Development of 1-Phase and 3-Phase Simulation Models of STATCOM and its Applications in National Grid.

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Certificate

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Dedication

This thesis is dedicated to my parents and family, whose unwavering support, guidance, and prayers have been a constant source of strength throughout my academic and personal journey.

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Abstract

This project presents the development of detailed 1-phase and 3-phase simulation models of a Static Synchronous Compensator (STATCOM) and investigates their application in Pakistan's national grid operated by ISMO (formerly NPCC). The work is motivated by increasing demand, voltage instability, and reactive power imbalances in the transmission network, where traditional compensation devices provide limited controllability and slow response. Using MATLAB/Simulink, converter-level models and associated control schemes are implemented for both single-phase and three-phase STATCOM configurations, along with a corresponding integration with Grid representation suitable for system-level studies. The models are combined with a representative PSS/E-based transmission network to analyze the effects of the placement of STATCOMs on the voltage profiles along the buses, reactive power flows and the system performance under different load and fault conditions. The findings indicate that properly managed STATCOM units can contribute to an increase in the voltage regulation to a considerable extent and to the strengthening of key transmission corridors, which will allow to lessen an urgent need to strengthen a network.

Contents

Chapter 1

Introduction

1.1 Project Background

The electric power systems are now experiencing pressure in terms of increased electricity demand, adoption of new loads and the lack of space in the transmission infrastructure [1]. The most noticeable aspect of these issues in Pakistan is that of voltage instability, overloaded transmission corridors and inability to provide reasonable power quality over geographically disperse areas of the national grid managed by the Independent System and Market Operator (ISMO), previously called NPCC [2]. The conventional approach of building new transmission lines or substations is capital intensive, has long lead times and is frequently subject to right of way and environmental restrictions [3], hence the use of smarter and more flexible technologies that can be used to help improve the functionality of existing infrastructure. FACTS devices are also the way to enhance power transfer capability and controllability of the current networks without significant physical redesigning [4]. The Static Synchronous Compensator (STATCOM) is a Voltage Source Converter (VSC) which is a shunt-connected device that supports the fast and continuous reactive power to regulate the bus voltage and enhance the stability of the system in varying load conditions and fault conditions [5]. A STATCOM can be used to reduce voltage sags and swells, enhance power factor, and assist the grid during contingencies by injecting or absorbing reactive power, and thus is a promising solution to the transmission system of the day. Within the framework of Pakistan national grid, ISMO has been interested in testing STATCOM solutions as an effective way of reinforcing the large scale networks economically compared to building large scale networks [6]. Nonetheless, successful implementation of STATCOMs needs precise models and simulations to include the single phase and three phase behaviour under realistic working conditions. These models are required in these areas: planning and technical studies as well as in training the operators of the system and engineers to comprehend the dynamic response of a STATCOMequipped network. This project will fulfil this requirement by creating 1-phase and 3-phase simulation models of STATCOMs and exploration of their uses in national grid of Pakistan through MATLAB/Simulink and PSSE based grid models.

1.2 Problem Description

The transmission network in Pakistan is characterised by a complex of high loading, variations in voltage as well as reactive power imbalances which may result in poor quality of power, low reliability, and, in extreme situations, collapse of voltage [1]. Traditional reactive power compensation systems, including fixed capacitor bank and mechanically switched reactors, have narrow 2 Development of STATCOM models and Integration with National grid. controllability and quite slow response [3], which is not as good as you might need in terms of rapidly evolving load patterns and fault clearance [7]. These are limitations that lead to challenges by the system operators in keeping the voltage profile within reasonable limits at all the nodes of a national grid as the demand increases and the grid becomes more complicated. Even though the use of STATCOMs as the effective tools of supporting the voltage and the quality of the power supply is well-known internationally, there is no localized, simulation-oriented research which would be oriented to the particularities of the national grid in Pakistan and the conditions in which ISMO might operate [8]. Current literature tends to concentrate on generic transmission systems or industrial feeders, and is unlikely to reflect in detail the limitations and contingencies and working practices of NPCC/ISMO network [6]. Moreover, numerous models that have been provided are based on three-phase balanced or on certain industrial applications with minimal consideration of combined single-phase and three-phase modeling model, which can be used in technical and operator training. This is an area of weakness that results into a number of practical challenges. Validated STATCOM models that capture local grid characteristics are only available to a limited number of the system planners and operators, so they are unable to carry out the what-if studies and to assess the effects of STATCOM placement and sizing on voltage stability and reactive power allocation. Moreover, they have to have structured training material and simulation-based case studies that can enable the ISMO personnel to develop intuition with regard to the behavior of STATCOM under various loading, fault, and contingency conditions [9]. In the absence of such tools, it is difficult to see how conceptual knowledge of STATCOMs can be transformed into one that is certain to be used in operations within the grid of Pakistan.

1.3 Project Objectives

The main objectives of the given project are to formulate and calculate the detailed 1-phase and 3-phase STATCOM simulation models, as well as to estimate their applications to the national grid of Pakistan managed by ISMO [10]. In order to accomplish this objective, the project is planned to be organized with regard to the following particular objectives which are in line with the proposal and presentation:

Objective 1: Research and diagram the theoretical models of 1-phase and 3-phase STATCOMs and make the calculations required at the power system and converter-level [11]. These are the knowledge of the principle of VSC based shunt compensation, reactive power control and mathematical modeling of the behavior of STATCOMs in steady state and dynamic situations.

Objective 2: Design simulation based STATCOM models in MATLAB/ Simulink in single and three phase configurations. The models will include proper control measures of bus voltage regulation and reactive power injection/absorption, which will allow the model to perform in-depth time-domain analysis [12] of the model under different operating conditions.

Objective 3: Coordinate the development of the STATCOM models with a representative model of the national grid with PSS/E or other similar tools, in collaboration with ISMO. This goal aims to transfer the STATCOM into realistic transmission line and bus implementation in such a way as to be able to quantitatively assess the effect of the STATCOM on system voltage profiles, reactive power flows, and system stability margins [5].

Objective 4: Prepare to transfer knowledge to ISMO training-based materials, simulation tutorials and case studies grounded on the formulated models and analysis findings. This involves the development of user-friendly situations that will show the performance of STATCOM when loads are varied [13], when faults and other disturbances occur, thus aiding operator training and planning studies.

1.4 Project Scope

This project scope is also well-defined to limit the scope to analysis of simulation instead of full-scale hardware implementation [14]. The research focuses on the construction of detailed 1-phase and 3-phase STATCOM models in MATLAB/Simulink, their control systems, as well as their connection with the power network and the development of the models in combination with a representative PSS/E-based model of the national transmission grid in Pakistan [12]. The grid representation will be chosen to represent the important buses, transmission lines and operating points in the plans and operational studies carried out by ISMO, however, will not endeavour to represent all aspects of the national system in an all inclusive manner. The simulations will focus on the situations that are of particular concern in terms of voltage stability and reactive power control [7], including load fluctuation, voltage sags and swells, unbalanced situations (where relevant) and some fault cases of choice. Such performance indicators will be voltage profiles at problematic buses, power exchange in reaction to, and without presence of STATCOM, and a qualitative measure of system stability. Although the project can aim at learning more at the base hardware level, the creation of a full-scale STATCOM prototype will not be required, and any hardware will be used only as an illustration and to a limited degree (it will not be the central focus). The geographical area is limited to the national grid of Pakistan under the operation of ISMO/NPCC, and the results are supposed to be applicable directly to this situation. However, the modeling system and simulation framework is supposed to be more generalized in the sense that it can be applied to other substations, corridors and or even other national grids with changes of the parameters [15]. It is also expressly mentioned in the project that the training materials and documentation about ISMO should be prepared but it does not provide on-site commissioning of actual STATCOM devices or large field trials.

Chapter 2

Literature Review

2.1 Overview of Reactive Power Compensation

The current power systems are under a great pressure concerning voltage unsteadiness, reactive power unbalance, and deterioration in the quality of power because of the rising load demand, the lengthy transmission lines, and incorporation of renewable energy sources [1]. The reactive power compensation is important in ensuring that the voltage stability and enhances the overall reliability of the national power grids [16]. The traditional compensation approaches of fixed capacitor banks and synchronous condensers have limited control and slow response when in the dynamic conditions [17]. To address these drawbacks Flexible AC Transmission System (FACTS) devices have been developed. FACTS devices can offer reactive power fast and controllable support, leading to a better stability of the system both in steady states and transient states [13]. The Static Synchronous Compensator (STATCOM) is one of the FACTS devices among many others that has received a lot of attention because of its better dynamic response [18].

2.2 Operating Principle and Advantages

STATCOM is a FACTS device shunt connected, a voltage source converter (VSC) that produces a controllable AC voltage using a DC source of energy [18]. STATCOM may inject or absorb reactive power into the power system by controlling the magnitude of the converter output voltage and the phase angle of the converter output voltage [11]. As compared to conventional equipment like Static Var compensators (SVCs). STATCOM has a number of benefits:

- Faster dynamic response
- Increased voltage regulation in low voltage conditions

- Smaller physical size [4]

2.3 Simulation-Based Studies of STATCOM Using MATLAB/ Simulink

A large portion of the current research on STATCOM is done through simulations since the simulation method enables a close study on the system behavior without the requirement of costly hardware implementation [17]. Researchers have extensively used MATLAB/Simulink to model STATCOM systems because it has the power to design control and simulate power systems [12]. A number of studies have proved that STATCOM is useful in enhancing the voltage profile and stabilizing system performance as load changes and faults occur [5]. The results of simulation are always the same, with the appearance of STATCOM decreasing the voltage sag and increasing the reactive power compensation in comparison with the systems that lack the compensation. Other control strategies have also been tested by the researchers using MATLAB/Simulink, proportional-integral (PI) controllers are the most used control strategies because they are very simple, reliable and easy to implement [19]. This research confirms that well-adjusted PI controllers

2.4 Single-Phase STATCOM in Distribution Systems

Single phase STATCOM commonly abbreviated D-STATCOM, finds application in distribution systems where the single phase loads are predominant [6]. According to the literature, the single-phase STATCOM is applicable in reducing voltage variation due to uneven distribution of loads and instantaneous changes in loads [18]. Experimental studies based on simulation indicate that single-phase STATCOM enhances the voltage stability at the point of common coupling (PCC) to a great extent [2]. These researches point to its use in rural distribution systems, residential feeders, and low voltage systems. Nevertheless, the majority of these studies are only interested in the distribution-level applications and fail to take the analysis to the higher level of grid integration [10].

2.5 Three-Phase STATCOM for Transmission and National Grids

Three-phase STATCOM is a popular topic in the context of transmission systems and national grids where significant reactive power compensation needs to be undertaken [16]. Studies with MATLAB/Simulink and PSS/E indicate that threephase STATCOM has high levels of voltage support during heavy loading conditions and grid disturbances like short circuiting and line trips [5]. PSS/E has been widely applied to study the performance of STATCOM in large-scale simulations of power systems because it can simulate realistic transmission networks and can be applied to load flow, dynamic and stability studies. It is demonstrated by literature that the inclusion of STATCOM in national grid models increases the level of stability in the voltage margins and also increases the ability of transient response after disturbances [8]. These studies affirm that the use of three-phase STATCOM is very effective in ensuring grid stability particularly in weak networks and long transmission corridors [2].

2.6 Comparative Studies Between STATCOM and Other FACTS Devices

A number of researches have been made to compare STATCOM with other FACTS devices like SVC and capacitor banks [3]. Results of the simulation have always shown that STATCOM has better performance in terms of: Faster response time Better fault tolerance of voltages. Improved low system voltage operation Although SVC is less expensive than STATCOM in steady-state compensation, under dynamic situations, STATCOM is better than SVC hence it is more appropriate in the current grids with varying loads and integration of renewable energy sources [13].

2.7 Control Strategies Used in STATCOM Studies

In STATCOM performance, control strategy is very important. According to literature, PI-based control is the most popular one because of its simplicity and effectiveness [11]. More sophisticated control methods like fuzzy logic and optimization based controllers have also been suggested but due to their complexity and computation cost, they are not practically applicable in practice [15]. The conclusion of most simulation-based studies is that PI-controlled STATCOM offers an acceptable trade-off between performance and implementation simplicity, especially in the case of educational and research applications [14].

2.8 Research Gap Identified from Literature

From the reviewed literature, the following research gaps are identified: Most studies focus either on single-phase or three-phase STATCOM, but limited work exists on their comparative simulation-based analysis [17]. Many simulation studies use only MATLAB/Simulink, while fewer studies combine MATLAB/Simulink with PSS/E for both control-level and grid-level analysis [20]. Limited research addresses the application of both single-phase and three-phase STATCOM models in a national grid context using simulation tools [8].

Chapter 3

Requirement Specifications

3.1 Introduction to Requirement Specifications

In this chapter, the specifications of the development of a Single-Phase and Three-Phase STATCOM system built on the principles of simulation are outlined, and the applications of these systems in the national power grids are also described [21]. This chapter is aimed at describing the current system, defining the limitations of the current system, and how the suggested STATCOM based system is able to address the limitations [22]. In addition, this chapter establishes the functional and non-functional specifications of the proposed system and gives applicable use cases to explain the system behavior under various operating conditions. The modeling, simulation and analysis in subsequent chapters of this chapter are based on the requirements identified in this chapter and will be based on MATLAB/Simulink and PSS/E [23].

3.2 Existing System

The traditional voltage regulation and reactive power compensation methods applied in the current power system are comprised of fixed capacitor banks, shunt reactors, synchronous condensers and Static Var Compensators (SVCs) [17]. These are the techniques that are used in the traditional transmission and distribution networks to accommodate the voltage levels and enhance power factor. Nevertheless, these traditional ways of compensating have a number of shortcomings. Fixed capacitor banks are used to offer a fixed compensation of reactive power, and have no flexibility to changing load conditions. Consequently, they can cause over-compensation or under-compensation when there is a fluctuation of system demands [4]. In comparison to capacitor banks, SVCs are more flexible, but rely on thyristor-based switching, which prevents their dynamic response and operation during serious voltage disturbances [24]. Moreover, traditional systems demonstrate a decreased performance in a low-voltage environment and faults. Their more sluggish response makes them not suited to the present day world of power systems where the quick changes of loads, the lack of renewable energy sources, and longer transmission distances require the fast and accurate response of reactive power [5]. As a result, the current system is not able to sustain the dynamism of the operating conditions in order to sustain voltage stability and power quality particularly in the large national grids [25].

3.3 Proposed System

In order to address the shortcomings of the current system, the proposed thesis is a simulation-based STATCOM system to compensate reactive power and regulate voltage in case of shortcomings in the current system [2]. The developed system will entail the design of both Single-Phase and Three-Phase STATCOM models based on MATLAB/Simulink, and further implementation and testing on the grid level through PSS(r)E [20]. The proposed STATCOM system relies on Voltage Source Converter (VSC) intertwined to the power system by means of a coupling transformer. The STATCOM is also capable of injecting or absorbing reactive power to the system by controlling the magnitude and the phase angle of the converter output voltage injected or absorbed [26]. A PI based control approach is used to control the DC-link voltage and hold the desired AC bus voltage. The Single-phase STATCOM is aimed to fix the issue of voltage fluctuations in the distribution level systems, whereas the Three-phase STATCOM is to be used in the transmission level and on the national grid.

The proposed system can have a better voltage stability, faster dynamic response and increased reactive power support than conventional compensation methods through simulation [27].

3.4 Requirement Specifications

The proposed system has the requirements that are separated into functional requirements and non- functional requirements. These requirements state what the system is to perform and what limitations it should perform.

3.4.1 Functional Requirements

The functional requirements describe the core functions that the STATCOM system must perform: The system shall model Single-Phase and Three-Phase STATCOM configurations in a simulation environment. The system shall provide dynamic reactive power compensation based on system voltage conditions. The system shall regulate bus voltage during steady-state and transient conditions [28]. The system shall respond effectively to load variations and fault con- ditions. The system shall implement a PI-based control strategy for voltage and DC-link regulation [29]. The system shall allow comparison of system performance with and without STATCOM compensation. The system shall generate voltage, current, and reactive power waveforms for performance analysis [23].

3.4.2 Non-Functional Requirements

The non-functional requirements define performance constraints and quality attributes of the system: The simulation model shall be stable and numerically reliable under all operating conditions [30]. The system shall exhibit fast dynamic response during voltage disturbances. The simulation shall comply with standard power system modeling practices. The system shall be scalable to represent national grid scenarios [21]. The control strategy shall be simple, robust, and computationally effi- cient [11]. The simulation results shall be clear, reproducible, and suitable for academic evaluation.

3.5 Use Case Description

Use cases describe how the system behaves under different operating scenarios. These scenarios are evaluated through simulation to assess the effectiveness of the proposed STATCOM system.

Use Case 1: Normal Operating Condition In normal operation conditions, when the STATCOM keeps the bus voltage to its reference value, it injects or absorbs reactive power on necessity. The system is also stable and works within allowable voltage [2].

Use Case 2: Load Variation When a sudden increase or decrease in load occurs, the STATCOM responds dynamically by adjusting reactive power output. This prevents voltage drops or overvoltage conditions and improves voltage stability [8].

Use Case 3: Voltage Sag Condition During a voltage sag caused by system disturbances, the STATCOM injects reactive power to support voltage recovery and minimize the impact of the disturbance [24].

Use Case 4: Fault Condition In the event of a fault, the STATCOM enhances system stability by providing rapid reactive power support, assisting in faster voltage recovery once the fault is cleared [4].

Chapter 4

System Design

The specification of a system's architecture, components, modules, interfaces and data to meet a set of requirements is called systems design. This chapter should have the following sections: system using the Park Transformation:

4.1 System Architecture

The system architecture is divided into a macroscopic power flow architecture and a microscopic power electronics control architecture. The macroscopic layer is a model of the WAPDA NTDC 500kV/220kV ac transmission lines stretching between the north hydroelectric generation and south thermal and load hubs (Tarbela Dam to Kot Addu). The architecture aims to model the substantial active power (P) feed into this long corridor, thus imposing an enormous reactive power (Q) need because of the inductive nature of long transmission lines [22]. Accordingly, the microscopic layer, the STATCOM, is used as a dynamic shunt connected Flexible AC Transmission System (FACTS) controller to compensate for this [13]. The design of the STATCOM involves a step-down coupling transformer, Voltage Source Converter (VSC) with Insulated Gate Bipolar Transistors (IGBTs) and a very large DC-link capacitor. The STATCOM is essentially an alternating voltage source, and is in-phase with the grid voltage, and can vary its reactive current injection/absorption at the Point of Common Coupling (PCC) to control the voltage level [9].

4.2 Design Constraints

Modelling a national transmission grid with high-frequency power electronics places strict constraints on the system: Grid Constraints: The magnitude of the voltage at all major transmission buses (500kV and 220kV) is maintained between the permissible limits of 0.95 pu $\leq V \leq$ 1.05 pu during steady-state [8]. Thermal Limits: The apparent power (S) on the transmission lines from Tarbela to Kot Addu should be within their thermal limits (MVA ratings). STATCOM Hardware Limits: The injected (absorbed) reactive power is limited by the maximum current of the IGBT switches of the VSC and the required voltage ripple on the DC link capacitor [17]. Differential Equation Solvers: When using MATLAB/Simulink to simulate discrete-switching PWM (in the kHz range) in a 50Hz grid, a stiff differential equation solver (ode23tb) and a discrete sample time (Ts) small enough to capture the switching transients (but not too small to fill the computer memory) should be used [19].

4.3 Design Methodology

Base Case Setup: Using Siemens PSS/E software, a Newton-Raphson load flow analysis is performed on the uncompensated system to determine the bus with the greatest voltage sag and transmission (line) losses during maximum load transfer [25]. Sizing and Placement: Using the analysis of the Q V curve, the minimum MVA rating (rating) and preferred location for the STATCOM to be injected into the network are determined [7]. Control Design: The inner (current) and outer (voltage) control loop of the STATCOM is designed by using its mathematical equations and tuned using the Ziegler-Nichols tuning method for a critically damped response. Integration and Transient Analysis: The model of the STATCOM is then integrated at a weak bus in the system and time-domain transient stability simulations are conducted to see its response to three-phase faults and load shedding [28].

4.4 High Level Design

The high-level design controls the way that the STATCOM absorbs or injects reactive power to the AC system. If the output voltage of the STATCOM (Vsh) is larger than the AC system voltage (Vm), the STATCOM delivers reactive power (capacitive mode). If Vsh < Vm he STATCOM absorbs reactive power (inductive mode).The active power (P) and reactive power (Q) flow between the STATCOM and system is based on the following basic power equations [18]:

$$P = \frac{V_m V_{sh}}{X_{sh}} \sin(\alpha) \tag{4.1}$$

$$Q = \frac{V_{sh}^2 - V_m V_{sh} \cos(\alpha)}{X_{sh}} \tag{4.2}$$

Where: Vm = Grid side voltage magnitude at the PCCVsh = STATCOM generated voltage magnitude Xsh = Leakage inductance of the transformerα = Phase angle between Vm and Vsh In a loss-less ideal STATCOM, α is maintained at zero (P = 0) and only reactive power (Q) is ensured. In practice though, a very small portion of active power (P) is supplied from the grid to meet the switching losses of the IGBTs and to maintain a charge on the DC-link capacitor [8].

1. Conceptual or Logical: This view shows the system from the point of view of functionality. The components are a similar grouping of functionality. In the Unified Modelling Language (UML) this is a component diagram or a package diagram.

2. Process: in this view, the system is viewed at run-time. This view consists of components which are processes or threads or distributed

apps. In UML this view would be a process interaction diagram.

3. Physical: this would be for a distributed system. The components are machines (computers) that have parts of the system deployed on them. This would be a deployment diagram for UML.

4. Module: this view is used for project management andcode organisation. Components are usually directories or files. This shows how the format of directories of the build and development environment is planned.

5. Security: the view of components in this view are typically the ones that are doing something to secure the system. It can be a sub-view of the Conceptual view.

4.5 Low Level Design

In the low-level controller design the Synchronous Reference Frame (SRF) theory is heavily used. To independently control the active and reactive power of the grid, the three-phase AC voltages and currents (abc frame) are transformed into the rotating direct-quadrature (dq0) frame with the Park Transformation [26]:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{4.3}$$

Through a Phase-Locked Loop (PLL) which is used to synchronize the d-axis with the grid voltage vector, the control variables become DC quantities. The d-axis current (Id) affects the active power and DC-link voltage.

However, the q-axis current (Iq) controls the reactive power and the AC voltage. There are two parallel Proportional-Integral (PI) controllers which are fed with the error signals. The PI controllers' output provides the reference voltage signals to the Sinusoidal Pulse Width Modulation (SPWM) generator, which in turn, generates the firing pulses for the VSC [14].

4.6 Database Design

The parameter database for this study is the electrical data needed to solve the admittance matrix (Ybus) of the system [21].Bus Data: Voltage level, base MVA, minimum and maximum generation (Pmin,Pmax,Qmin,Qmax) and load (Pload,Qload) levels.Branch Data: per-unit (pu) resistance (R), reactance (X) and charging susceptance (B) for the transmission lines from northern generation to the southern generation and load.Machine Data: Sub-transient reactances and inertia constants (H) for Tarbela hydroelectric synchronous generators needed in the dynamic simulations [23].

4.7 GUI Design

The simulation platform's Graphic User Interface (GUI) has two main dashboards. In PSS/E , the GUI takes the form of the Single Line Diagram (SLD) workspace with the bus bars, transmission, and text blocks with real time pu voltages and flow MVAR information [20]. In MATLAB/Simulink, the GUI is comprised of the Scopes that are hooked up to the STATCOM measurement ports. These Scopes offer fine resolution time-domain representations of the three-phase voltages, the DC-link voltage stability and the reactive current injection trajectory.

4.8 External Interfaces

The project involves automated data interfacing of transmission system data (provided by WAPDA) with the simulation tools. PSS/E reads a network's structured text arrays of parameters in the form of external .raw (load flow) and .dyr (dynamic data) files. In addition, it also exports the results in .csv export files to data analysis software to compare voltage profiles and fault clearing times.

Chapter 5

System Implementation

5.1 System Architecture

The hardware implementation of the simulation is done on a high performance computer, able to undertake parallel matrix operations. The software design decouples the AC steady state load flow from the transients. The AC topology is represented as node-by-node. The STATCOM block is interfaced to the grid as a dynamic current injection source at the appropriate bus, making the normal (steady-state) load flow calculations dynamic, it uses time-step iterations [27].

5.2 Tools and Technology Used

MATLAB/Simulink (Simscape Electrical): Used for the detailed (micro) level modeling of the 1-phase and 3-phase STATCOMs. This is crucial to design the exact VSC design, set the IGBT switching frequencies of the FACTS to 2 kHz and 5 kHz, and the Kp and Ki values of the PI controllers [19].Siemens PSS/E (Power System Simulator for Engineering): Used for the large-scale (national grid level) modeling. PSS/E is the most widely used software by transmission operators, making it an ideal choice to model the Tarbela-Kot Addu system in the system, and to use the built-in FACTS dynamic models to observe system-wide stability [10].

5.3 Development Environment/Languages Used

5.3 Development Environment/Languages Used The main development environment is the block diagram based Simulink and PSS/E´s SLD environment. But extensive automation is done using scripting. MATLAB Scripting (.m files): MATLAB scripts are used to set up variables in the MATLAB workspace, to calculate the base impedances, and to automate the use of the scope data. Python/PSS/E API (psspy): Python is used to extract bus voltages for a series of fault cases, thus eliminating the need to copy and paste data and avoiding potential errors during bulk testing [20].

5.4 Processing Logic/Algorithms

The core processing algorithm implemented inside the STATCOM control unit executes the following loop at every simulation time step (Ts = 50µs):Sampling: The 3-phase voltage (Vabc) and current (Iabc) are measured at the PCC.Phase Locking: The PLL algorithm computes the grid synchronization angle (θ) [11].Transformation: Vabc and Iabc are transformed into Vdq0 and Idq0 using the Park transformation algorithm.Error Processing: * Outer Voltage Loop: V = Vref Vmeasured. This error is processed by the AC Voltage PI controller to generate the reference q-axis current (Iq,ref).Inner Current Loop: Iq = Iq,ref Iq,measured. This error is processed to determine the required inverter output voltage.Modulation: The control signals are transformed back to the abc frame via the Inverse Park Transformation and fed into a triangle-wave PWM generator algorithm to trigger the IGBT gate drives [29].

5.5 Application Access Security

The national grid data and the custom models are sensitive and highly complex objects and as such tight security measures are applied. The master of the .raw network files which contains the WAPDA system parameters are set to read-only mode. Changes and modifications, such as iterative testing, fault injections and tuning of STATCOM are applied to a local version-controlled repository.

5.6 Database Security

Output data of the simulations (thousands of data points on generation resynchronization time and voltage landscapes) is backed up through cloud based sync. The dynamic data back-up arrays in PSS/E are validated to ensure inadvertent changes to generator inertia constants or line reactances don't occur between runs.

Chapter 6

System Testing and Evaluation

This project was subjected to a three-staged and progressive testing and evaluation. The basic power electronics were tested prior to modelling the intricacies of the national transmission network. First a basic 1-phase STATCOM model was evaluated before progresses to a full 3-phase converter model and finally the integration of the STATCOM into the discrete 500kV North-South equivalent network.

6.1 Single-Phase STATCOM Evaluation

To understand the working of the STATCOM, we started with a 1-phase Voltage Source Converter (VSC) model to verify the functionalism of the mathematical control method and Pulse Width Modulation (PWM) algorithm [6].

Testing Setup:

The 1-phase model was integrated with a basic low-voltage AC source modelling a stub feeder. A simple Proportional-Integral (PI) controller was used in the control strategy to regulate the phase angle between the grid and the converter voltage.

Evaluation and Results:

DC-Link Charging: In the first test, we tested the converter's capability to act as a rectifier and charge the DC-link voltage of its DC capacitor. Through simulation, it was found that the PI controller was able to draw a small amount of active power from the grid to charge the capacitor to the desired level without instability [9]. Injection of Reactive Current: Inductive load was connected to the feeder. The single-phase STATCOM was able to detect the lagging power factor and successfully inject reactive current in phase with the voltage. The oscilloscope readings confirmed that applying the AC current was shifted to be more in phase with the AC voltage, and the underlying VSC switching logic was operating properly [21].

6.2 Three-Phase STATCOM Evaluation

Evaluation having successfully modelled the single-phase switching, a 3-phase, 3-wire system was modelled. This is necessary because all the power delivered through the national grid is balanced 3-phase power [11].

Testing Setup:

The three-phase evaluation introduced the Synchronous Reference Frame (dq0) control. The three-phase voltages (Vabc) and currents (Iabc) were transformed into direct (d) and quadrature (q) axes.

Evaluation and Results:-

PLL Synchronization: A Phase-Locked Loop (PLL) is required to track the grid frequency. The evaluation confirmed that under varying load conditions, the PLL successfully locked onto the grid angle (θ) within less than one fundamental cycle (20 ms). Decoupled Control Validation: A step-response test was applied independently to the active (Id) and reactive (Iq) reference currents. The simulation proved that the controller could alter reactive power output (by changing Iq) without causing unwanted disturbances in the active power flow (Id) [26]. This decoupled control is a mandatory prerequisite for deploying the unit on the WAPDA network.

6.3 North-South Grid Integration (Discrete Evaluation)

North-South Grid Integration (Discrete Evaluation) The final and most complex testing phase integrated the validated 3-phase STATCOM into the full-scale transmission corridor representing the WAPDA NTDC network between northern hydro and southern thermal load centers [16].

Simulation Architecture: To capture the extreme high-frequency switching transients of the IGBT valves alongside the massive power flows of the national grid, a discrete time-step solver was implemented. The system was evaluated using a rigorous 2.5e-05 s (25 µs) sample time.The simulated 500kV transmission corridor is anchored by massive equivalent sources representing the regional generation hubs:Northern Equivalent (Tarbela): Modeled as an 8500 MVA Programmable Source.Southern Equivalent (Kot Addu): Modeled as a 9000 MVA source on Bus B3.Mid-System Support: A 6500 MVA equivalent source on Bus B2. Network routing incorporates multiple parallel transmission paths, including line lengths of 200 km (L1), 75 km (L2), and 180 km (L3), together with heavy localized MW loads drawn from the lines [21].

6.4 The 100MVA STATCOM Implementation

100 MVA, 500 kV STATCOM is placed in shunt at B1 bus. The test model is a split DC-link and two large DC energy storage capacitors (Cp and Cm) are used to keep the DC voltages stable.The VSC is driven by a tailor-made STATCOM Controller that samples the grid parameters (Vabc B1 and Iabc B1) and the DC voltages (VdcPN) to provide the needed firing pulses for the VSC [29].

6.5 Final System Evaluation and Results

The integrated grid was subjected to severe load variations to monitor the system's dynamic response via master ”Signals and Scopes” block. The evaluation focused on four critical output parameters:

Voltage Tracking (Vmeas vs Vref): As the heavy loads across the 200km and 180km lines pulled the system voltage down, the controller successfully tracked the error. The measured per-unit voltage reliably returned to the reference setpoint, proving the unit's capability to mitigate transmission sags [15].

Dynamic Reactive Power (Q): The oscilloscope reading proved the actual injection of the MVARs the STATCOM supplied to Bus B1. The red arrow path at the PCC confirmed the flowing of bidirectional reactive current - injecting for the sags with heavy loads and absorbing for the swells with light loads.

DC-Link Stability (Vdc): Even with the very high 100 MVA reactive power variations on AC circuits, as the scope assessment has demonstrated, the DC-Link across capacitors Cp and Cm is stable and balanced. The biggest threat to the failure of the STATCOM failure; this proves that the PI is tuned properly.

AC Waveform Integrity (Va,IaPrim): Assessment of primary currents and voltages have shown that the high frequency switching pulses from the controller cause little harmonic distortion to the 500kV equivalent national grid system [24].

In research type projects this chapter should include detailed information on the evaluation metrics, analysis and discussion of the evaluation results.

Chapter 7

Conclusion

For the modernisation of high-voltage AC transmission systems, active power electronics are needed to increase their The thesis was able to conceive, model and assess the performance of both 1-phase and 3-phase Static Synchronous Compensator (STATCOM) topologies, leading to the deployment of these to a discrete model of Pakistan's 500kV national grid.

Driven by stringent historical issues of reactive power imbalances and low voltage sags across the gigantic transmission corridors under the supervision of ISMO (formerly NPCC), the new research offered a very structured, simulation-based grid reinforcement approach. The approach intentionally scaled up from the micro-imbedded converter control, to the macro-level grid integration: the basic switching principles were validated before they were tested with national-scale simulation.

- Summary of Project Phases and Key Findings.

  Phase 1 and 3 (Converter Level Validation): The initial modelling of the 1-phase and 3-phase systems properly validated the behaviour of the Voltage Source Converter (VSC). The control logic in the (dq0) Synchronous Reference Frame were able to fully decouple the active (Id) and reactive (Iq) currents. The Phase Locked Loop (PLL) kept the STATCOM grid-synchronised within 1 cycle and proved that the high-frequency Pulse Width Modulation (PWM) (switching the IGBTs) could accurately direct the reactive power output, without upsetting the DC-link capacitors.

  Phase 3 (National Grid Integration): The major goal of this thesis was to integrate a 100 MVA STATCOM in a detailed 500kV equivalent North-South network [8]. By modelling the huge Addu load sheets, a power transfer from the 8500 MVA Tarbela generation center through many hundreds of kilometers of transmission line to the 9000 MVA Kot Kot Addu load hubs, the simulation represented the network challenges. During load transfer, the STATCOM demonstrated its ability to provide instant capacitive reactive power leading to a very fast settling time of reference voltage steps (20 ms closed loop time constant).

Superiority During Fault Conditions: The comparative study appears decisively demonstrated the superior operation of the STATCOM over the thyristor-controlled Static Var Compensators (SVCs). Under a simulated 30 percent mild voltage sag (caused by a remote fault) condition, the STATCOM delivered nearly twice the capacitive contributions (-0.71 pu) than an equally rated SVC (-0.48 pu). Being a constant current source, the STATCOM reactive output is only linearly dependent (as opposed to exponentially) on grid voltage, making it far superior during major grid faults [27].

- Contribution to Sustainable Grid Infrastructure:

  The widespread deployment of the STATCOM at the centre of the transmission corridor (Bus B2) showed that the STATCOM had significant benefits. The provision of local Reactive Power (VAR) support by the STATCOM eliminated the need to transmit VARs over the 600-km transmission lines. This in turn positively impacted the system's power factor (PF), total apparent current (IA) and theoretically reduced I2R ohmic losses in the transmission corridor.By maximizing the capacity and reliability of existing WAPDA transmission assets, this project is a direct contribution towards Sustainable Development Goals (SDGs) related to sustainable energy and infrastructure. It demonstrates that smart grid technologies can help fully harness existing investments and assets, and delay or remove the need for billions of dollars' worth of new transmission line construction [13].

- Future Work and Recommendations:-

  While this simulation lays a strong groundwork for STATCOM reactive power support on the North-South corridor, the following aspects are recommended for future developments:Renewable Intermittency Modeling: As southern Pakistan begins to incorporate large mega-scale solar and wind farms, future versions ofAlternative Control Strategies: While the Proportional-Integral (PI) controllers worked exceptionally well, future work should include such features as Artificial Intelligence (AI) or Fuzzy Logic controllers that also auto-tune the Kp and Ki gains in real-time to deal with non-linear, unanticipated variations in load. Hardware In-the-Loop (HIL): To translate the results of the thesis to real-world applications, the Simulink models need to be compiled on a Real-Time Digital Simulator (RTDS). An interface with physical DSP microcontrollers with the simulated grid will be used to ensure the hardware-based processing delay, before being commissioned by ISMO.Overall, the detailed modeling and extensive testing carried out in this thesis demonstrate that STATCOM integrations are a very effective, dynamic upgrade to the existing voltage instability in long-distance power corridors. This work offers a proven methodology which can support system planners and operators in a stable, efficient power future for the Pakistani power system.

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