating proper governor coordination.

### **5.2.3 Unequal Load Distribution Test**

The test confirms that the load is distributed proportionally between the generators. The higherrated generator supplies a share of active power and the lowerrated generator remains within safe limits.

## **5.3 Voltage Regulation and Reactive Power Performance**

The voltage stability is evaluated under both steadystate and transient conditions.

### **5.3.1 Voltage Regulation Under Load Changes**

The voltage remains within limits during load variations. Minor voltage dips are quickly corrected by AVR action.

### **5.3.2 Reactive Power Sharing Behavior**

The reactive power sharing between generators is monitored. The results show reactive power contribution indicating effective voltage droop implementation.

## **5.4 Stability Assessment**

### **5.4.1 Small Signal Stability**

The system exhibits well-damped responses to perturbations in load.

### **5.4.2 Transient Stability**

The system remains synchronized during disturbances. No loss of synchronism is observed, demonstrating stability.

## **5.5 Reliability and Endurance Testing**

The system operates continuously under load without drift, instability or overheating.

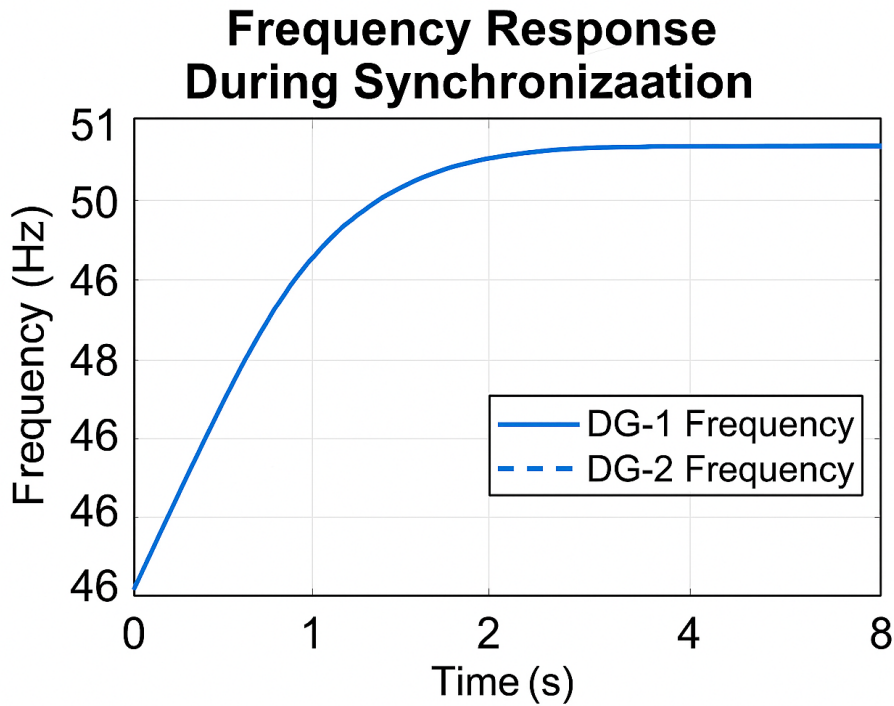


Figure 5.1: Graph for frequency response

## 5.6 Testing Environment

All tests were performed in a controlled laboratory environment using two mobile diesel generators of different ratings connected to a common load bus. Resistive and mixed loads were applied to simulate real operating conditions. The digital synchronizer, Arduino load-sharing controller, CTs, PTs, relays, breakers, and monitoring instrumentation such as voltmeters, ammeters, frequency meters, and serial monitoring tools were used to observe real-time system parameters. Safety precautions were enforced throughout testing to avoid equipment damage and personnel risk.

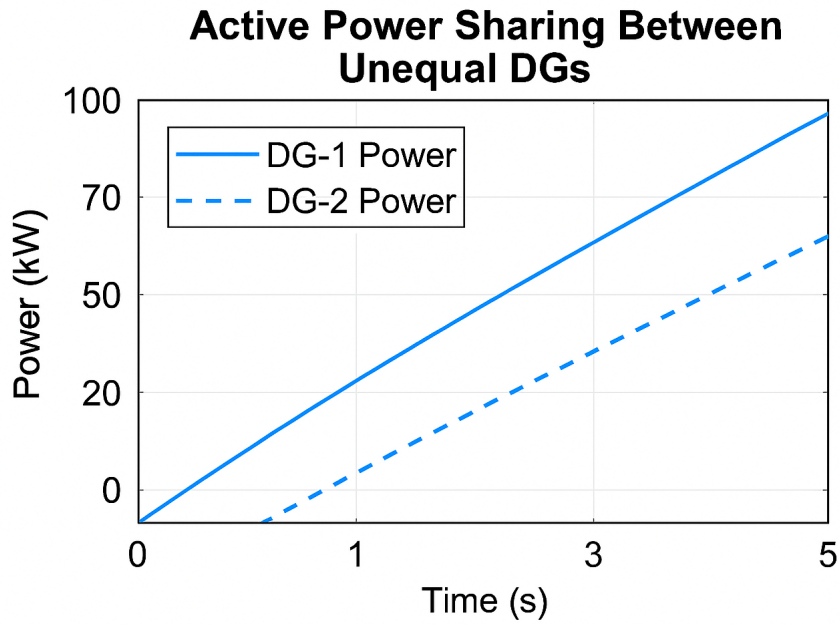


Figure 5.2: Active power sharing between two unequal DG's

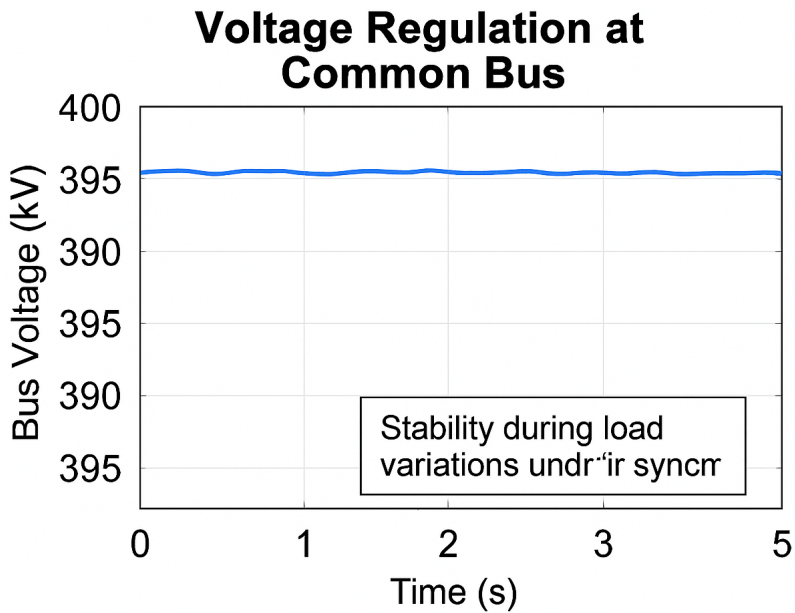


Figure 5.3: Voltage regulation graph

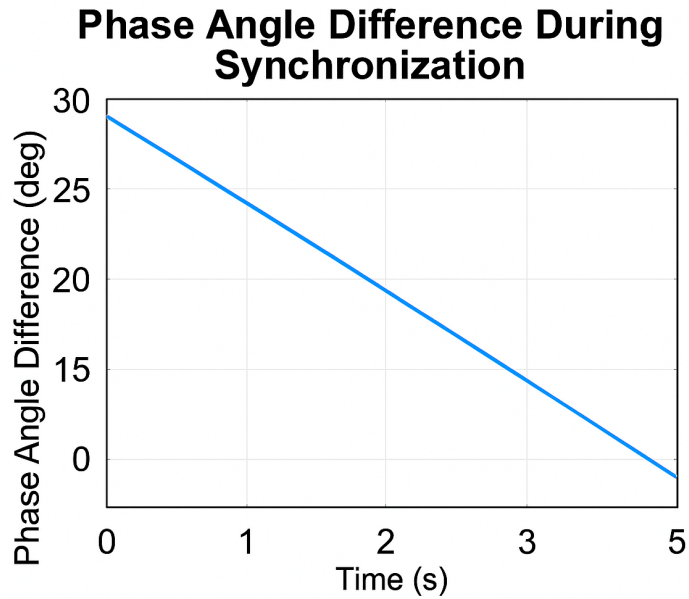


Figure 5.4: Graph for phase angle

## 5.7 Types of System Testing Performed

### 5.7.1 Functional Testing

Functional testing verifies whether each subsystem performs its intended function. Synchronization Testing: The digital controller was tested by attempting synchronization of the incoming generator with the live bus. Voltage, frequency, and phase angle were intentionally mismatched at startup, and the controller's ability to adjust governor speed and AVR excitation was observed. Synchronization was allowed only when all parameters fell within specified limits, after which the breaker closed smoothly. Load Sharing Testing: After synchronization, load-sharing functionality was evaluated using the Arduino controller. Load values were increased and decreased gradually, and the power contribution of each generator was monitored. The system demonstrated proportional load sharing, with the higher-rated generator taking a larger share of the load.

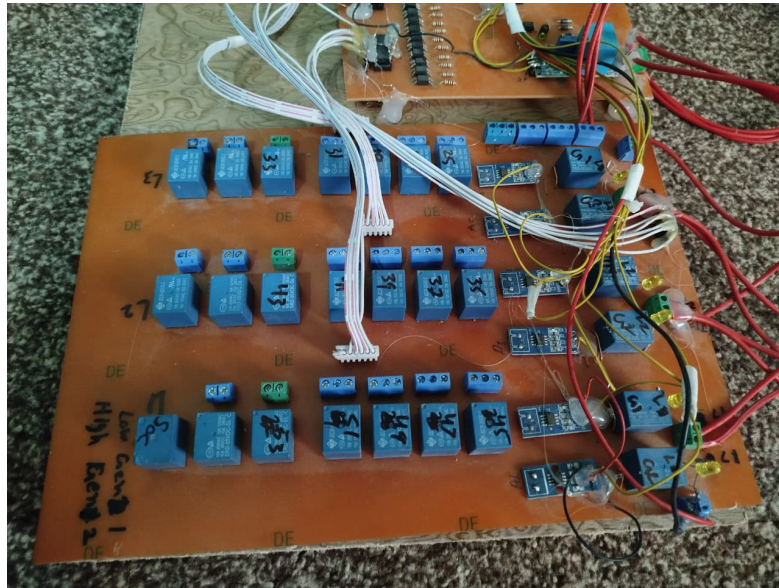


Figure 5.5: CT/PT Connection

### 5.7.2 Load Testing

Load testing assessed system behavior under varying load levels. Three cases were tested:

Low load condition: Only the larger generator supplied the load

Medium load condition: Both generators operated in parallel

High load condition: Load approached combined capacity limit

During load increase, the system automatically adjusted generator outputs without instability. No visible oscillations, hunting, or tripping occurred, indicating stable load distribution.

### 5.7.3 Voltage Stability Testing

Voltage stability is critical during parallel operation. Generator terminal voltage and bus voltage were continuously monitored during:

Synchronization Load changes Sudden load rejection and results showed that voltage remained within acceptable tolerance limits, and no severe dips or spikes were observed. Minor transient variations were quickly cor-

rected by the AVR and control logic.

#### **5.7.4 Frequency Regulation Testing**

Frequency performance was tested by observing system behavior during load addition and removal. Initially, slight frequency deviations were noticed during load transitions; however, the digital controller and governor responded rapidly to restore the frequency to its nominal value. Frequency stability improved significantly once both generators were operating in parallel, confirming effective power sharing and governor coordination.

#### **5.7.5 Protection and Safety Testing**

Protection features were tested to ensure safe operation. Reverse Power Protection: Artificial conditions were introduced to simulate reverse power flow. The system detected abnormal behavior and issued a breaker trip command, successfully isolating the affected generator. Over-current Conditions: High load conditions close to rated limits were applied. The system maintained operation within safe thresholds, and protective actions would initiate if limits were exceeded. These tests confirmed that protection algorithms and relay logic were functioning as intended.

#### **5.7.6 Graphical User Interface (GUI) Testing**

GUI testing evaluated accuracy, usability, and responsiveness. The GUI displayed real-time values of:

Voltage Frequency Real power Reactive power Breaker status

All displayed values matched actual measured parameters. Alarms and indicators responded correctly during fault and synchronization events, making the interface effective and operator-friendly.

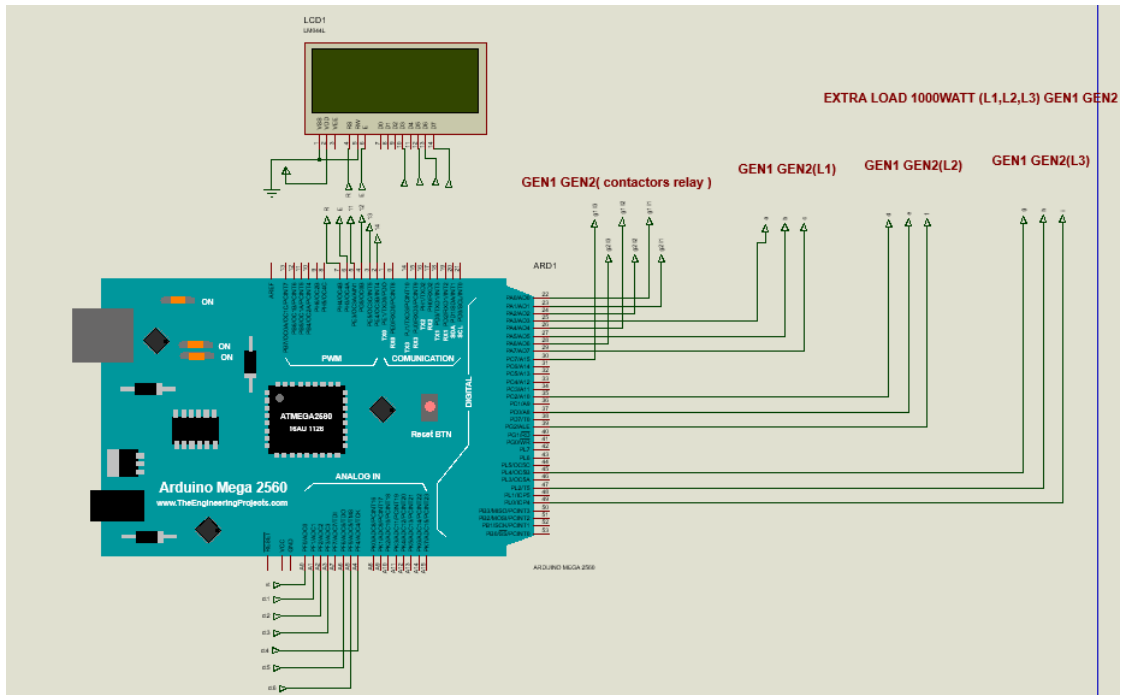


Figure 5.6: Arduino proteus diagram

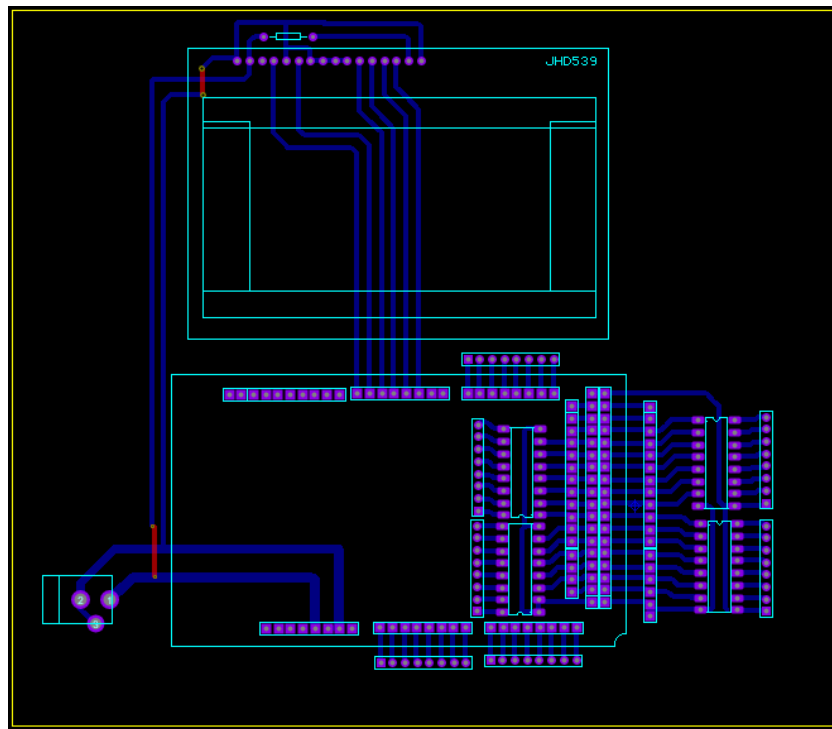


Figure 5.7: Arduino pcb layout from left side

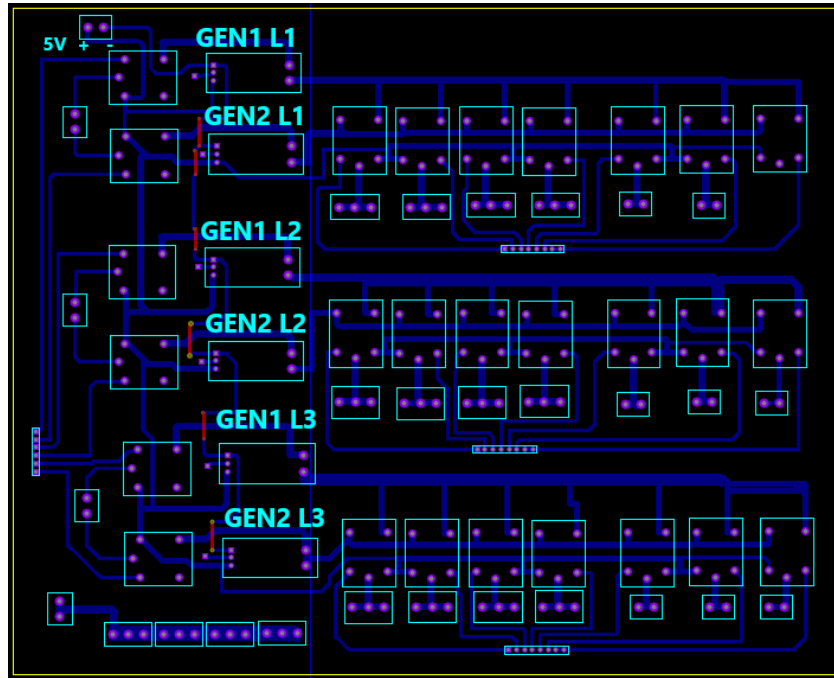


Figure 5.8: Arduino pcb layout from right side

### 5.7.7 Usability Testing

The system was operated by users with limited technical background to assess ease of use. The simplified interface and automated control reduced human intervention and minimized operational errors. Manual override and emergency stop functions were accessible and effective.

### 5.7.8 Stability and Reliability Testing

Long-duration tests were conducted to assess system reliability. The generators were allowed to operate in parallel for extended periods under stable load. The system exhibited no drift, instability, or overheating, indicating reliable continuous operation.

## 5.8 Evaluation Metrics

The following metrics were used for evaluating system performance:

Synchronization Time: Time required to match voltage, frequency, and phase  
Load Sharing Accuracy: Ability to distribute load proportionally  
Voltage Regulation: Deviation from nominal voltage  
Frequency Stability: Ability to maintain nominal frequency  
Response Time: Controller reaction to load changes  
Fault Response: Speed and accuracy of protective actions

Each metric demonstrated satisfactory performance aligned with project objectives.

## 5.9 Analysis of Results

The testing results show that the proposed system fulfills its design goals. Automatic synchronization was smooth and reliable, preventing mechanical shock and electrical stress. Load sharing between unequal generators was stable and proportional, validating the effectiveness of the Arduino-based droop logic. Compared to manual synchronization and traditional equal-rating paralleling systems, the implemented solution offers improved safety, reduced operator dependency, and better adaptability for mobile power applications.

## 5.10 Strengths of the System

Successful parallel operation of unequal-rated DGs  
Automated synchronization and load sharing  
Reduced risk of overload and equipment damage  
Cost-effective implementation using Arduino  
Scalable and adaptable for mobile applications.

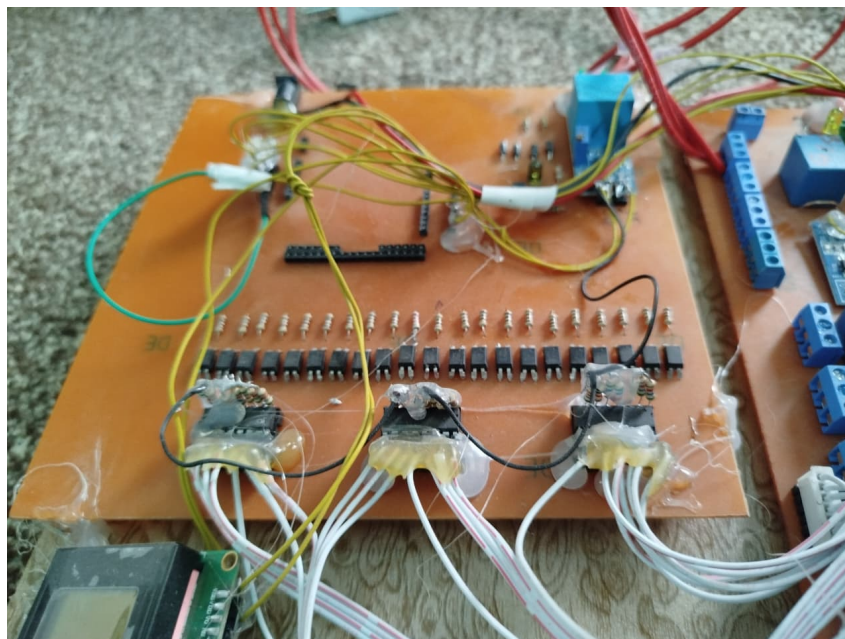


Figure 5.9: Circuit diagram

## 5.11 Limitations of the System

Limited to two generators only Manual tuning required for droop parameters, no integration with renewable energy sources, Limited data logging capacity, Recognizing these limitations helps guide future improvements.

## 5.12 Overall Evaluation

Overall, the system performed reliably under all tested conditions. The testing and evaluation process confirmed that the implemented solution is technically sound, practically viable, and suitable for real-world deployment in industries requiring mobile power generation.

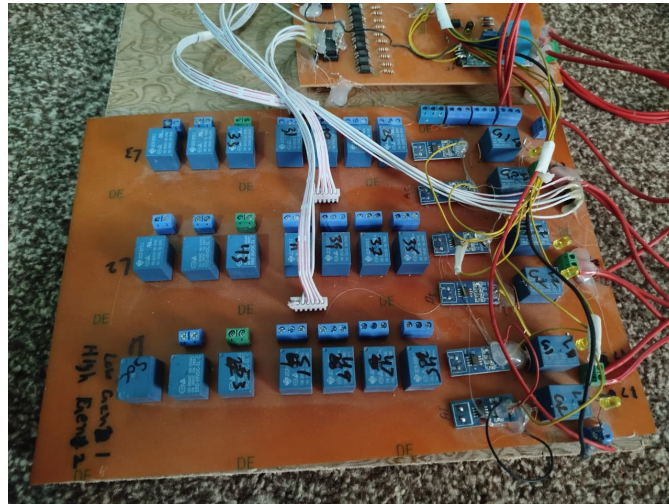


Figure 5.10: Working of CT/PT for Synchronization

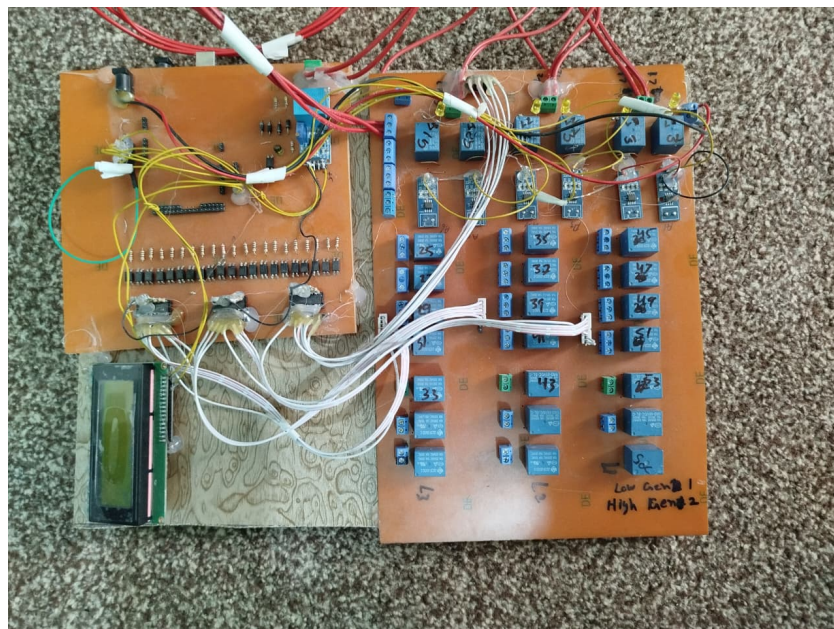


Figure 5.11: CT/PT, ICs' Connections



Figure 5.12: Hardware result when both DG's is ON



Figure 5.13: Hardware result when DG1 in ON



Figure 5.14: Hardware result when DG2 is ON

# Chapter 6

## Conclusion

This project was about designing, building, testing and evaluating a system for running two diesel generators together. These generators had power ratings. The main reason for doing this was to solve the problems that come up when trying to connect and share load between generators of different sizes. This is an issue in mobile, remote and emergency power situations.

i) Traditional systems for connecting generators assume they are the size. This makes them not work well in real-life situations.

ii) Our system solves this problem by using synchronization and smart load-sharing techniques.

One of the achievements of this project was successfully automating the process of synchronizing generators. We used a controller to make sure the voltage, frequency and phase angle were exactly matched before connecting the generators. This prevents stress, electrical disturbances and other problems. Tests showed that this process was smooth, fast and reliable in situations. This automation made it much easier to operate the generators and errors.

Another key achievement was developing a load-sharing controller using Arduino. This controller could distribute the load between the generators according to their power ratings. It did this by monitoring the voltage and current. The system made sure the bigger generator carried more of the load while the smaller one was protected from overload. Tests showed that the load sharing was stable and worked well.

The system worked well in tests. It kept the voltage and frequency during synchronization, normal operation and sudden changes in load. This made the system safe and reliable.

iii) From a point of view this project showed that it's possible to run generators of different sizes together reliably using affordable and widely

available parts.

iv) The Arduino-based system is flexible, simple and easy to modify. This makes it suitable for both industrial use.

v) The systems modular design allows it to be easily adapted to generator sizes and operational needs. However the project also has some limitations. It currently only works with two generators. Needs manual tuning of control parameters. The data logging is basic. Integrating it with renewable energy sources or grid-connected operation was not part of this project. These limitations highlight areas for improvement [26]. Overall the project objectives were successfully achieved. The system demonstrated synchronization, accurate load sharing, stable electrical performance and reliable protection in real-world conditions. This work provides a foundation for further research and development in generator paralleling systems. It also offers a solution for mobile and off-grid power generation scenarios

## 6.1 Summary of System Performance

The work demonstrates the design, implementation and evaluation of a parallel operation system for two mobile diesel generators with unequal power ratings. The system maintains operation under various conditions, including no-load synchronization, incremental load application and sudden load variations.

## 6.2 Key Technical Contributions

The main technical contributions are:

- Mathematical modeling of diesel generators
- Automatic synchronization scheme for mobile generators

- Proportional loadsharing control using Arduino
- Experimental validation on a platform

### **6.3 Practical Implications for Mobile and Industrial Power Systems**

The findings have direct relevance for mobile, temporary and offgrid power applications. The proposed solution provides a method, for integrating generators with different ratings without requiring costly replacement or infrastructure changes.

The IEEE research on distributed generation economics says that we should be able to use generators in a way that's efficient. We should be able to use them and this will help us to reduce the time they are running use less fuel and make the equipment last longer. These are the things that the research from the IEEE emphasizes.

### **6.4 Role of Direct Utility Supply and Optimized Generator Usage**

It is better to use the utility supply when we can. This is because it costs less needs maintenance and is better for the environment. We should only use diesel generators when we need to. This could be when the grid is not available or when we need power. The control strategies we developed in this work are still useful even when we are connected to the grid. They help us to switch between using the grid and using generators without any problems. The IEEE has done studies on microgrids. They say that we need to be able to synchronize and manage the load when we are using both the grid and diesel generators. So the work we did here is not just

useful for systems that are not connected to the grid. It is also useful for systems that use a combination of grid supply and diesel generation.

## 6.5 Future Work

Even though the system worked well there are ways it could be improved:

- I) Supporting more than two generators
- II) Adding SCADA or IoT-based monitoring for remote supervision
- III) Implementing control algorithms
- IV) Including energy sources like solar or wind
- V) Improving cybersecurity for communication interfaces

These improvements could make the system more intelligent, scalable and suitable, for smart-power applications.

# References

- [1] IEEE Industry Applications Society, “Engine generator paralleling concepts,” 2013.
- [2] IEEE Power System Relaying and Control Committee, “Practices for generator synchronizing systems,” IEEE Power & Energy Society, 2024.
- [3] M. J. Thompson, D. Finney, N. Fischer, and A. Kalra, “Fundamentals and advancements in generator synchronizing systems,” 2012.
- [4] Cummins Power Generation, “Paralleling dissimilar generators—Part 3: Load sharing compatibility,” Power Topic #9017, 2017.
- [5] “Load sharing and synchronization techniques for distributed generation systems,” vol. 67, no. 3, pp. 617–624, 2021, doi: 10.24425/ijet.2021.137822.
- [6] F. A. Farhan, D. I. Minja, W. J. P. Sun, and P. H. Kirkup, “Paralleling incompatible generators: Mismatching requirements, challenges, and interoperability issues,” 2025.
- [7] M. S. Wagle, “Generator load sharing principle: Mastering parallel operation for stability and efficiency,” Power Projects Training, 2024.
- [8] Marine Public, “The parallel operation, synchronization and load sharing for generators,” 2023.
- [9] IEEE Industrial Electronics Society, “Optimal scheduling of diesel generators to minimize fuel costs,” in Yokohama, Japan, 2015, pp. 4726–4731, doi: 10.1109/IECON.2015.7392838.

- [10] Cummins Power Generation, “Droop versus isochronous load sharing in generator systems,” 2019.
- [11] Engineer Fix, “How droop control enables automatic load sharing,” 2025.
- [12] H. Hussaini, T. Yang, Y. Gao, C. Wang, T. Dragicevic, and S. Bozhko, “Droop coefficient design in droop control of power converters for improved load sharing,” 2021.
- [13] H. Bevrani, *Robust Power System Frequency Control*. Cham, Switzerland: Springer, 2014, doi: 10.1007/978-3-319-07278-4.
- [14] J. M. Guerrero, M. Chandorkar, T.-L. Lee, and P. C. Loh, “Advanced control architectures for intelligent microgrids—Part I,” *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1254–1262, Apr. 2013, doi: 10.1109/TIE.2012.2194969.
- [15] IEEE Power & Energy Society, “Basics of generator paralleling,” 2017.
- [16] Caterpillar Inc., “Paralleling generator set systems and design,” 2021.
- [17] Jubaili Bros., “Multi-generator paralleling: Synchronization and load sharing,” 2024.
- [18] V. Pangonilo, “Paralleling dissimilar generators: Requirements, issues, and compatibility,” 2025.
- [19] M. D. Alford, “Fundamentals of turbine-generator speed control,” IEEE Region 5, 2018.
- [20] N. M. Sheetal, V. C. Jnaneshwar, and J. M. Aishwarya, “Automatic load sharing transformer with cutoff system using Arduino,” vol. 13,

no. 5, pp. 205–208, 2025.

- [21] M. Vasanthakumar, A. Rao, and H. Jabil, “Automatic load sharing system using Arduino,” 2020.
- [22] P. P. Thete, K. V. Bhadane, and M. R. Desale, “Arduino-based smart load control system,” vol. 5, no. 3, pp. 53–57, 2020.
- [23] Schweitzer Engineering Laboratories, “Generator motoring protection—Are you protected?” 2017.
- [24] Electrical4U, “Reverse power protection working principle (ANSI 32),” 2018.
- [25] IEEE Power & Energy Society, “Tutorial on the protection of synchronous generators,” 2011.
- [26] M. J. Thompson, D. Finney, N. Fischer, and A. Kalra, “Fundamentals and advancements in generator synchronizing systems,” *IEEE Transactions on Industry Applications*, vol. 48, no. 6, pp. 2056–2064, Nov./Dec. 2012, doi: 10.1109/TIA.2012.2226854.

# Appendix A

## User Manual

This appendix is a user manual for the system of Operation of two mobile diesel generators with different ratings in parallel. This manual aims to assist operators, technicians and supervisors in the safe and efficient operation of the developed system. The manual describes the startup of the system, the synchronization process, the load sharing operation, monitoring, safety measures, and the shutdown process.

- **A.1 System Overview**

The system can run two mobile diesel generators (DG-1 and DG-2) with different capacities in parallel. The generators are paralleled with a load bus through circuit breakers and operated using a digital synchronization controller and Arduino-based load-sharing controller. The system offers the following features:

- Automatic synchronization of generators Load sharing according to generator capacities Voltage and frequency regulation Protection against abnormal operating conditions.
- The system is designed for off-grid, mobile, emergency and temporary power installations.

- **A.2 System Components**

The system consists of the following components:

- Digital Synchronization Controller
- Arduino-based Load Sharing Controller
- Circuit Breakers
- Current Transformers (CTs) and Potential Transformers (PTs)

- Power Relays
- current and Voltage sensors (ACS712, ZMPT101B)

- **A.3 Starting the System**

Start DG-1 and wait until it reaches rated voltage and frequency. Make sure that DG-1 is feeding the load bus alone. Start DG-2 and reach the no-load operating condition and make sure the synchronizer is switched on. At this point, the two generators are running independently.

- **A.4 Monitoring and Display**

The GUI shows real-time parameters, such as:

- Generator voltages and generator currents
- Frequency
- Active power (kW) and Reactive power (kVAR)
- Breaker status

- **A.5 Safety and Protection**

The system provides the following protection:

- Reverse power protection
- Over-frequency protection
- Under-frequency protection
- Over-voltage and under-voltage protection

In the event of a fault, the system trips a generator and disconnects it from the bus.

# Parallel Operation Of 2x Mobile DG's With Different Ratings

## ORIGINALITY REPORT

<b>12%</b>	<b>9%</b>	<b>1%</b>	<b>8%</b>
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

## PRIMARY SOURCES

<b>1</b>	<b>bnhgenerators.com</b> Internet Source	<b>4%</b>
<b>2</b>	<b>Submitted to HELP UNIVERSITY</b> Student Paper	<b>2%</b>
<b>3</b>	<b>Submitted to Higher Education Commission Pakistan</b> Student Paper	<b>1%</b>
<b>4</b>	<b>ewh.ieee.org</b> Internet Source	<b>1%</b>
<b>5</b>	<b>woodstockpower.com</b> Internet Source	<b>1%</b>
<b>6</b>	<b>Submitted to INTI International University</b> Student Paper	<b>&lt;1%</b>
<b>7</b>	<b>dokumen.pub</b> Internet Source	<b>&lt;1%</b>
<b>8</b>	<b>Submitted to Foundation University, Islamabad</b> Student Paper	<b>&lt;1%</b>
<b>9</b>	<b>Submitted to Glasgow Caledonian University</b> Student Paper	<b>&lt;1%</b>
<b>10</b>	<b>Submitted to Swinburne University of Technology</b>	<b>&lt;1%</b>

- 
- 11 Submitted to Wigan and Leigh College,  
Greater Manchester  
Student Paper <1 %
- 
- 12 repository.psa.edu.my  
Internet Source <1 %
- 
- 13 link.springer.com  
Internet Source <1 %
- 
- 14 Submitted to CTI Education Group  
Student Paper <1 %
- 
- 15 Sufyan Yakubu, Ravi Samikannu, Abid  
Yahya, Irfan Anjum Badruddin et al.  
"Feasibility design, comparative evaluation,  
and energy consumption prediction of  
standalone hybrid energy system for rural  
electrification in Ghana using machine  
learning models", Results in Engineering,  
2025  
Publication <1 %
- 
- 16 M. S. Vijaya Kumar, K. Srujan Raju, K.  
Rajakumar, S. Saravanakumar. "A Study on  
Next-Generation Materials and Devices -  
International Conference on A Study on  
Next-Generation Materials and Devices",  
CRC Press, 2025  
Publication <1 %
- 
- 17 mafiadoc.com  
Internet Source <1 %
-