Modeling of Hybrid STATCOM in PSSE

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Abstract

Flexible AC Transmission Systems (FACTS) have the ability of voltage support and increase transmission capacity. In order to specify a FACTS device that is performing according to expectations in a network, a set of studies and network analyses must be performed. Part of these studies are done using power system analysis programs such as PSS®E, which is a planning tool simulating large power systems in phasor domain using RMS values. These planning tools are used for evaluating stability and reinforcement needs in a power system. The results play a vital role in investment decisions in the power system. FACTS devices are modeled in PSS®E using a programming language called FORTRAN. It is important to model FACTS devices accurately to avoid misleading results. In this Master thesis, STATCOM and Hybrid-STATCOM models are proposed and programmed according to ABB’s control strategy. The models are tested in PSS®E and verified against detailed models in PSCAD. Also, the models are compared against other industry wide spread generic models.

Key words: FACTS, STATCOM, TSC, TSR, Hybrid-STATCOM, PSSE, FORTRAN, ABB, Dynamic model
Sammanfattning


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Acronyms

API  Application Program Interface.
BJT  Bipolar Junction Transistor.
CHB  Cascaded H-Bridge.
DAE  Differential Algebraic Equation.
DLL  Dynamically Linked Libraries.
EAF  Electric Arc Furnace.
EMT  Electromagnetic Transient.
FACTS Flexible AC Transmission Systems.
FC   Flying Capacitor.
GTO  Gate Turn-off Thyristor.
IGBT Insulated Gate Bipolar Transistor.
IGCT Integrated Gate-Commuted Thyristor.
MMC  Modular Multilevel Converter.
MOSFET Metal Oxide Semiconductor Field Effect Transistor.
MSC  Mechanically Switched Capacitor.
MSR  Mechanically Switched Reactor.
MSS  Mechanically Switched Shunts.
OV   Overvoltage.
PCC  Point of Common Coupling.
PI  Proportional Integral.
PLL  Phase Locked Loop.
POD  Power Oscillation Damping.
POM  Program Operation Manual.
PSS  Power System Stabilizer.
PSS®E  Power System Simulator for Engineering.
PWM  Pulse Width Modulation.
RMS  Root Mean Squared.
SMIB  Single Machine Infinite Bus.
STATCOM  Static Synchronous Compensator.
SVC  Static Var Compensator.
TCLC  Thyristor Controlled LC.
TCR  Thyristor Controlled Reactor.
TSC  Thyristor Switched Capacitor.
TSR  Thyristor Switched Reactor.
TSS  Thyristor Switched Shunts.
UV  Undervoltage.
VSC  Voltage Source Converter.
WECC  Western Electricity Coordinating Council.
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Chapter 1

Introduction

1.1 Background

In recent years, the electric power system have been expanding rapidly, especially the integration of renewables. The stability of the electric power system is always a topic of concern when installing new components in the system. The rise of Flexible AC Transmission Systems (FACTS), with their capabilities of supporting reactive power in the system and regulating the voltage levels, allows more flexible and stable power transmission in the system. There are many FACTS devices that could be used for voltage stability. This study is considering two of the shunts devices, the Static Synchronous Compensator (STATCOM) and Static Var Compensator (SVC). Both devices have the capability of injecting or consuming reactive power in order to regulate the voltage at their Point of Common Coupling (PCC). The difference between the STATCOM and SVC is in their components. The STATCOM uses Voltage Source Converter (VSC) to synthesize AC voltage from a DC reference voltage. The difference of voltage magnitude and angle between the VSC and the voltage at the PCC allows the current to either flow towards the STATCOM or the system. The SVC uses Thyristor Switched Capacitor (TSC) or Thyristor Switched Reactor (TSR) or both. Thyristor Switched Shunts (TSS) can have 2 modes, full conduction and block. The reactor branch can use Thyristor Controlled Reactor (TCR), which allows the SVC to adjust the firing angle of the thyristor to various values. The difference between TSR and TCR is that TSR can have 2 modes only, full conduction and block, on the other hand, TCR can adjust its output to any value between full conduction and blocking modes. Consequently, the voltage at the PCC can be regulated smoothly.

STATCOM used to be a device with high voltage and current harmonics components when VSC was using 2-and 3-level converters. But with the technology of H-bridge converters, which is a cascaded multilevel full bridge
IGBT modules, the harmonics are dropped down significantly in addition to the reduction in active power losses caused by switching [2].

Although STATCOM showed a better voltage support and a faster response than SVC in undervoltage conditions, the use of SVC is more popular around the world [1]. The reason is that STATCOM has a symmetrical operation range only. Also, for high reactive power ratings, SVC is much economical than STATCOM. But since STATCOM has a smaller physical footprint compared to SVC (it doesn’t require tuned filters to suppress harmonics), in some cases, STATCOM or Hybrid-STATCOM could be more economical to use than SVC. On the other hand, the STATCOM is superior to SVC when it comes to undervoltage disturbances due to the reduction of SVC’s reactive power output by the square of the voltage at PCC, whereas the reactive power of STATCOM is reduced linearly with the drop in the voltage at PCC as shown in the following equations:

\[ Q_{VSC} = I_{VSC} U_{VSC} \]  
\[ Q_{SVC} = I_{SVC} U_{SVC}^2 \]

The equations are derived in sections 3.1.2 and 2.3.1 respectively. The solution is to use a hybrid STATCOM, which is a combination of VSC and TSS branches. The main topology is to install VSC in parallel with TSC/TSR or both. It incorporates the capabilities of both STATCOM and SVC. The advantages of hybrid STATCOM is the wider range of operation, smaller size, reduced footprint (asymmetrical operation ranges), removal of filters and a faster response [2, 1]. ABB developed a Hybrid-STATCOM solution but it needs modeling in a power system simulation software for further analysis. The model of Hybrid-STATCOM is developed in Power System Simulator for Engineering (PSS®E) in order to be used in dynamic RMS simulations.

1.2 Problem Statement

The PSS®E library includes a STATCOM model, called SVSMO3U2, which has the capability of utilizing Mechanically Switched Shunts (MSS). The STATCOM model source code cannot be modified; however, the parameters used in tuning the model can be altered. The external shunts can be switched in or out depending on the STATCOM output current. There are three delays associated with the operation of MSS, the breaker operation delay, the delay associated with switching in a MSS and the time shunt capacitor should be out before being connected again. If the breaker delay is zero and the MSS switch in delay was reduced, MSS can operate as TSC/TSR. Hence, the STATCOM model can behave as a Hybrid-STATCOM.
But the problem with this existing model is the large overshoot that occurs when the MSS switches in or out. The reason behind that is when MSS switch in/out, STATCOM doesn’t counteract the injection/consumption of reactive power. STATCOM control in \textbf{SVSMO3U2} lacks this control function, which will cause a large overshoot as shown in figure 1.1. The following example shows the behaviour of a STATCOM in parallel with Mechanically Switched Capacitor (MSC). A step change was applied on the scheduled voltage at the STATCOM. $V_{\text{ref}}$ was raised from 1 p.u. to 1.05 p.u. The first graph shows the reference voltage in the STATCOM and the Voltage at PCC. The second graph shows the STATCOM output current, where positive current refers to capacitive operation. The third graph shows the reactive power compensation from MSC, where positive MVAR refers to capacitive operation. The step change is applied at 0.2 seconds. The STAT-
COM starts increasing the injected current until it reaches 0.5 p.u., which is the threshold for MSC to switch in. When MSC switch in, the voltage will overshoot and the STATCOM will try to bring down the voltage by switching to the inductive mode. The voltage will take around 50ms to reach the \( V_{\text{ref}} \) point. The control is missing a feed-forward loop that can expect MSC switching and switch the STATCOM to inductive mode of operation to counteract MSC; hence, reduce the overshoot and help the voltage at PCC to reach \( V_{\text{ref}} \) in a shorter time. In order to create a Hybrid-STATCOM model that includes the previous property, a STATCOM model should be developed first.

### 1.3 Goals and Objectives

#### 1.3.1 Goal

The goal of this master thesis project is to program and model Hybrid-STATCOM in PSS/E for dynamic simulations. The developed model should behave as close as possible to an actual Hybrid-STATCOM under different contingencies.

#### 1.3.2 Objectives

In order to develop an accurate Hybrid-STATCOM model in PSS®E, the following objectives were achieved:

1. Literature review:
   A thorough review of different STATCOM models and controls was conducted. Also, the topics of integrating TSS in parallel with VSC was looked into. The advantages of multilevel converters and their topologies are topics of concern since the VSC in Hybrid-STATCOM is built by MMC. Finally, dynamic simulation in PSS®E and programming models in Fortran are very important topics that helped in completing the rest of the objectives.

2. STATCOM Model and control:
   There are many STATCOM models that have been used in dynamic simulations. The Model to be used in this project is clearly defined in a control block diagram. All state variables are stated, and the control strategy is demonstrated. The functionality of the control blocks are explained as well.

3. Hybrid-STATCOM Model and control:
   The Hybrid-STATCOM is defined as a control block diagram. The control strategy and blocks are defined and explained in details.
4. Program the Model in Fortran:
The STATCOM and Hybrid-STATCOM mathematical models are programmed in Fortran. The developed model are converted to Dynamically Linked Libraries (DLL) file and imported into PSS®E for verification.

5. Verify STATCOM and Hybrid-STATCOM models in PSS®E:
The functionality of the Fortran models are tested in PSS®E. Several cases were used to test different functions and control blocks in the models.

6. Verify STATCOM and Hybrid-STATCOM models in PSS®E against PSCAD models:
The STATCOM and Hybrid-STATCOM models in PSCAD are using the actual controls implemented in the real components. Hence, these models represents the real devices accurately. The outputs of the developed PSS®E models are compared to PSCAD outputs for verification.

7. Prepare comprehensive documentation for the developed models:
The developed models are documented by means of the project report and a user manual. The report contains the project description, implementation, discussion and conclusion. The user manual is a guide for using the models in PSS®E.

8. Suggest future work:
A list of recommendations is prepared to help future development of the models.

1.4 Literature Review
The literature review section discusses the topics and papers related to the thesis, including the search methodology used to obtain the information.

1.4.1 Overview and search methodology
In order to conduct a comprehensive literature review on modeling of Hybrid-STATCOM in PSS®E, many topics are covered. The review started by understanding the functionality of power electronics switching devices such as the thyristor valve, IGBT and Gate Turn-off Thyristor (GTO). These power electronics devices are the building blocks of the VSC branch (STATCOM) and the TSR/TSC branch (SVC). After getting familiar with the functionality of VSC and thyristors, the topics of STATCOM (VSC branch) and SVC (TSC and/or TSR branches) were covered. The topics of interest in STATCOM and SVC were there functionality and importance in power
grids. The difference between the two devices is an important topic as well since it forms the basis of the notion of Hybrid-STATCOM. The different models and control methodologies of STATCOM and SVC were the next topics in the review. It was important to search for existing models for Hybrid-STATCOM, or VSC branch in parallel with TSC/TSR. The literature review was concluded with FACTS models in PSS®E and dynamic simulation in PSS®E.

The Hybrid-STATCOM model and control developed in PSS®E for this master thesis project is taken from the model used by ABB. A STATCOM model is built in Fortran first and verified in PSS®E, then the TSR and TSC branches are integrated in the model. Most of the papers reviewed are modeling STATCOM for Electromagnetic Transient (EMT) studies. This level of modeling cannot be applied in PSS®E since it is a Root Mean Squared (RMS) based software. However, it is important to conduct a generic review on different STATCOM models and controls before proceeding in the project.

The literature review was conducted by searching on different journals' and universities’ websites. The search words used were general at the beginning then it became more specific as the review progressed. Search words used were (STATCOM, SVC, Thyristor valve, VSC, TSR, TSC, Hybrid-STATCOM, Hybrid-SVC, STATCOM modeling, STATCOM control, STATCOM MMS, STATCOM TSC/TSR, SVC modeling, SVC control, SVC MSS, SVC TSC/TSR, PSS®E, PSS®E dynamic simulation). Many scientific papers are available on the topics of modeling and control of STATCOM and SVC. However, only three papers were found that combines the VSC branch and TSR/TSC branch to create Hybrid-STATCOM. Two of the papers are published by ABB and Siemens. Both of the papers introduce the concept of hybrid-STATCOM and its advantages. ABB and Siemens create the Hybrid-STATCOM by using VSC branch in parallel with TSC/TSR or both. The third paper was published by the university of Macau. The authors provided a mathematical model and control strategy for their proposed model. The models cascaded the VSC and the TSS branch.

1.4.2 Power electronics switching devices and MMC

The topics of the switching devices are not crucial for the actual modeling of FACTS devices in PSS®E since these modules are not part of the model. Therefore, an overview of the functionality and differences between the switching devices was sufficient for this study. The materials covering power electronics switching devices was taken from 'Power Electronics, Converters Applications and Design' [3]. Multilevel converters utilized in STATCOM generate an AC synthesized voltage from a DC source. Multi-
level converters can have three topologies in general, diode-clamped, Flying Capacitor (FC) and Cascaded H-Bridge (CHB). The most used topology is CHB since it proved to give a better performance over FC and diode-clamped topologies [4]. MMC’s can have many topologies by cascading the converters. The modularity refers to the technique of integrating (cascading in this case) small subsystems to create a large system. The cascading of MMC is referred to as chain-links. The advantage of chain-link modules is less stress on switching devices and higher compensation range. The drawback is the separate dc sources for each module. Some papers such as [2][1] used different voltage levels in the modules to achieve smoother output wave. The ABB MMC consists of chain-link modules. Each Module is composed of H-bridge multilevel converters. [5] introduces a novel hybrid cascade multilevel inverter scheme. It uses multiple modules with different DC voltages. The STATCOM modeled in [5] have multilevel H-bridge converters. The number of modules depends on the rating of the STATCOM. Most of the papers that concentrates on STATCOM modeling with MMC state that the advantages obtained by integrating MMC are less power losses, reduced harmonics and higher compensation range [5][6][7].

1.4.3 STATCOM and SVC Performance

In order to understand the need for Hybrid-STATCOM, it was important to go through papers that compare between STATCOM and SVC in terms of performance and functionality. In [8] the author concludes that STATCOM performs better than SVC with first-swing stability enhancement. Based on the calculations, STATCOM provides higher reactive power output than SVC under voltage disturbance. [9] compares the damping performance of STATCOM, SVC and Power System Stabilizer (PSS). The author concluded that PSS have the best damping on inter-area oscillation modes. STATCOM and SVC can provide adequate damping if placed in the right location in the system. STATCOM have a better damping than SVC since it can exchange active power during transient response. This paper is not of large importance to the thesis project since it is focused on different aspect of STATCOM and SVC. However, It can be used to show that STATCOM and SVC have power oscillation damping capabilities. [10] is comparing the performance of STATCOM and SVC with several study cases in the Chinese grid. The authors expressed three advantages of using SVC and STATCOM:

1. Enhanced voltage support.

2. Improved transient stability.

3. Improved damping of low frequency oscillation.

The authors concluded that the use of a single FACTS device in the grid is not sufficient for voltage support. Multiple devices should be installed in
order to achieve the expected result. In transient stability, both devices improve the stability of the system; however, STATCOM has a better response due to its “short time over load capability”. Finally, the STATCOM has a better time response but the authors state that the correlation between the time response, voltage support and transient stability is not clear. In [11] the author discusses the connection of STATCOM and SVC to a grid with Asynchronous generator. STATCOM and SVC improved the transient response under load fluctuations with STATCOM having a better response. On the other hand, with short circuit faults, the contributions of SVC and STATCOM were not significant, but SVC had a better response.

[12] compares SVC and STATCOM in a specific application. Electric Arc Furnace (EAF) uses a large amount of power in a non-linear manner which causes large fluctuations in voltage. Therefore, the use of FACTS devices would improve voltage stability by providing the required reactive power to raise the voltage at PCC and minimize the effect of power swings in EAF. By comparing the performance of SVC and STATCOM, both devices provided the required voltage support. But STATCOM with the help of a capacitor bank can compensate for active power which makes it superior to SVC in this application. The problem with having a capacitor bank only is the recharge time. The use of a battery is more efficient for active power compensation. Most of the studies showed that STATCOM is superior to SVC. However, the studies made on the Chinese grid and on EAF present the need of having a VSC branch in parallel with TSR/TSC branch for a better reactive power compensation and voltage support. [13] shows the benefits of STATCOM and SVC for utility applications. The authors modeled STATCOM and SVC and compared their performances. The main topics compared were undervoltage/overvoltage contingencies, physical footprint, harmonics, cost and losses. In general, STATCOM has smaller physical footprint and reduced low order harmonics generation compared to SVC. Also, STATCOM has a better performance during undervoltage conditions. Where as SVC has a better performance during overvoltage conditions. SVC can have lower cost and losses in general. The authors in [13] concluded that these comparisons depends on the design and application of STATCOM and SVC.

1.4.4 Hybrid-STATCOM

The advantages of Hybrid-STATCOM was realized by large companies such as ABB and Siemens. A paper published by Siemens was reviewed [2]. The paper discusses the advantages of SVC and STATCOM and their applications in the power system. A hybrid SVC, which is a combination of VSC and TSS, is introduced in the paper to combine the advantages of STATCOM and SVC. The main topology is to install VSC in parallel with TSC, TSR or both. ABB as well published a paper on the same topic [1]. The
authors outlined the main difference between STATCOM (SVC Light) and SVC (SVC Classic). The STATCOM is superior during undervoltage disturbances, whereas SVC outperform STATCOM during overvoltage events. The reason for these behaviors is the relation between voltage and the reactive power supplied by STATCOM and SVC to the power system. MVAR generated by STATCOM has a linear relation to the bus voltage. On the other hand, MVAR generated by SVC has a quadratic relation to the bus voltage as shown earlier. This being said, a drop in bus voltage will cause the MVAR provided by SVC to drop by a factor of $V^2$, which is not the case with STATCOM since it has a linear relation. STATCOM can provide constant MVAR during undervoltage disturbances. For overvoltage events, SVC can provide a better MVAR compensation for the same reason mentioned, $V^2$. The authors also mentioned the utilization of MMC in STATCOM and harmonics and active power losses reduction. The advantage of reducing harmonics is the removal of low order harmonics filters. The Hybrid-STATCOM is introduced at the end of the paper to solve the issues mentioned earlier.

1.4.5 STATCOM modeling

The author in [14] states different types of STATCOM modeling. For steady-state, STATCOM can be modeled as an ideal reactive current source. On the other hand, in dynamic studies, STATCOM can be modeled in two different methods. The first model is a balanced 3-phase voltage source with controllable magnitude and angle. This model is usually used for studies that does not require fast response of STATCOM. The other dynamic model of STATCOM is realized as a controllable reactive current source. The dynamic model includes a Phase Locked Loop (PLL) that capture the phase angle of the current supplied by the STATCOM. Authors in [15] are using fuzzy logic to obtain gains and time constants of Proportional Integral (PI) regulator of the STATCOM. The dynamic model uses d-q reference frame with PLL. In [16] STATCOM is modeled as a voltage source with the AC side voltage multiplied by a parameter $k$ that relates dc side voltage to ac side voltage. $k$ is usually dependent on the VSC topology. The phase angle of the ac side can be controlled by a logic block to produce the desired output. Another approach to STATCOM modeling is to use a voltage source to represent the VSC in series with a transformer with tap changer as in [17]. A similar model is used in [18]. STATCOM is modelled using a voltage source to represent the VSC in series with a transformer with a tap changer. Voltage at Point of Common Coupling (PCC) controls the switching of power electronics components in VSC. Another paper was reviewed that introduces a STATCOM with a capacitor bank, it is called Hybrid-STATCOM by the author [19]. It consists of a VSC and a shunt capacitor.
bank. The authors claim that the integration of the capacitor bank will decrease the stress on the switching devices and reduce the required converter rating. The STATCOM will be operating in inductive mode to regulate the voltage. The existence of the capacitor bank will allow the STATCOM to go from inductive to fully capacitive and restore the voltage fast in under-voltage events. STATCOM is modeled as voltage source in parallel with a capacitor bank.

1.4.6 Alternative Hybrid-STATCOM

The authors in [20] proposed another topology for a Hybrid-STATCOM. The model consists of an active inverter (VSC) cascaded with a Thyristor Controlled LC (TCLC), the name used for this topology in this paper is Hybrid-STATCOM. LC is defined in the paper as a reactor in parallel with a capacitor. TCLC is connected through a coupling inductor, for filtering, to the grid. TCLC consists of a TCR in parallel with a capacitor. The VSC is in series with the TCLC. The motivation behind this design is that SVC and STATCOM have disadvantages from performance and economical perspective. The problem with SVC devices are the speed of response, injection of harmonics current (the need for filters) and resonances. The STATCOM with active filters proved to be better in performance and harmonics reduction compared to SVC. The main issue with STATCOM is the cost when used with high power ratings since the power electronic switches should be dimensioned to withstand high voltage stress. In the proposed model in [20], the main compensation is done by the TCLC part of the Hybrid-STATCOM. The VSC part is responsible for tuning any mismatch of firing angle in TCLC. The authors claim that by adjusting the firing angle, the Hybrid-STATCOM can compensate for unbalanced currents and reduce harmonics generated by TCLC. In this thesis project, the Hybrid-STATCOM modeled uses a different topology. Instead of cascading the VSC and TCLC branches, the VSC is in parallel with TSS.

1.4.7 PSS®E and model verification

There are different programs to perform RMS power system analysis on networks. PSS®E, E-TAP and PowerFactory are such programs. These programs are widely used by different companies for planning studies. These power simulation programs produce equivalent outputs when used for power flow calculations since they use equivalent models in power flow calculations. However, in dynamic simulations, each power simulation program has its own models with different parameters. Therefore, their outputs for the same network could differ significantly if the parameters were not tuned.
correctly [21]. This raises the concept of the importance of accurate modeling and parameter tuning. A significant part of this thesis is done using PSS®E. The best method to learn about the software and its functions is to review the Program Operation Manual (POM) [22]. PSS®E is capable of performing different calculations and applying several functions on power systems. Many powerful functions can be used like power flow calculations, dynamic simulations, building network equivalent and fault and contingency analysis. In order to perform dynamic simulations, a model of the device to be tested should either be in the library provided by PSS®E, or a user defined model can be used.

The main objective of the final part of this thesis is to prove the functionality of the model in PSS®E. All functions and blocks of STATCOM and Hybrid-STATCOM should be tested. Model verification and testing method are taken from the guideline produced by Western Electricity Coordinating Council (WECC) for developing a generic STATCOM and SVC models [23]. These models are part of the PSS®E model library. WECC used different types of tests to verify the functionality of the controls and logic blocks of their STATCOM and SVC models. As WECC suggests, the applied tests could be faults at different times and locations in the network. Also, a step changes for different STATCOM parameters in order to observe the effect of these changes on the dynamic behavior of the STATCOM.

1.5 Tools and Limitations

The development of a Hybrid-STATCOM model in PSS®E requires prior knowledge of the PSS®E software environment, understanding of FACTS devices, programming skills, especially in Python and Fortran, capabilities of modeling controllers and high understanding of power systems. The modeling is mostly done in Fortran, a scripting language used by PSS®E to model components. Python is used to control the PSS®E environment since the Application Program Interface (API) of PSS®E is Python compatible. A thorough study of FACTS devices, their controls and power system dynamics must be performed. The verification of the Hybrid-STATCOM model is required to ensure full functionality during different events and disturbances. One of the limitations is that the time-span of the project might be short to complete the implementation of the model. It might require additional time to fulfill all the requirements of the model. Another limitation is the programming language used for modeling. Fortran is a programming language which requires building a lot of common blocks and algorithms from scratch. Finally, the integration of the model in PSS®E might be limited by the capabilities of PSS®E. Where for example the voltage source converter (VSC) with its building blocks is represented by a current source.
1.6 Overview of the report

The report is organized in the following structure. Chapter 1 covers the introduction and background of the thesis with the literature review. Chapter 2 is the theoretical background of all the important topics covered in the report. Chapter 3 covers the implementation and development of the STATCOM model. Chapter 4 covers the implementation and development of the hybrid-STATCOM model. Chapter 5 is the verification of the implemented models. Chapter 6 covers the discussion of the proposed model and its performance. Chapter 7 is the final chapter and it covers the summary of the report with recommendations.
Chapter 2

Theoretical Background

The theory behind the main topics required to develop a model is discussed in this chapter. The working principle of SVC proposed in this chapter is used to explain the operation of the devices only.

2.1 Power Electronics Switching Devices

FACTS are based on power electronics switching devices. These devices differ in their structure, which will generate different $V-I$ characteristics for each device. Some devices have advantages over others in terms of speed of switching, harmonics generation and active power losses. The following are the most common switching devices for FACTS.

2.1.1 Thyristor

The thyristor can be seen as a diode with a turn-on switch. This switch is a gate that controls the operation of the thyristor. In order to turn on the thyristor (i.e. turn the thyristor to forward biased state of operation), a voltage signal, with certain magnitude and duration, must be sent to the gate. The thyristor then will be forward biased (full conduction mode). Thyristors cannot be turned off from the gate. In order to turn off the thyristor, a voltage with reverse polarity should be applied across it for a certain duration. Figure 2.1 show the symbol of a thyristor.

![Thyristor Symbol](image)

Figure 2.1: Symbol of a thyristor

off mode is called the reverse biased mode or blocking state. During the
blocking state, the thyristor will act as an open switch with some leakage current $i_T$. On the other hand, during full conduction state, thyristor will act as a closed switch with a small drop of voltage across it $v_T$. The product of $v_T$ and $i_T$ is the active power losses $p_T$. By applying a small current to the gate, thyristor can switch from blocking state to on-state at low voltages across it. During conduction state, thyristor can conduct currents up to 4 kA with low voltage drop. One of the main advantages of the thyristor is its high power capability. It can handle a reverse voltage up to 8 kV [24]. Thyristors are used in the SVC branches. It controls the reactor and capacitor branches by regulating the gate firing angle.

2.1.2 Gate Turn-off Thyristor

The structure of the thyristor and Gate Turn-off Thyristor (GTO) Thyristor is similar. GTO is a switching device that operates like a normal thyristor but with the ability to turn-off. The gate can turn-off GTOs by applying a high negative current that can be up to -750 A. The turn-off capability of GTOs reduced the reverse voltage blocking to 20-30 V. The forward blocking state of GTOs is equivalent to a thyristor. Normal thyristors valves lack the turn off capability, which makes GTOs a better candidate for switching devices. However, normal thyristors will always be the best to handle high power stress across it. GTOs are used in voltage source controllers, i.e. STATCOM. However, GTOs are being replaced by Integrated Gate-Commuted Thyristor (IGCT).

2.1.3 Insulated Gate Bipolar Transistor

Metal Oxide Semiconductor Field Effect Transistor (MOSFET)s have a fast switching capability, but it features high switching losses. On the other hand, Bipolar Junction Transistor (BJT)s has a low conduction losses but slower switching speed compared to MOSFETs. A new semiconductor device that combine the best features of MOSFETs and BJTs has been developed, Insulated Gate Bipolar Transistor (IGBT). IGBTs are capable of switching between conduction state and blocking state in a high frequency, much higher than the network frequency. Figure 2.2 shows the IGBT symbol. It only requires a voltage at the gate to switch. IGBTs are usually connected in stacks, many modules are connected in series. It is crucial to keep synchronism among all modules connected. They all must switch at the same instant. The VSC in STATCOMs are usually built by IGBTs since they can switch in a high frequency and synthesize AC voltage through Pulse Width Modulation (PWM), which is explained in section 2.2.1.
2.1.4 Integrated Gate-Commuted Thyristor

Integrated Gate-Commuted Thyristor (IGCT) is an electronics device developed from GTOs. The main difference between the two devices is the internal structure, and the fact that IGCT doesn’t require a snubber circuit. These changes allowed IGCT to have lower on-state losses and turn-off losses compared to GTOs [25]. IGCTs have the blocking capability of an IGBT and the conduction capability of thyristors (with lower on-state losses). Both IGBTs and IGCTs are used in building VSCs for STATCOMs. For applications with high power and lower switching frequency, IGCT is the best choice. For high switching frequency applications IGBTs are the better choice.

2.2 Voltage Source Converter

Voltage Source Converter (VSC) has been used for voltage regulation in transmission lines for years. It has the capability of synthesizing AC voltage from a DC voltage source. There are many topologies, configurations and controls for VSC. Considering a simple VSC topology, a basic 3 phase 2-level converter. The 2-level refers to the number of possible voltage levels synthesized by the converter, in this case $+V_A$ and $-V_A$. A capacitor is used in the DC side to generate the voltage $V_{dc}$. The switching devices must have the capability of turning on and off in a fast manner, therefore, GTOs or IGBTs are used with antiparallel diodes. In order to generate the AC voltage from $V_{dc}$, the switching devices can be controlled using PWM or square wave modulation. The problem with 2-level VSC is the high level of harmonics generated by the converter. There are many topologies and configurations that can reduce the harmonics and synthesize a smoother sinusoidal wave. To achieve this, the number of voltage levels can be increased by using the Modular Multilevel Converter (MMC).
2.2.1 Pulse Width Modulation

Pulse Width Modulation (PWM) is a control strategy that creates the signals sent to the VSC switches to synthesize the desired wave. The control strategy consists of two waves, the control signal $v_{\text{control}}$ and the triangular signal $v_{\text{tri}}$. PWM can be controlled by varying the width and amplitude of the control signals. By switching the IGCTs or IGBTs, the desired output voltage can be obtained. PWM can create low order harmonics in the system [3]. A parameter that relates the AC side voltage to the DC side voltage is the amplitude modulation ratio $m_a$, and it can be found by:

$$m_a = \frac{\hat{v}_{\text{control}}}{\hat{v}_{\text{tri}}}$$  \hspace{1cm} (2.1)

Then the peak fundamental output voltage can be found as:

$$\hat{V}_{o1} = m_a V_d \quad \text{for} \quad (m_a \leq 1)$$  \hspace{1cm} (2.2)

Where $V_d$ is the DC side voltage. Equation 2.2 is used for 2-level single phase converter. Different converter topologies will have different equations. For this thesis, the topology of the VSC is not important since the VSC is modeled as an ideal current source.

2.2.2 Modular Multilevel Converter

As mentioned earlier, the 2-level VSC topology generates harmonics into the system. Harmonics and voltage stress on the switching devices are reduced with Modular Multilevel Converter (MMC). The Hybrid-STATCOM model proposed in this project is using CHB in VSC branch. Figure 2.3 shows a three phase five-level CHB STATCOM. Each phase is composed of two full bridge modules (H-bridge) connected in series. CHB topology requires separate DC voltage sources for each module. Each module (cell) is capable of generating 3 voltage levels $V_+$, $V_-$ and zero. Hence, the relation between the voltage levels ($V_L$) and the number of cells ($N$) is $V_L = 2N + 1$. Figure 2.4 shows the output voltage and harmonics of different VSC topologies. A higher number of voltage level produces a smoother wave. Hybrid-STATCOM can be built without active filtering since the harmonics magnitude is very low, which will drop down its cost and footprint.
Figure 2.3: Five-level CHB STATCOM (2 cells)

Figure 2.4: Voltage level and harmonics in different VSC topologies [1]
2.3 Static Var Compensator

2.3.1 SVC Overview

Static Var Compensator (SVC) is a FACTS device that provides reactive power compensation. SVC can regulate the voltage at the PCC and increase the transmission capacity of the line. It is usually composed of at least 3 branches, a TCR and filters for specific harmonic components. It can include a TSC branch as well in parallel with the TCR and the filters. Figure 2.5 shows a simple SVC with a TCR in parallel with a fixed capacitor, which is used as a harmonics filter. The reactor branch has antiparallel thyristor valves in order to conduct in both directions. Each thyristor will conduct for half a cycle. The firing angle of the thyristors (α) is regulated by the SVC controller. The conduction interval of the thyristors can be defined as \( \sigma = 2(\pi - \alpha) \). α must not be chosen in the range [0,90] degrees since that would create asymmetrical currents. The allowable range for α is [90,180] degrees for TCR, but for TSR is either α = 90 or α = 180, where α = 90 degrees corresponds to \( \sigma = 180 \) which is the maximum conduction interval (full conduction). For α = 180 degrees, the corresponding conduction interval is \( \sigma = 0 \) which is the minimum conduction interval (zero conduction). As α increases, the conduction interval \( \sigma \) decreases. Assuming that the voltage at PCC is \( u(t) = \hat{U}\sin(\omega t) \), the current through the reactor for the 2-half

\[
\text{Figure 2.5: Basic structure of SVC}
\]
cycles can be defined as follows:

\[ i_L(t) = \frac{\hat{U}}{\omega L} (\cos(\alpha) - \cos(\omega t)) \quad \text{for} \quad (\alpha < \omega t < \alpha + \sigma) \quad (2.3) \]

\[ i_L(t) = -\frac{\hat{U}}{\omega L} (\cos(\alpha) + \cos(\omega t)) \quad \text{for} \quad (\alpha + \pi < \omega t < \alpha + \sigma + \pi) \quad (2.4) \]

By applying Fourier transformation on equations 2.3 and 2.4 and taking the fundamental component, the amplitude of the current going through the reactor \( i_{L(1)}(t) \) can be calculated as shown in equation 2.5:

\[ \hat{I}_L(\alpha) = \frac{\hat{U}(2(\pi - \alpha) + \sin(2\alpha))}{\pi \omega L} \quad (2.5) \]

The TCR branch is usually modeled as a controllable susceptance \( B_L(\alpha) \), where the thyristors firing angle \( \alpha \) is the control signal. Hence, the susceptance as a function of \( \alpha \) is defined as:

\[ B_L(\alpha) = \frac{\hat{I}_L(\alpha)}{\hat{U}} = \frac{2(\pi - \alpha) + \sin(2\alpha)}{\pi \omega L} \quad (2.6) \]

And the overall susceptance of the SVC \( B_{SVC}(\alpha) \) is found as:

\[ B_{SVC}(\alpha) = B_C - B_L(\alpha) \quad \text{where} \quad B_C = \omega C \quad (2.7) \]

Assuming active power exchange is zero, then the reactive power output can be found as:

\[ Q_{SVC}(\alpha) = I_{SVC}(\alpha)U_{PCC} = (B_{SVC}(\alpha)U_{PCC})U_{PCC} \]

\[ Q_{SVC}(\alpha) = B_{SVC}(\alpha)U_{PCC}^2 \quad (2.8) \]

### 2.3.2 SVC Model

SVC is modeled as a controllable susceptance as shown in figure 2.6. \( B_{SVC} \) is a combination of a fixed capacitor and a TCR as shown in figure 2.5, and it can be found using equation 2.7.

SVC can have other configurations such as a TCR in parallel with TSC. Also, in addition to the TCR and TSC branches, SVC will have a filter branches tuned to suppress a certain harmonic components. These filters depends on the network impedance and the rating of the SVC. The filers will not be studied in this project since the model to be developed are in RMS and will not consider EMT.
Figure 2.6: SVC model

SVC have two operation regions, Capacitive and inductive. In the Capacitive region, the current $I_{SVC}$ is leading the voltage at PCC, and the SVC is injected reactive power into the power system. In the Inductive region, the current $I_{SVC}$ is lagging the voltage at PCC, and the SVC is consuming reactive power from the power system. $B_{SVC}$ will be limited by the rating of the SVC. It will have a range $B_{SVC}^{min} < B_{SVC} < B_{SVC}^{max}$. The V-I characteristics of SVC is shown in figure 2.7. The nominal operation point of SVC is at $U_{ref}$ when $I_{SVC} = 0$. $I_{cap}^{max}$ and $I_{ind}^{max}$ represent the maximum capacitive and inductive currents at which SVC can regulate the current in a continuous manner. $U_{maxref}$ and $U_{minref}$ represent the maximum and
minimum reference voltages for continues current control. If the voltage increased beyond $U_{maxref}$, SVC will be kept at $B_{SVC}^{min}$ until the voltage come back to the controllable range. The same procedure is followed when the voltage drops below $U_{minref}$. SVC will be kept at $B_{SVC}^{max}$ until the voltage come back to the controllable range. The actual strategy for Undervoltage (UV) and Overvoltage (OV) events is more complicated than this. It is similar to the strategies used for STATCOMs, which is explained in section 3.1.3.

The linear slope (droop) $X_{SL}$ is the ratio of the change of voltage to the change of current over the controllable range of operation. The droop value is regulated by the grid operators, it represents the allowable amount of reactive power contribution from different sources in the grid. It prevents the SVC from injecting/consuming more reactive power than the allowable amount by the grid operator. The slope ensures that the contributions of various devices at the grid don’t counteract each other, which would compromise the stability of the network. The droop typically ranges between 1-10%. The slope can have different values for capacitive and inductive regions. As shown in figure 2.7, the slope for the capacitive region is $X_{C}$, where the slope for the inductive region is $X_{I}$. Considering the simple model in figure 2.6, the SVC characteristics can be calculated as follows:

$$U = U_{ref} \pm (X_{c} \text{ or } X_{i})I_{SVC} \text{; controllable range} \quad (2.9)$$

2.4 PSS®E and Dynamic Simulations

Most of the thesis work was done in this phase. The STATCOM model developed in section 3.1.3 will be interpreted to Fortran and used as a model in PSS®E. It must be mentioned that models of STATCOM and SVC have already been developed by Western Electricity Coordinating Council (WECC), and they are part of PSS®E models library. The models developed by WECC is a generic models and can be used for several applications. All the parameters of STATCOM and SVC models such as gains and time constants can be tuned to meet the required specifications. However, the models are part of PSS®E library and cannot be modified as mentioned earlier. Hybrid-STATCOM doesn’t have a model to be used in PSS®E that would represent its behaviour accurately. Some tests were made by using a STATCOM in parallel with fixed switch shunt with zero time constant on the breaker as shown in section 1.2. But the results of these tests did not show the actual behaviour of hybrid-STATCOM since the model lacked the actual control loops that coordinates the outputs of VSC and TSR/TSC in hybrid-STATCOM. Therefore, it is necessary to develop a model in PSS®E that contains all the controls required for a hybrid-STATCOM. The STATCOM model is developed in Fortran programming...
language then the TSR/TSC branch will be added after verifying STATCOM model functionality in PSS®E.

2.4.1 Power System Simulator for Engineering (PSS®E)

Power System Simulator for Engineering (PSS®E) is an electric power system simulator as the name suggest. It is capable of performing different calculations and applying several functions on power systems. Many powerful functions can be used like power flow calculations, dynamic simulations, building network equivalent and fault and contingency analysis. Many companies use PSS®E for feasibility studies when integrating a new electric power component into the grid. There are two types of models used in PSS®E. The first type are the models exists in the PSS®E library such as the WECC models mentioned earlier. The other type of models are the user defined models. These models are developed by the user in Fortran, and then they are converted to a Dynamically Linked Libraries (DLL) file and imported to PSS®E. The STATCOM and hybrid-STATCOM models developed in this thesis work are of the second kind. All the parameters used in the model can be tuned by the user through PSS®E or a dynamic file (.dyr).

Table 2.1: The different types of parameters used by models in PSS®E

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Parameter Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONs</td>
<td>Constant parameters</td>
</tr>
<tr>
<td>VARs</td>
<td>Algebraic variables that can be determined at any instant of time if all States and constants are known</td>
</tr>
<tr>
<td>STATEs</td>
<td>State variables that can be determined at any instant by differential equations</td>
</tr>
<tr>
<td>ICONs</td>
<td>Integer parameters (can be constants or algebraic variables)</td>
</tr>
</tbody>
</table>

The main objective of doing dynamic simulation is to observe the behavior of the system at different instants of time when exposed to disturbance. All the component of the network have a dynamic model that contains state
and algebraic variables. These variables are determined by solving the DAE at each time step \( T + t \). Figure 2.8 shows the flow chart of dynamic simulations. At the first stage all constant data are accumulated and state variables are initialized by the output of the load flow calculations. The time derivative of the state variables are then found in order to be used in the DAE. Finally, the equations will be integrated and the new state variables will be found. At this stage, all the variables are known and the system behaviour at this instant of time is determined. Then, the time is increased by one integration step and the whole process is repeated until the finish time. During simulations, several types of disturbances can be applied such as faults, the loss of a system component or a sudden change of one of the system parameters. These disturbances can be used to understand the system behaviour under different conditions. It can also be used to test the system behaviour after installing a new component in the system.
The STATCOM and hybrid-STATCOM models will be tested under several types of disturbances in order to verify their functionality.

2.4.3 Fortran Programming

The user-defined models must be written in Fortran while abiding PSS®E rules for models. Fortran is a programming language that is used by PSS®E in all its models. There are many rules specified by PSS®E that must be followed accurately in order for the model to perform as intended by the user. Different types of calculations are applied by PSS®E during each time step. These calculations are applied in different stages during one time step, or as PSS®E defines it ‘Modes’. The model in Fortran must specify the calculations or actions done in each mode. These modes must be considered carefully in the Fortran model. Table 2.2 demonstrates the different modes of operations and its description. All the parameters in table 2.1 must be specified clearly in the script.

Table 2.2: Modes of operations and its description in PSS®E

<table>
<thead>
<tr>
<th>Mode Number</th>
<th>Mode Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initialization stage, all state and algebraic variables must be initialized</td>
</tr>
<tr>
<td>2</td>
<td>All the blocks in the model must find the output of their time derivatives and place them in an array called DSTATE.</td>
</tr>
<tr>
<td>3</td>
<td>Since Elementary blocks are used in Fortran, mode 3 can be omitted.</td>
</tr>
<tr>
<td>4</td>
<td>The variables of subsequent models must be initialized at this stage.</td>
</tr>
<tr>
<td>5</td>
<td>The model data report is written</td>
</tr>
<tr>
<td>6</td>
<td>The output data recorded is written</td>
</tr>
<tr>
<td>7</td>
<td>Data check mode, this mode ensures that all the constants used in the model are within the acceptable limits.</td>
</tr>
<tr>
<td>8</td>
<td>Description mode, this mode provides description of ICONs and CONs when it is called</td>
</tr>
</tbody>
</table>
Chapter 3

STATCOM Modeling

The STATCOM representation described in this chapter is developed using ABB’s control logic. The Hybrid-STATCOM model is proposed in chapter 4.

3.1 Static Synchronous Compensator

3.1.1 STATCOM Overview

Static Synchronous Compensator (STATCOM) is a reactive power compensator that uses VSC to regulate the voltage using PWM at PCC. The benefits of STATCOM over SVC is the speed of operation and reduced footprint (physical size). The operations of VSC and PWM have been explained in section 2.2. Figure 3.1 shows a simple structure of STATCOM. The VSC branch is usually connected to the grid through a transformer that reduces the voltage on the power electronics components in the VSC. The DC voltage source of the VSC can be a capacitor or a battery. The reactive power exchange between the grid and the STATCOM depends on the voltage and phase angle of STATCOM AC-side. If voltage magnitude and phase angle are the same at VSC and PCC, there will be no exchange of reactive power. The voltages considered here are in (pu) since the VSC is connected to the PCC through a transformer. If the voltage magnitude at the VSC is raised, the current will start to flow from VSC to the grid. STATCOM will inject reactive power in the grid and raise the voltage at PCC. On the other hand, lowering the voltage magnitude at VSC will cause the current to flow from the grid towards VSC. STATCOM will consume reactive power and reduce the voltage at PCC. The DC side voltage in the VSC can be controlled by regulating the active power exchange between the grid and VSC. Active power exchange occurs when the VSC current and voltage at PCC are out of phase. Power electronics switching devices do not have the capability to store energy; hence, the capacitor is the only element that can
store or generate active power. The change in active power exchanged will
cause the voltage across the capacitor to change. Therefore, DC voltage can
be regulated by regulating the phase angle of VSC current with respect to
PCC voltage.

### 3.1.2 STATCOM Model

STATCOMs can be modeled as an ideal voltage source or current source.
Figure 3.2 shows the STATCOM as a voltage source. The voltage magnitude
$E_{sh}$ and angle $\gamma_{sh}$ can be controlled to inject or consume reactive power. The
current $I_{ST}$ is going through the reactance $X_{ST}$, which can be considered
as the transformer leakage reactance. In some literature, the losses in the
VSC is considered in the model by either adding a resistor in parallel with
the capacitor at the DC side, or by adding a resistance to $X_{ST}$ to make
it $R_{ST} + jX_{ST} = Z_{ST}$. For simplicity in calculations, assume losses are
negligible $X_{ST} >> R_{ST}$, hence, $Z_{ST} = X_{ST}$. The complex power transferred
from $bus_{PCC}$ to $bus_{sh}$ is calculated in equation 3.1.
Figure 3.2: Simple STATCOM model

\[
\vec{S}_{ST} = \vec{U}_{pcc}\vec{I}_{ST}^* \\
= \vec{U}_{pcc} - \vec{E}_{sh}^* \\
= \frac{U_{pcc}^2 - \vec{U}_{pcc}\vec{E}_{sh}^*}{Z_{ST}} \\
= jX_{ST} \\
= jB_{ST}(U_{pcc}^2 - U_{pcc}E_{sh}\angle(\theta - \gamma_{sh})) \\
= jB_{ST}[U_{pcc}^2 - U_{pcc}E_{sh}[\cos(\theta - \gamma_{sh}) + j\sin(\theta - \gamma_{sh})]] \\
\]

\[
\vec{S}_{ST} = b_{ST}U_{pcc}E_{sh}\sin(\theta - \gamma_{sh}) + jB_{ST}[U_{pcc}^2 - U_{pcc}E_{sh}\cos(\theta - \gamma_{sh})] \\
(3.1)
\]

And,

\[
P_{ST} = b_{ST}U_{pcc}E_{sh}\sin(\theta - \gamma_{sh}) \\
(3.2)
\]

\[
Q_{ST} = b_{ST}[U_{pcc}^2 - U_{pcc}E_{sh}\cos(\theta - \gamma_{sh})] \\
(3.3)
\]

From equation 3.2, it is clear that active power exchange can only occur when the voltage phase angles at \textit{bus}_{PCC} and \textit{bus}_{sh} are out of phase. Assuming the phase angle is kept constant at \(\theta = \gamma_{sh}\), then equations 3.2 and 3.3 becomes:

\[
P_{ST} = b_{ST}U_{pcc}E_{sh}\sin(\theta - \gamma_{sh}) = 0 \\
(3.4)
\]
Equation 3.6 shows that it is possible to represent STATCOM by a current source with the control signal as the voltage at the AC side of VSC. By regulating $E_{sh}$, the current $I_{ST}$ can flow from the VSC towards the grid ($Q_{ST}$ injection), or $I_{ST}$ can flow towards the VSC from the grid ($Q_{ST}$ consumption). The current source then can be limited by $-I_{cap}^{max} < I_{ST} < I_{ind}^{max}$. The $V-I$ characteristic of STATCOM is shown in figure 3.3. STATCOM have two operation regions, Capacitive and inductive. In the Capacitive region, the current $I_{ST}$ is leading the voltage at PCC, and the STATCOM injects reactive power into the system, which raises the voltage at PCC. On the other hand, in the Inductive region, the current $I_{ST}$ is lagging the voltage at PCC, and the STATCOM consumes reactive power from the system, which reduces the voltage at PCC. $I_{ST}$ will be limited by the rating of the STATCOM. The nominal operation point of STATCOM is at $U_{ref}$ when $I_{ST} = 0$. $I_{cap}^{max}$ and $I_{ind}^{max}$ represent the maximum capacitive and inductive currents at which STATCOM can regulate the current in a continues manner. STATCOM has the capability to provide $I_{cap}^{max}$ or $I_{ind}^{max}$ when the voltage is outside...
the linear region. This characteristic makes STATCOM superior to SVC in undervoltage events as mentioned in chapter 1. STATCOM has the same droop concept mentioned earlier in section 2.3.2. Capacitive slope $(X_C)$ and inductive slope $(X_I)$ can differ in value depending on the network operator.

### 3.1.3 Control

The dynamic model of STATCOM consists of different functions that can be split into control functions and protective functions. The control functions are responsible for regulating the output of the STATCOM. The protective functions have two main roles: The first role is to protect the system by applying undervoltage and overvoltage ride through strategies. The second role is to protect the power electronics devices in VSC by limiting the output. The following sections describe the objective and implementation of all STATCOM functions.

#### 3.1.3.1 STATCOM Control functions

The STATCOM control function developed in the PSS®E model are as follows:

##### 3.1.3.1.1 Automatic Voltage Regulator:

The voltage regulator loop is the most important logic block in the model. It uses a Proportional Integral (PI) regulator with the proportional gain as $K_{pv}$ and the integral gain as $K_{iv}$. The block takes the voltage error as input and tune $I_{VS C}$ to the desired value. The regulator has a non windup function that limits the output to $I_{VS C MAX}$ and $I_{VS C MIN}$. The dynamic model of the PI regulator is shown in figure 3.4. The lag block after the

![Figure 3.4: Voltage regulator in STATCOM](image)

voltage regulator block represents the delay of the STATCOM firing circuit with $T_0$ as time constant. The delay block with $T_s$ as time constant is used to add additional delay to model the firing circuit as well. The voltage error $V_{err}$ is calculated by subtracting the voltage at the regulated bus from
the reference voltage. The Lead-Lag block after $V_{bus}$ is representing the delay in voltage measurements. The reference voltage consists of four signals $S_{Vref}$, $V_{ref}$, $V_{POD_L}$ and $V_{slope}$. The main reference voltage is set by the STATCOM internal signal $V_{ref}$. The other three signals are outputs of the Power Oscillation Damping (POD), Slow MVAR and Droop functions. They are used to correct the reference voltage. $V_{max1}$ and $V_{min1}$ are limits for the reference voltage. In a real STATCOM, there is an inner control that regulates the current to the reference $I_{VSC}$. However, since PSS®E typically have time steps in the range 2-7 ms, it is not applicable to add the inner current control because in PSS®E the whole STATCOM is modeled as a current source. VSC outputs any current supplied by the model if it was within its limits.

3.1.3.1.2 Slow MVAR Control:

The slow MVAR function is a high operation function that regulates the voltage with the PI regulator. This function is slow compared to the PI regulator. Figure 3.5 shows the dynamic model of slow MVAR. The function allows the STATCOM to operate dynamically in the range $[V_{REFMIN}, V_{REFMAX}]$ and $[Q_{Prim} > Q_{REGMAX}]$ for capacitive operation, and the range $[Q_{Prim} < Q_{REGMIN}]$ for inductive operation. Slow MVAR will bring the voltage at PCC slowly below $V_{REFMAX}$ during capacitive operation and above $V_{REFMIN}$ during inductive operation. The small change in STATCOM output saves some capacitive or inductive MVAR for emergency operation. The difference between STATCOM MVAR output $Q_{Prim}$ and $Q_{REGMAX}$ (capacitive) or $Q_{REGMIN}$ (inductive) is passed to an integrator. To ensure the slow operation of this function, the integrator contains a large time constant $T_{IREG}$. The output of this function is $S_{Vref}$ which is added...
to the reference voltage. The maximum allowable change to the reference voltage is $DV_{IREGMIN}$ (capacitive) and $DV_{IREGMAX}$ (inductive).

### 3.1.3.1.3 Power Oscillation Damping (POD):

POD is a function used to damp active power oscillations in the system by regulating the STATCOM output. It takes the change of the system’s frequency or active power as input. The output signal is $V_{PODL}$ which is added to the STATCOM reference voltage. POD consists of a series of Lead-Lag and Washout filters as shown in figure 3.6. The time constants of these blocks must be tuned according to the system’s modes. $V_{PODL}$ is limited by $H_{LIM}$ and $L_{LIM}$. These limits are founded by multiplying $V_{PODMAX}$ and $V_{PODMIN}$, which are constants specified by the user, by the output of the ramp function. The ramp function is used to increase the POD limits gradually instead of using the full value of $V_{PODMAX}$ and $V_{PODMIN}$. The ramp function is useful in extreme events immediately after UV or OV strategies are switched off since POD might start acting during the switching off events. It helps in avoiding unnecessary damping in the system. Each time step, the ramp function output increases by $ramprate$, which is a constant specified by the user. Eventually, the output will reach 1 and the full range $[V_{PODMIN}, V_{PODMAX}]$ will be utilized. If UV or OV strategies are on, the $ramprate$ will be a large negative value (-1000), which forces the ramp function to output zero and disable POD since The limits...
will become zeros. POD is not allowed to operate during these events since it will create a conflict with UV and OV strategies.

3.1.3.1.4 Slope (droop) Control:

Is a gain block that multiplies the STATCOM output current $I_{VSC3}$ by the slope value $X_{SL}$. The output is $V_{slope}$ which is subtracted from the reference voltage. The slope function is shown in figure 3.7. The droop can have different values for inductive and capacitive modes of operation. $X_{SL}$ will have one value only during the controllable each region. For capacitive operation region, the applied slope is $X_C$. And for inductive operation region, the applied slope is $X_I$.

3.1.3.1.5 Gain Supervisor and Optimizer:

The gain supervisor regulates the integral gain used in the PI regulator. This function monitors the output of the regulator and reduces the gain if $I_{VSC}$ is oscillating. The gain will be reduced by 5% each time step until the peak-to-peak value in $I_{VSC}$ is below a specified value and the current is stabilized. The gain optimizer will monitor $I_{VSC}$ as well and resume the
integral gain to its original value used. The Gain Supervisor and Optimizer are shown in figure 3.8. Their outputs are fed directly to the PI-regulator.

3.1.3.1.6 External Bank Control (MSS):

MSS can be used as an external shunt reactors or capacitors. The MSC and MSR are usually connected to buses on the high voltage side of the transformer, close to PCC. MSS switching is controlled by the STATCOM controller. The MSS logic block monitors the STATCOM output current $I_{VSC3}$ and send a switching in/out signal to MSS. There are two switching methods applicable for both MSC and MSR. The first method is slow switching. Three parameters are used in this method $I_{High}^{slow}$, $I_{Low}^{slow}$ and $T_{Delay}^{slow}$. MSS is switched in if $I_{VSC3} > I_{High}^{slow}$ for $T_{Delay}^{slow}$. MSS is switched out if $I_{VSC3} < I_{Low}^{slow}$ for $T_{Delay}^{slow}$. The second method is fast switching. Three parameters are used in this method $I_{High}^{fast}$, $I_{Low}^{fast}$ and $T_{Delay}^{fast}$. MSS is switched in if $I_{VSC3} > I_{High}^{fast}$ for $T_{Delay}^{fast}$. MSS is switched out if $I_{VSC3} < I_{Low}^{fast}$ for $T_{Delay}^{fast}$. Fast switching is applied in extreme conditions. The relationship between the parameters used for fast and slow switching is:

$$I_{Low}^{fast} < I_{Low}^{slow} < I_{High}^{slow} < I_{High}^{fast}$$

$$T_{Delay}^{fast} < T_{Delay}^{slow}$$

The STATCOM controller prevents MSC and MSR from being switched in at the same time. For instance, if MSR was in and the current dropped below the MSC switching-in threshold, the controller will switch out MSR first and monitor the current. If the current is still below the MSC switching-in threshold, the controller will switch in MSC. This feature is important to prevent rapid switching between MSC and MSR. The delay for switching MSS in/out can be specified by the user. In reality, the switching delay is long in MSS, it takes a long time to be switched in or out.

![Figure 3.9: STATCOM MSS control](image-url)
3.1.3.2 STATCOM protective functions

The protective functions are developed to protect the STATCOM and the network. The STATCOM controller imposes limits on the output current and reactive power in addition to the voltage at the STATCOM bus. The limiters are tuned according to the equipment used in the STATCOM. For instance, the IGBTs can withstand a certain amount of current through them, the limiters should reduce the output current if a limit is violated for some specified time. Some protective functions such as thermal protection cannot be modeled accurately in PSS®E; hence, they will be dropped from the model. The network protection functions applied in the model are the overvoltage and undervoltage strategies.

3.1.3.2.1 Limiters:

STATCOM model used in this project contains 5 limiters as shown in figure 3.10. The limiters are either for capacitive or inductive mode of operation. The capacitive limiters control the maximum current limit on the PI regulator. The minimum output of the capacitive limiters will be passed to the PI regulator and will overwrite $I_{VSCMAX}$. The inductive limiters control the minimum current limit on the PI regulator. The maximum output of the inductive limiters will be passed to the PI regulator and will overwrite $I_{VSCMIN}$. The 5 limiters are:

1. Secondary Voltage Limiter:
The limiter monitors the voltage on the secondary side of the transformer $V_{2LV}$ and ensures that it doesn’t exceed $V_{2max}$ for a period longer than $T_{on1}$. The lag block with time constant $T_6$ represents a delay in voltage measurements. The error signal is passed to the integrator with time constant $T_7$, which controls the speed of integration (i.e. the speed of the limiter).

2. Capacitive Current Limiter:
The limiter monitors the current between STATCOM and the secondary side of the transformer $I_{1HV}$. It ensures that the current doesn’t exceed $I_{1maxC}$ for a period longer than $T_{on2}$. The lag block with time constant $T_8$ represents a delay in current measurements. The error signal is passed to the integrator with time constant $T_9$, which controls the speed of integration (i.e. the speed of the limiter).

3. Capacitive Reactive Power Limiter:
The limiter monitors the reactive power between STATCOM and the secondary side of the transformer $Q_{Prim}$ (STATCOM MVAR output). It ensures that the reactive power doesn’t exceed $Q_{1maxC}$ for a period longer than $T_{on3}$. The error signal is passed to the integrator with time
constant $T_{14}$, which controls the speed of integration (i.e. the speed of the limiter).

4. Inductive Current Limiter:
   The limiter monitors $I_{1HV}$ as well. It ensures that the current doesn’t exceed $I_{1min}$ for a period longer than $T_{on4}$. The lag block with time constant $T_{10}$ represents a delay in current measurements. The error signal is passed to the integrator with time constant $T_{11}$, which controls the speed of integration (i.e. the speed of the limiter).

5. Inductive Reactive Power Limiter:
   The limiter monitors $Q_{Prim}$ as well. It ensures that the reactive power doesn’t exceed $Q_{1min}$ for a period longer than $T_{on5}$. The error signal is passed to the integrator with time constant $T_{15}$, which controls the speed of integration (i.e. the speed of the limiter).
3.1.3.2.2 Undervoltage and Overvoltage Strategy:

The main purpose of Overvoltage (OV) and Undervoltage (UV) strategies are STATCOM and network protection. The OV and UV strategies output will override the PI regulator as shown in figure 3.11. OV and UV functions monitor the voltage at \( V_{bus} \). If a voltage limit was violated, the OV and UV function will switch the STATCOM output from the PI regulator to a constant value specified in the strategy. The OV and UV strategies are developed as follows:

1. **Overvoltage Strategy:**
   
   There are 2 voltage levels specified in the OV strategy \( OV_{threshold} \) and \( OV_{trip} \), where \( OV_{threshold} < OV_{trip} \). If \( V_{bus} \) is within the range \([OV_{threshold} \leq V_{bus} < OV_{trip}]\), the OV strategy will do the following:
   
   (a) **Full inductive:**
   
   The STATCOM output current will be at the maximum inductive current. If \( V_{bus} \) remained within \([OV_{threshold} \leq V_{bus} < OV_{trip}]\) for \( T_{OV\text{Block}} \), the strategy will switch to the next stage.
   
   (b) **Block:**
   
   The output current will be blocked to protect the equipment \((I_{VSC3} = 0)\). If \( V_{bus} \) remained within \([OV_{threshold} \leq V_{bus} < OV_{trip}]\) for \( T_{OV\text{Trip}} \), the strategy will switch to the next stage, where \( T_{OV\text{Block}} < T_{OV\text{Trip}} \).
   
   (c) **Trip:**
   
   The STATCOM will trip and it cannot be reconnected. The user should restart the simulation to use the STATCOM model.
2. Undervoltage Strategy:

The UV strategy is usually applied with severe undervoltage conditions which is caused by a fault. UV function is a voluntary strategy that is not required in all applications. Ideally, STATCOM should be able to support fully during undervoltage conditions. During a fault, the STATCOM will initially attempt to bring the voltage back to $V_{ref}$ by applying maximum capacitive current until UV strategy is applied. There are 2 voltage levels specified in the UV strategy $UV_{1Low}$ and $UV_{2Low}$, where $UV_{2Low} < UV_{1Low}$. UV strategy is applied as follows:

(a) Constant Value:
If $V_{bus}$ is within the range $[UV_{2Low} < V_{bus} \leq UV_{1Low}]$, STATCOM output current will be at a user-specified value $I_{UV1}$. The chosen value should be close to zero to prevent a voltage overshoot when the fault is cleared. STATCOM output will remain at $I_{UV1}$ until $V_{bus} > UV_{1Low}$.

(b) Block:
If $V_{bus} \leq UV_{2Low}$, the output current will be blocked to protect the equipment ($I_{VSC3} = 0$). STATCOM output will remain blocked until $V_{bus} > UV_{1Low}$. 

---

Figure 3.12: Overvoltage Strategy
Figure 3.13: Undervoltage Strategy
Chapter 4

Hybrid-STATCOM Modeling

The Development of the Hybrid-STATCOM model starts with STATCOM dynamic modeling, i.e. modeling of VSC branch. The dynamic model of STATCOM is described in section 3.1.3. This chapter describes the integration of TSR/TSC branches into the PSS®E STATCOM model with all the required functions and parameters.

4.1 VSC Branch Modeling

The developed STATCOM model will be modified slightly to control TSC and TSR branches. TSR and TSC could have their own dynamic models in PSS®E; however, this modeling configuration doesn’t work because it is necessary for all three branches to exchange control signals, and it is not possible to have an external controller. Therefore, TSC and TSR must be controlled from the STATCOM model.

4.2 TSC/TSR Branch Modeling

Thyristor valves cannot be modeled in PSS®E. Therefore, TSC and TSR are modeled as switched shunts in PSS®E. The parameter of a switched shunt that can be controlled in PSS®E is the susceptance. Hence, TSC and TSR are defined by their susceptance as $B_{TSC}$ and $B_{TSR}$ respectively. Figure 4.1 shows the hybrid-STATCOM configuration implemented in PSS®E. TSC and TSR branches are in parallel with the VSC branch. The VSC device contains the STATCOM dynamic model developed earlier. Modeling the Hybrid-STATCOM for load flow calculations can be realized by the models developed in chapter 2 for STATCOM and SVC as shown in figure 4.2. The VSC branch is modeled as an ideal current source. The TSC and TSR branches are modeled as controllable susceptance. Assuming no exchange of active power exists, hence, $\theta = \gamma_{sh}$. By modifying equation 3.6, the total
The output current of the Hybrid-STATCOM is calculated as follows:

\[ I_{Tot} = b_{ST} [U_{pcc} - E_{sh}] = I_{VSC} + I_{TSC} + I_{TSR} \]  \hspace{1cm} (4.1)

Where, \( I_{TSC} \) and \( I_{TSR} \) are calculated from equation 2.7 as follows:

\[ I_{TSC} = E_{sh} B_{TSC}(\alpha) \]  \hspace{1cm} (4.2)

\[ I_{TSR} = E_{sh} B_{TSR}(\alpha) \]  \hspace{1cm} (4.3)

Since the developed model is using switched shunts, \( \alpha \) can take two values only \( \alpha = 90 \) (full conduction) or \( \alpha = 180 \) (block). The V-I characteristics
of Hybrid-STATCOM is shown in figure 4.3. The controllable region for the VSC is the same as the STATCOM discussed in section 3.1.2. The additional part is the operational regions when TSC or TSR are switched-in for capacitive or inductive operation respectively. As shown in figure 4.3, TSC and TSR expands the operational region of VSC when it reaches $I_{\text{cap,max,VSC}}$ and $I_{\text{ind,max,VSC}}$. The exact switching method is discussed in section 4.4. The I-V characteristics of hybrid-STATCOM includes capacitive $X_c$ and inductive $X_i$ slopes as the case of STATCOM V-I plot.

4.3 Hybrid-STATCOM Regulator

Most of the functions developed in the STATCOM model will be used in the Hybrid. The main change in the model is the regulator. The currents from TSC ($I_{\text{TSC}}$) and TSR ($I_{\text{TSR}}$) branches are subtracted from the total output of the Hybrid STATCOM $I_{\text{Tot}}$ (voltage regulator output). VSC current $I_{\text{VSC}}$ is the output required from the VSC branch in order to achieve $I_{\text{Tot}}$, and counteract the injection of $I_{\text{TSC}}$ or $I_{\text{TSR}}$. When TSC and TSR are off, $I_{\text{VSC}} = I_{\text{Tot}}$. The currents are calculated as follows:

$$I_{\text{TSC}} = (V_{2LV})(B_{\text{TSC}})(TSC_{\text{sig}}) \quad \text{where } TSC_{\text{sig}} = \{0, 1\} \quad (4.4)$$

$$I_{\text{TSR}} = (V_{2LV})(B_{\text{TSR}})(TSR_{\text{sig}}) \quad \text{where } TSR_{\text{sig}} = \{0, 1\} \quad (4.5)$$

$$I_{\text{VSC}} = I_{\text{Tot}} - I_{\text{TSC}} - I_{\text{TSR}} \quad (4.6)$$

Figure 4.4 shows the Hybrid-STATCOM regulator model. The voltage regulator limits are extended to include the maximum TSC current ($I_{\text{TSCmax}}$)
in capacitive operation and maximum ($I_{TSR_{\text{max}}}$) in inductive operation. $TSC_{\text{sig}}$ and $TSR_{\text{sig}}$ are integer values used to determine whether to include $I_{TSC}$ and $I_{TSR}$ in the calculations. $TSC_{\text{sig}}$ and $TSR_{\text{sig}}$ can be either 0 or 1. $V_{2LV}$ is the voltage on the secondary-side of the transformer. $B_{TSC}$ and $B_{TSR}$ are constants defined by the user in the PSS®E network. The VSC ensures that it switches at the same moment as TSC or TSR switch to avoid voltage overshoot.

### 4.4 Hybrid-STATCOM Switching

The functions used to switch in/out MSS can be modified and used for TSC and TSR switching. But there is only fast switching in TSC and TSR. The

![Figure 4.5: Hybrid-STATCOM switching methodology](image)

(a) TSC switching in

(b) TSC switching out
switching functions uses 4 constants (CONs) defined by the user $I_{TSC}^{\text{switch in}}$, $I_{TSR}^{\text{switch in}}$, $I_{TSC}^{\text{switch out}}$ and $I_{TSR}^{\text{switch out}}$. These constants are determined by the user. They are VSC current values in pu used to determine TSC and TSR switching. As shown in figure 4.5a, When $I_{VSC}$ exceeds $I_{TSC}^{\text{switch in}}$, TSC will be switched in. $I_{VSC}$ counteracts $I_{TSC}$ to maintain $I_{Tot}$ constant during TSC switching in state. TSC is switched out when $I_{VSC}$ is smaller than $I_{TSC}^{\text{switch out}}$ as shown in figure 4.5b. $I_{VSC}$ counteracts $I_{TSC}$ to maintain $I_{Tot}$ constant during TSC switching out state. The switching function prevents TSC and TSR from being switched in at the same time. If an OV event occurred while TSC is switched in, the controller will switch out TSC first and monitor the voltage. If the voltage remained high, TSR will be switched.

Figure 4.6: TSC and TSR switching function
in. The same logic applies for inductive mode of operation. The switching mechanism is shown in figure 4.6.

4.5 OV and UV Strategies with Hybrid-STATCOM

The OV and UV strategies must be modified to account for TSC and TSR switching. The VSC controller should regulate the TSC/TSR switching and VSC output according to the disturbance in order to avoid constant switching.

4.5.1 UV strategy in Hybrid STATCOM

UV strategy will go full capacitive at the beginning (TSC+VSC). Then VSC will be forced to a certain value and TSC will be blocked to avoid overshoot when clearing. The last step is to block VSC as well to avoid misfiring if the voltage is still below the UV threshold. Figure 4.7 shows the UV Strategy in Hybrid-STATCOM.

![Figure 4.7: Undervoltage strategy in Hybrid-STATCOM](image)
4.5.2 OV strategy in Hybrid STATCOM

The OV strategy will go full inductive at the beginning (TSR+VSC), then it will block after a certain period (only VSC blocked) to protect the VSC since the power electronics switching devices (IGBTs or IGCTs) might not be able to handle the stress of the high voltage. If the voltage is still above the OV threshold for a certain time, Hybrid-STATCOM will trip. Figure 4.8 shows the OV Strategy in Hybrid-STATCOM.

4.6 Limiters with Hybrid-STATCOM

The limiters functions are modeled in the same way as in STATCOM. The main difference is the the limits on the PI regulator. The limits now consist of $I_{\text{VSC}}^{\text{max}} + I_{\text{TSC}}^{\text{max}}$ and $I_{\text{VSC}}^{\text{min}} + I_{\text{TSC}}^{\text{max}}$. All four signals are variables that must be updated in every time step. The limiters should be acting on VSC current only, but it appears that they are acting on the total current required by TSC/TSR and VSC. However, since TSC and TSR currents are subtracted
from the total and their limits are being updated continuously, the limiters will actually only be applied on VSC. Figure 4.9 shows the limiters in hybrid-STATCOM model.

4.7 Slope with Hybrid-STATCOM

The slope functionality was explained in section 3.1.3.1.4. The main difference between the slope function in STATCOM and hybrid-STATCOM is the input current. STATCOM uses the VSC output $I_{VSC3}$. Hybrid-STATCOM uses the total output current $I_{Tot}$ as an input for the function. Slope is a gain block that multiplies the hybrid-STATCOM output current $I_{Tot}$ by the slope value $X_{SL}$. The output is $V_{slope}$ which is subtracted from the reference voltage. The slope function is shown in figure 4.10.

The droop can have different values for inductive and capacitive modes of
operation. $X_{SL}$ will have one value only during the controllable each region. For capacitive operation region, the applied slope is $X_C$. And for inductive operation region, the applied slope is $X_I$. 

Figure 4.10: Hybrid-STATCOM Slope function
Chapter 5

Model Verification

In this section the developed STATCOM and Hybrid-STATCOM models are verified. The functions of the models are tested first with different events and models parameter. STATCOM model is also verified against WECC STATCOM model and PSCAD model. Hybrid-STATCOM model is verified against a PSACAD model only.

5.1 STATCOM model

The STATCOM model developed in chapter 3 is verified in this section. In this chapter, the current and reactive power from STATCOM to the grid (capacitive operation) is considered as positive values. The current and reactive power from the grid to STATCOM (inductive operation) is considered as negative values. The test system used in the model verification is shown in

![Test System used for STATCOM model verification](image)

Figure 5.1: Test System used for STATCOM model verification

A network Thevenin equivalent is used to represent the grid. MSS
are connected directly to PCC to test the MSC/MSR switching function. The VSC is connected to the grid through a step-down transformer.

5.1.1 STATCOM Functions Test

All the functions mentioned in section 3.1.3 will be tested. Each STATCOM function is tested separately. The list of STATCOM functions tests are as follows:

5.1.1.1 Automatic Voltage Regulator:

The voltage regulator is tested by applying several steps to the voltage reference and monitoring the voltage and VSC output current. As shown in figure 5.2.(a), the voltage at the PCC follows the change in $V_{ref}$ accurately.

![Figure 5.2: Voltage regulator test for STATCOM model in PSS®E](image)

Figure 5.2: Voltage regulator test for STATCOM model in PSS®E
The VSC output in figures 5.2.(b) and 5.2.(c) shows the current and reactive power output respectively. It corresponds to the required change in VSC output by the voltage regulator.

5.1.1.2 Slow MVAR Control:

Slow MVAR function is tested by applying a voltage change at PCC bus. The voltage change is applied by connecting a shunt capacitor to raise the voltage, and a shunt reactor to reduce the voltage at PCC. The monitored signal is the change in reference voltage applied by slow MVAR. The shunt capacitor is connected at 0.1 sec and disconnected at 0.6 sec. The voltage at PCC is raised and STATCOM operational point changed as shown in figure 5.3.(a). It can be seen that the voltage is raised above $V_{ref}$ in inductive operation. The shunt reactor is connected at 1.3 sec and disconnected at
1.5 sec. The voltage at PCC is reduced and STATCOM operational point changed. It can be seen that the voltage is reduced below $V_{ref}$ in capacitive operation. The slight change allows the STATCOM to operate dynamically. The VSC output in figures 5.3.(b) and 5.3.(c) shows the current and reactive power output respectively. Figure 5.3.(d) shows $V_{ref}$ and $V_{refL}$, which is the new voltage reference signal after being modified by the slow MVAR function. The voltage at PCC follows the new signal $V_{refL}$. The time constant used in Slow MVAR is slow but in order to test the function, a fast one is used.

5.1.1.3 Slope (droop) Control:

The slope test is the same as voltage regulator test but with adding two different slopes for inductive and capacitive operation. The slope values

![Slope Test](image)

Figure 5.4: Slope test for STATCOM model in PSS®E
used are $X_i = %.6$ and $X_c = %.2$. Monitor signals are VSC output and voltage at PCC. As shown in figure 5.4.(a), the voltage at the PCC follows the change in $V_{ref}$ accurately with the addition of a slope. The voltage doesn’t reach the required $V_{ref}$ in capacitive and inductive operation due to the addition of a slope. It can be seen from figure 5.4.(a) that two different slope values are used for capacitive and inductive operation. The VSC output in figures 5.4.(b) and 5.4.(c) shows the current and reactive power output respectively. It corresponds to the required change in VSC output by the voltage regulator.

5.1.1.4 Gain Supervisor:

Gain Supervisor test is done by applying two large changes to the reference voltage with raising the integral gain in the voltage regulator to a very large value. The first change in $V_{ref}$ is done with the gain supervision function.

![Gain Supervision Test](image)

Figure 5.5: Gain Supervisor test for STATCOM model in PSS®E
turned off. The second change in $V_{ref}$ is done with the gain supervision function turned on. Signals to be monitored are VSC output, voltage at PCC and gain supervision factor. As shown in figure 5.5.(a), the voltage at the PCC follows the change in $V_{ref}$. Since the gain in the voltage regulator is raised to a very large value, the voltage at PCC is oscillating as seen in figure 5.5.(a). The oscillation triggers the gain supervision function and it starts acting as shown in the second part of figure 5.5.(d). Gain reduction reduces the signal’s settling time. The VSC output in figures 5.5.(b) and 5.5.(c) shows the current and reactive power output respectively.

5.1.1.5 Mechanically Switched Capacitor (MSC):

MSC test is done by raising $V_{ref}$. The signals to be monitored are VSC output, voltage at PCC and MSC reactive power output. As shown in

![MSC Switching Test](image)

Figure 5.6: MSC test for STATCOM model in PSS®E
figure 5.6.(a), the voltage at the PCC follows the change in $V_{ref}$. As soon as
the current reaches the switching threshold, MSC is turned on. The MSC
used in the test consists of 4 shunt capacitors. The MSC switching function
turns the shunt capacitors in steps to avoid constant switching of breakers.
The STATCOM used in the test can raise the voltage at PCC to 1.05 pu
only. However, with the aid of MSC, the voltage is raised to a value close
to 1.09 pu as shown in figure 5.6.(a). The VSC output in figures 5.6.(b)
and 5.6.(c) shows the current and reactive power output respectively. $V_{ref}$
is changed back to 1.0 pu and VSC current starts increasing. The current
reaches the switching out threshold, and MSC will start turning off in steps.

5.1.1.6 Mechanically Switched Reactor (MSR):

MSR test is done by reducing $V_{ref}$. The signals to be monitored are VSC
output, voltage at PCC and MSR reactive power output. As shown in figure

![MSR Switching Test](image)

Figure 5.7: MSR test for STATCOM model in PSS®E
5.7. (a), the voltage at the PCC follows the change in $V_{ref}$. As soon as the current reaches the switching threshold, MSR is turned on. The MSR used in the test consists of 4 shunt reactors. The MSR switching function turns the shunt reactors in steps to avoid constant switching of breakers. The STATCOM used in the test can lower the voltage at PCC to 0.95 pu only. However, with the aid of MSR, the voltage is lowered to a value close to 0.91 pu as shown in figure 5.7. (a). The VSC output in figures 5.7. (b) and 5.7. (c) shows the current and reactive power output respectively. $V_{ref}$ is changed back to 1.0 pu and VSC current starts decreasing. The current reaches the switching out threshold, and MSR will start turning off in steps.

5.1.1.7 Limiters:

The Limiters are tested by raising or reducing $V_{ref}$. High $V_{ref}$ value tests

![figure 5.8](image-url)  
Figure 5.8: Limiters test for STATCOM model in PSS®E
the capacitive limiters, and low $V_{ref}$ tests inductive limiters. The limiters are turned on at different times to clarify the behavior of each limiter. The signals to be monitored are VSC output, voltage at PCC and the limits of the voltage regulator. As shown in figure 5.8.(a), the voltage at the PCC follows the change in $V_{ref}$, but the limiters function forces the STATCOM output to a certain value defined by the user. The windup limits at the voltage regulator are shown in figure 5.8.(d). The limiters change these limits to restrict the output of VSC. The capacitive limiters are acting between 0.5 sec and 1.5 sec, and the inductive limiters are acting between 1.7 sec and 2.1 sec. Each limiter has an on and off delays. The secondary voltage limiter and capacitive current limiter were turned off before 1.45 sec, but the reactive power limiter was still acting. At 1.45 sec, the capacitive reactive power limiter was turned off since the reactive power output was not violating the limit anymore. At the turning off moment, the difference between $V_{PCC}$ and $V_{ref}$ was high. The current was not limited anymore, and it jumped back to its maximum capacitive output. All the delays can be modified by the user. The VSC output in figures 5.8.(b) and 5.8.(c) shows the current and reactive power output respectively.

5.1.1.8 Overvoltage Strategy:

Overvoltage test is done by connecting a shunt capacitor to PCC bus. The sudden high voltage will trigger the OV strategy. The signals to be monitored are VSC output, voltage at PCC and the limits of the voltage regulator. As shown in figure 5.9.(a), the voltage is raised above the OV threshold. STATCOM output shown in figures 5.9.(b) and 5.9.(c) become fully inductive. The windup limits at the voltage regulator are shown in figure 5.9.(d). The limiters change these limits to restrict the output of VSC. The OV strategy change the windup limits at the voltage regulator to be full inductive (-1.0 pu). The OV strategy blocks STATCOM output after a certain time to avoid an overshoot. The output is blocked at the time 0.3 Sec. If the voltage remained high for a predefined time after STATCOM block, OV strategy trips the STATCOM to protect the equipment as shown in figures 5.9.(b), 5.9.(c) and figures 5.9.(d). All STATCOM variables will become zeros when it trips at 0.3 sec.
5.1.1.9 Undervoltage Strategy:

Undervoltage test is done by applying a fault at PCC bus. The sudden change in voltage will trigger the UV strategy. The signals to be monitored are VSC output, voltage at PCC and the limits of the voltage regulator. As shown in figure 5.10.(a), the voltage has dropped below the UV threshold (0.3 pu). STATCOM output shown in figures 5.10.(b) and 5.10.(c) become fully capacitive. The UV strategy change the windup limits at the voltage regulator as shown in figure 5.10.(d). STATCOM output usually is kept at full capacitive for a longer time, but for the purpose of testing, the output is changed to a predefined value in a fast manner. The UV strategy change the STATCOM output current after a certain time to avoid an overshoot. The value chosen here is 0.6 pu as shown in figure 5.10.(d). STATCOM will continue injecting 0.6 pu until fault clearance as shown in figures 5.10.(b)
Figure 5.10: Undervoltage test for STATCOM model in PSS®E and 5.10.(c). The STATCOM resumes normal operation after fault clearance with a small delay defined by the user.

5.1.2 Comparison between STATCOM Model and WECC Model

Comparing the developed STATCOM model to the WECC model to observe the difference in performance. A common test that can be used in both models is the regulator test with slope. Another function that can be tested is MSC switching. All the other main functions are modeled differently. Hence, it is irrelevant to compare them. For instance, UV/OV strategies and Slow MVAR functions exist in both models, but they use different parameters in each model. The functions used to compare the models are:
5.1.2.1 Automatic Voltage Regulator:

The voltage regulator and the slope tests are equivalent to the ones done earlier. They are performed by applying different \( V_{\text{ref}} \) values. Figures 5.11 and 5.12 show the regulator and slope test respectively. It can be observed that the response of both models to the changes in \( V_{\text{ref}} \) are equivalent. Thus, the regulator and slope functions in the developed STATCOM model are performing as expected.

![ABB STATCOM Model and WECC Model Regulator Test](image)

Figure 5.11: Comparing Regulator function between STATCOM model and WECC model
5.1.2.2 Mechanically Switched Capacitor (MSC):

MSC test is done by raising $V_{ref}$. The signals to be monitored are VSC output, voltage at PCC and MSC reactive power output. As shown in figure 5.13.(a), the voltage at the PCC follows the change in $V_{ref}$ for both models. The current switching threshold is the same in both models. As soon as the current reaches the switching threshold, MSC is turned on. The output current and switching times are equivalent as shown in figures 5.13 (a), (b) and (c). Thus, the MSC switching function in the developed STATCOM model is valid.
Figure 5.13: Comparing MSC switching function between STATCOM model and WECC model

5.1.3 Comparison between STATCOM Model and PSCAD Model

The developed STATCOM model is verified against the PSCAD model in this section. As mentioned earlier, the PSCAD STATCOM model is using the real controller installed in ABB STATCOMSs. Therefore, it is important to validate the PSS®E model by comparing it to the PSCAD one. Some functions are not tested in PSCAD because they are being updated. The STATCOM functions tested are the following:
5.1.3.1 Automatic Voltage Regulator:

The regulator test is equivalent to the one done earlier with $V_{ref}$ altered as shown in figure 5.14 (a). The current and reactive power outputs are equivalent for both models as shown in figures 5.14 (b) and (c). There is a small delay in the output of the PSCAD model, which could be the result of a slight difference in the network or transformer parameters.

![Graph showing Voltage (pu) vs Time [s] comparison between PSSE STATCOM Model and PSCAD Model Regulator Test](a)

![Graph showing Current (pu) vs Time [s] comparison between PSSE STATCOM Model and PSCAD Model Regulator Test](b)

![Graph showing Q (MVAr) vs Time [s] comparison between PSSE STATCOM Model and PSCAD Model Regulator Test](c)

Figure 5.14: Regulator with a slope test for PSS®E and PSCAD models

5.1.3.2 Limiters:

In order to clarify the functionality of each limiter, the limiters test is split into three separate tests. The first test is the secondary side voltage limiter test shown in figure 5.15. As in the previous limiters test, the function is tested by changing $V_{ref}$. The secondary side voltage limiter acts in the capacitive region only. The function parameters used in PSS®E and PSCAD

62
models are equivalent. Figure 5.15 shows that the limiter function in both models are behaving similarly. The second test is intended for the current

![Graphs showing voltage, current, and reactive power with time](image)

Figure 5.15: Secondary side voltage limiter test for PSS®E and PSCAD models

The function is tested by changing $V_{\text{ref}}$ as shown in figure 5.16. The capacitive and inductive regions have separate limiter functions. Both limiters are acting perfectly in the PSS®E model by matching the PSCAD model output. The third test is intended for the reactive power limiter test. The function is tested by changing $V_{\text{ref}}$ as shown in figure 5.17. The capacitive and inductive regions have separate limiter functions. There is a small difference between the PSS®E model output and PSCAD model output, especially in the reactive power output. The difference could be caused by a harmonics filter used in the PSCAD model. The filter value is not included anywhere in the PSS®E model.
Figure 5.16: Current limiter test for PSS®E and PSCAD models
5.1.3.3 Undervoltage Strategy:

The UV strategy is tested by applying a fault at 0.3 sec for a duration of 0.1 sec. The fault used in the simulation is a balanced 3-phase to ground fault. As shown figure 5.18, the voltage at PCC drops at 0.3 sec. The VSC in both models goes to full capacitive mode. The UV strategy in both models is turned on after 40ms. The VSC is set to 0 pu to avoid overshoot when clearing. The PSS®E model output is stable with no oscillation since the VSC is modeled as a controllable current source. The output of the current source can be exactly as specified by the model even in extreme events. On the other hand, the PSCAD model contains a lot of components that could cause oscillations or instability especially in extreme events. Hence, it is very hard to get a matching output from both models during UV events. But it can be seen that the outputs are close with a slight delay in the
PSCAD output. The voltage in PSCAD is slower to return to 1.0 pu after fault clearance because the PSCAD model is an EMT based software. The 3-phases are cleared separately unlike PSS®E, which is instantaneous and based on RMS values.

![Figure 5.18: Undervoltage Strategy test for PSS®E and PSCAD models](image)

5.2 Hybrid-STATCOM Model Verification

The Hybrid-STATCOM model developed in chapter 4 is verified in the following sections. First the Hybrid-STATCOM functions are tested and verified in PSS®E. Then, the PSS®E model will be verified against an equivalent model in PSCAD.
5.2.1 Hybrid-STATCOM Functions Test

The main model developed for STATCOM is used in the development of Hybrid-STATCOM. In this section, the modified functions only will be verified. The test system used in Hybrid-STATCOM model verification is shown in figure 5.19. A network Thevenin equivalent is used to represent the grid.

![Test System used for Hybrid-STATCOM model verification](image)

MSS are connected directly to PCC to test the MSC/MSR switching function. The VSC is connected to the grid through a step-down transformer in parallel with TSC and TSR branches. The following functions were tested in the Hybrid-STATCOM model:

### 5.2.1.1 Thyristor Switched Capacitor (TSC):

TSC switching test is done by raising $V_{ref}$. The signals to be monitored are VSC and TSC outputs, and the voltage at PCC. As shown in figure 5.20.(a), the voltage at the PCC follows the change in $V_{ref}$. As soon as the current reaches the switching in threshold (1.5 pu), TSC is turned on. At the switching in instance the VSC will counteract TSC current by consuming the same amount of current injected by the TSC. A small notch in PCC voltage is visible at the switching instance, which is caused by a small difference between TSC output current and VSC consumed current. The same switching method is applied when $V_{ref}$ is changed back to 1 pu. The current reaches the switching out threshold (-0.8 pu), and TSC is turned...
At the switching out instance the VSC will inject the same amount of current injected by the TSC before switching out to keep $I_{Tot}$ constant. The STATCOM used in the test can raise the voltage at PCC to 1.05 pu only. However, with the aid of TSC, the voltage is raised to a value close to 1.09 pu as shown in figure 5.20.(a). The VSC and TSC outputs in figures 5.20.(b) and 5.20.(c) shows the current and reactive power output respectively.

### 5.2.1.2 Thyristor Switched Reactor (TSR):

TSR test is done by reducing $V_{ref}$. The signals to be monitored are VSC and TSC outputs, and the voltage at PCC. As shown in figure 5.21.(a), the voltage at the PCC follows the change in $V_{ref}$. As soon as the current reaches the switching in threshold (-1.5 pu), TSR is turned on. At the switching in instance, VSC will inject the same amount of current consumed by the
TSR. A small notch in PCC voltage is visible at the switching in instance, which is caused by a small difference between TSR consumed current and VSC injected current. The same switching method is applied when \( V_{\text{ref}} \) is changed back to 1 pu. The current reaches the switching out threshold (-0.8 pu), and TSR is turned off. At the switching out instance the VSC will consume the same amount of current consumed by the TSR before switching out to keep \( I_{\text{Tot}} \) constant. The STATCOM used in the test can reduce the voltage at PCC to 0.95 pu only. However, with the aid of TSR, the voltage is reduced to a value close to 0.93 pu as shown in figure 5.21.(a). The VSC and TSR outputs in figures 5.21.(b) and 5.21.(c) shows the current and reactive power output respectively.
5.2.1.3 Limiters:

The Limiters are tested by raising or reducing $V_{ref}$. High $V_{ref}$ value tests the capacitive limiters, and low $V_{ref}$ tests inductive limiters. The limiters are turned on at different times to clarify the behavior of each limiter. The limiters functions are applied on the VSC output only. TSC and TSR output are not affected by the limiters functions. However, if the VSC current was limited to the point of TSC or TSR switching threshold it could cause them to switch out. The signals to be monitored are VSC output, voltage at PCC and the limits of the voltage regulator. As shown in figure 5.22.(a), the voltage at the PCC follows the change in $V_{ref}$, but the limiters function forces the VSC output to a certain value defined by the user. The limiters change the windup limits at the voltage regulator as shown in figure 5.22.(d). Figures 5.22.(b) and 5.22.(c) shows the current and reactive power outputs.
respectively. It can be seen from figures 5.22.(b) and 5.22.(c) that TSC and TSR outputs remained constant during capacitive and inductive operations respectively.

5.2.1.4 Overvoltage Strategy:

Overvoltage test is done by connecting a shunt capacitor to PCC bus. The sudden high voltage will trigger the OV strategy. The signals to be monitored are VSC output, voltage at PCC and the limits of the voltage regulator. As shown in figure 5.23.(a), the voltage is raised above the OV threshold. VSC output shown in figures 5.23.(b) and 5.23.(c) become fully inductive and TSR is switched on. The OV strategy change the windup limits at the voltage regulator as shown in figure 5.23.(d) to control VSC output. The OV strategy forces the VSC output to a settable value after a
certain time to avoid an overshoot. The output is changed to 0.0 pu (Block) at the time 0.3 Sec. If the voltage remained high for a predefined time after the VSC output change, OV strategy trips the STATCOM to protect the equipment as shown in figures 5.23.(b), 5.23.(c) and figures 5.23.(d). TSR remained on until VSC is tripped.

5.2.1.5 Undervoltage Strategy:

Undervoltage test is done by applying a fault at PCC bus. The sudden change in voltage will trigger the UV strategy. The signals to be monitored are VSC output, voltage at PCC and the limits of the voltage regulator. As shown in figure 5.24.(a), the voltage has dropped below the UV threshold. Hybrid-STATCOM output shown in figures 5.24.(b) and 5.24.(c) become fully capacitive with TSC switched on. The UV strategy change the windup limits at the voltage regulator as shown in figure 5.24.(d). STATCOM out-

![Undervoltage Strategy Test](image-url)
put usually is kept at full capacitive for a longer time, but for the purpose of testing, the output is changed to a predefined value in a fast manner. The UV strategy change the VSC output current after a certain time to avoid an overshoot. TSC is blocked when UV strategy starts operating. The value chosen here is 0.3 pu as shown in figure 5.24.(d). VSC output is blocked after a certain time to protect the equipment if the fault was not cleared in a predefined time. Hybrid-STATCOM resumes normal operation after fault clearance with a small delay as shown in figures 5.24.(b), 5.24.(c) and figures 5.24.(d).

5.2.2 Comparison between Hybrid-STATCOM Model and PSCAD Model

In this section, the developed Hybrid-STATCOM model is compared to the PSCAD model. Since most of the functions modeled in STATCOM and Hybrid-STATCOM are equivalent, the main function to be tested against PSCAD model is TSC/TSR switching. The power system used in this test is different than all the previous tests. The network, transformer and STATCOM parameters are changed. However, the network configuration is equivalent to the one shown in figure 5.1. Only TSC switching is used in the comparison between the PSS®E and PSCAD models since TSC and TSR switching methodologies are equivalent.

5.2.2.1 Thyristor Switched Capacitor (TSC):

TSC switching test is done by raising \(V_{ref}\). The signals to be monitored in PSS®E and PSCAD simulations are the primary and secondary voltages, \(I_{VSC}\) and reactive power outputs of VSC and TSC. The hybrid-STATCOM used contains a TSC+VSC. The capacity of TSC is roughly 1.5 the capacity of VSC. The secondary currents are not shown since they should be identical to the primary side currents in pu as there is no path for the secondary currents to go through except the transformer. As shown in figure 5.25.(a) and (b), the primary and secondary voltages follow the change in \(V_{ref}\) respectively. The secondary side voltage is different in PSS®E and PSCAD since TSC switching is done differently. PSCAD switches TSC in 3 stages with some delays while PSS®E does it in one large step. As such VSC will counter only parts of TSC in 3 stages, while in PSS®E, VSC will counter one large Mvar step. Since the reactive power provided by TSC is proportional to \(V_{sec}^2\), TSC will provide more reactive power in PSS®E initially because it is switched in one large step. As a result, \(V_{sec}\) is higher in PSS®E than PSCAD. The secondary side voltage limiter is acting in PSS®E to bring the voltage down to the PSCAD level. \(I_{VSC}\) is plotted in figure 5.25.(c). As soon as the current reaches the switching threshold, TSC is turned on. At the switching instance the VSC will counteract TSC current by consuming
Figure 5.25: TSC switching test for PSS®E and PSCAD models
the same amount of current injected by the TSC. This behavior is clear in PSS®E output more than PSCAD. The reason for this difference in $I_{VSC}$ is explained in section 6.3. A small notch in PCC voltage is visible at the switching instance, which is caused by a small difference between TSC output current and VSC consumed current. The same switching method is applied when $V_{ref}$ is changed back to 1 pu. The reactive power outputs of VSC and TSC are plotted in figure 5.25.(d).
Chapter 6

Discussion

6.1 Performance of the Hybrid-STATCOM Model

The main issue solved in this project is TSC/TSR switching. Section 1.2 demonstrates the problem of using MSC with STATCOM as an equivalent model to Hybrid-STATCOM. The missing feed-forward loop causes a

![Graph of voltage comparison](image)

![Graph of current comparison](image)

![Graph of reactive power comparison](image)

Figure 6.1: Comparison between Hybrid-STATCOM and STATCOM+MSC with a step in $V_{ref}$
voltage overshoot which doesn’t actually exist in Hybrid-STATCOM solutions as indicated in chapter 5. Figures 6.1 and 6.2 shows the difference in performance between Hybrid-STATCOM switching and STATCOM+MSC switching. As mentioned in section 1.2, STATCOM is used with MSC to mimic the behavior of hybrid-STATCOM. The comparison is done using an MSC switched in with 2ms delay compared to the developed Hybrid-STATCOM model’s switching. The signals indicated by STATCOM are the output of the STATCOM + MSC. Where as the signals indicated by Hybrid are the output of the Hybrid-STATCOM model. As the figures show,

![Figure 6.2: Comparison between Hybrid-STATCOM and STATCOM+MSC with a step in Vref (Total currents and Q)](image)

TSC switching would not cause a voltage overshoot at PCC as in the case of MSC switching. VSC output in Hybrid-STATCOM adjust to the TSC switching-in before it occurs. The injected current and reactive power by MSC is not shown in the figures. But the switching time is clear from the voltage overshoot at 0.12 sec. All the other functions in both models are important to perform a complete network study. The performance of these functions are shown in chapter 5.
6.2 Hybrid-STATCOM Switching issues

TSC and TSR switching depends on the parameters provided by the user in the Hybrid-STATCOM model. There are some requirements for TSC/TSR switching values and capacities with respect to the capacity of VSC. The following two issues must be taken under considerations when using the hybrid-STATCOM model.

6.2.1 TSC/TSR capacities with respect to VSC capacity

In order for the hybrid-STATCOM to function properly, VSC capacity must be more than 50% of the capacity of TSC and TSR. The VSC must be able to compensate for TSC/TSR switching completely. Figure 6.3 shows the capacity issue. The case is shown for TSC and VSC only, but the same concept applies for TSR. VSC must be at least half the capacity of TSC.

![Diagram showing the importance of choosing proper TSC and VSC capacities for correct switching behavior]

Figure 6.3: The importance of chosen the proper TSC and VSC capacities for correct switching behavior

to compensate for TSC/TSR switching completely. Figure 6.3 shows the capacity issue. The case is shown for TSC and VSC only, but the same concept applies for TSR. VSC must be at least half the capacity of the TSC in order to counteract the switching of TSC. The total output current of the hybrid-STATCOM must remain constant before and after the switching. In the transition state, TSC will be at full capacitive current and VSC will be close to its maximum inductive current. The total output current will remain constant only if

\[ I_{\text{max}}^{\text{VSC}_{\text{cap}}} - I_{\text{max}}^{\text{VSC}_{\text{ind}}} = I_{\text{max}}^{\text{TSC}} \]

(in the case where VSC is roughly 50% the capacity of TSC). Since the operational region of STATCOM is symmetrical, VSC must be at least half the capacity of TSC.
6.2.2 TSC/TSR switching parameters

When both TSC and TSR branches exist in a hybrid-STATCOM, the capacity of VSC must be larger than 50% of TSC and TSR to allow for correct switching and to avoid hunting, which is a constant switching of TSC and TSR. Figure 6.4 explains the concept. Four parameters are important for

![Figure 6.4: The importance of chosen the correct switching parameters for TSC and TSR](image)

TSC and TSR switching $I_{in}^{TSC}$, $I_{out}^{TSC}$, $I_{in}^{TSR}$, and $I_{out}^{TSR}$. $I_{in}^{TSC}$ and $I_{out}^{TSC}$ must not overlap, the same case is important for $I_{in}^{TSR}$ and $I_{out}^{TSR}$. Also, the following two equation must be valid for a proper switching:

$$I_{in}^{TSC} - I_{out}^{TSC} > I_{\text{max}}^{TSC}$$

$$I_{in}^{TSR} - I_{out}^{TSR} > I_{\text{max}}^{TSR}$$

If these two equation were not satisfied, Hybrid STATCOM might get into hunting state, which is a state where the TSC or TSR will frequently switch in and out because $I_{VSC}$ is alternating between the ON and OFF thresholds of TSC, TSR or both. Therefore, choosing the correct switching parameters are crucial.

6.2.3 Operating in the region between switching on/off

This is a special issue, it occurs when TSC or TSR are switched on and $I_{VSC}$ reaches the required voltage by $V_{ref}$ without crossing the switching off threshold. Figure 6.5 shows a case where this issue occurs. The TSC is switched on but never switched off. VSC is operating in the inductive mode and compensating for the voltage increase caused by TSC. The voltage at PCC reached $V_{ref}$, and VSC will not consume more reactive power. Consequently, TSC will continue operating since $I_{VSC}$ didn’t reach the switch off
Figure 6.5: Hybrid-STATCOM operating in the middle operational region between TSC switch on/off threshold. Hybrid-STATCOM is operating in the region between the switch on and off thresholds. The main problems are the efficiency of the device and power losses caused by operating in that region. This case can happen if VSC capacity is larger than TSC/TSR, or the switching-off threshold is large. A solution to this problem could be to add a function that checks if hybrid-STATCOM is operating in that region and manage to move the operational point to a more efficient region by switching out the TSC and adjust the output of VSC. However, this problem can be avoided if Hybrid-STATCOM capacity and parameters were designed properly, and by using hysteresis.
6.3 PSS®E and PSCAD simulation differences

As mentioned earlier, PSCAD is used for Electromagnetic Transient (EMT) studies, which uses 3-phase, where as PSS®E is used for RMS based network studies. Also, PSCAD models and controls are complex and contains all the actual components used in the real system. PSS®E uses a simplified version (model or a representation) of the whole system without modeling all the components of each device. Therefore, in dynamic simulations, there must be a slight difference in the outputs of these softwares, especially in transient states. The difference in output can be seen in Figure 6.6 when TSC is switched on or off. PSCAD switch-on the thyristor valves in TSC in a phase by phase sequence as shown in Figure 6.6. The figure shows the pulses sent to each valve in TSC. There are two thyristor stacks in each phase, for positive and negative directions. The total number of pulses are six as shown in the figure. The pulses are sent periodically to the valves until TSC is switched off. When the output of TSC (PSCAD) is plotted in RMS values, it can be seen that reactive power injection is done in 3-steps. However, in PSS®E, when TSC is switched on, the reactive power is injected in one step.

![Figure 6.6: TSC valves pulses with respect to PSS®E and PSCAD currents](image-url)
6.4 Dynamic Stability with Hybrid-STATCOM

A brief study on the dynamic stability impact of Hybrid-STATCOM is performed. A Single Machine Infinite Bus (SMIB) is used to conduct this study. The system used is shown in figure 6.7. Hybrid-STATCOM is connected to the remote bus through a zero impedance line, and it controls the voltage at that bus. The total output current of Hybrid-STATCOM \( I_{Tot} \) is measured through the zero impedance line. The lines connected to the remote bus are assumed lossless with \( R = 0 \) pu and \( L = 0.1 \) pu. The load is initially at 0 MVA. After 1 sec, the load changes to 300 MVA, which creates oscillations in the system. The frequency of oscillations is 0.54 Hz, which is an inter-area mode of oscillations. Three simulations were performed on the system:

1. Hybrid-STATCOM:
   The full Hybrid-STATCOM is connected to the remote bus. The capacity of VSC is +/- 100 MVA and the susceptance of TSC is 150 Mvar. TSR is not used in the simulation but it is connected with a susceptance of -150 Mvar. POD function is not used in this simulation.

2. STATCOM only:
   Only STATCOM is connected to the remote bus. The capacity of VSC is +/- 100 MVA. TSC and TSR were disabled in this simulation. POD function is not used in this simulation.

3. No FACTS:
No FACTS device is connected to the remote bus. Hybrid-STATCOM was disabled in this simulation.

The results of the three simulations are shown in figure 6.8. The change in the remote bus voltage with respect to the nominal voltage (1.0 pu) is shown in figure 6.8a and the total output current $I_{Tot}$ is shown in figure 6.8b. The

![Graph showing dynamic stability comparison]

Figure 6.8: Comparison between the dynamic stability of Hybrid-STATCOM, STATCOM only and No FACTS

No FACTS simulation is poorly damped and cannot bring the voltage back to 1 pu. The STATCOM only simulation shows pretty good damping. It can compensate for the extra load connected to the system and bring the voltage back to 1 pu. However, it is limited by the capacity of VSC. The Hybrid-STATCOM simulation damps the oscillations very fast because of the additional compensation current injected by the TSC. The total current injected by Hybrid-STATCOM is more than twice of the current injected by VSC alone. $I_{Tot}$ in Hybrid-STATCOM simulation is smooth although
the TSC was being switched in and out constantly. VSC was counteracting TSC current in all the switching moments as shown in figure 6.9b. VSC kept reaching the switching in (0.8 pu) and out (-0.7 pu) thresholds of TSC until 20 sec. After that, VSC was capable of regulating the voltage without the help of TSC. TSR was not used because VSC didn’t reach to the switching in threshold of TSR, which was at -0.8 pu. The notches at the change in the remote bus voltage shown in figure 6.9a is due to the switching of TSC. It can be seen that Hybrid-STATCOM can improve the dynamic stability of the system with its high compensation current.

Figure 6.9: Dynamic stability of Hybrid-STATCOM
Chapter 7

Closure

7.1 Summary

A STATCOM and a Hybrid-STATCOM models were developed for dynamic simulations in PSS®E. A control block diagram was created to represent the functionality of STATCOM first. Then the block diagram was interpreted into FORTRAN code and used as a user defined model in PSS®E for dynamic simulations. Most of the developed functions were tested in PSS®E and compared to PSCAD and WECC models. The Hybrid-STATCOM model is a modification of the STATCOM one. TSC and TSR branches were added to the model and all the functions were modified accordingly. The Hybrid-STATCOM model was tested fully in PSS®E, and the TSC/TSR switching function was compared to the PSCAD model. The developed STATCOM model showed a perfect step response when compared to WECC model. The comparison with the PSCAD STATCOM model was done using three functions, Regulator, Limiters and UV strategy. In all tests the primary voltage showed a good match between PSS®E and PSCAD models. There were small differences in Current and reactive power outputs because of inherent differences between the two models. The developed Hybrid-STATCOM model was compared as well to the PSCAD model. TSC switching function was compared between the two models. The primary voltage was equivalent in both models with a small error. The difference in TSC switching methodology between PSS®E and PSCAD models caused the current and reactive power outputs to be slightly different. A brief study on the dynamic stability of the system with Hybrid-STATCOM was conducted. It showed that Hybrid-STATCOM with the additional compensation of TSC and TSR can enhance the dynamic stability of the system. The developed models are property of ABB and will be used for planning studies in the future.
7.2 Recommendations

The models were developed to include most of the functions required for studies in PSS®E. Although the models were developed to withstand most events, some special cases could cause the models to behave inaccurately. The models are ready to be used for PSS®E dynamic simulations. Using inaccurate parameters could cause PSS®E to crash. Users are advised to check the parameters before running the dynamic simulations.

7.2.1 Future work:

1. Some functions such as UV strategy and gain supervision can be optimized to accurately match the output of the PSCAD model.

2. The models should be tested in other networks to verify its functionality. Code bugs might appear during special cases tests.

3. A subroutine that checks the validity of user input data could be added to avoid corrupted data or unrealistic parameters.

4. The models could be added to PSS®E models library.

5. For hybrid-STATCOM, applying a step-wise switch-in of TSC to mimic that of each phase has some inherent delay from each other.
References


