

**POWER FACTOR IMPROVEMENT IN POWER SYSTEM
WITH THE INTEGRATION OF RENEWABLE ENERGY**

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PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Specially dedicated to
My beloved father and mother,
My family for their support and guidance
My dearest friends for being there whenever I needed them
Thanks for all the encouragement and support

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In the name of ALLAH S.W.T, most gracious, most merciful

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ABSTRACT

In the power grid system, the ultimate goals are to transmit power with high power quality and power factor, economical and low risk of system failure. The ever increasing of power demands and loads especially non-linear loads making the power system network become complex to operate and the system becomes insecure with large power flows without adequate control. Renewable energy sources, which are expected to be a promising alternative energy source, can bring new challenges when connected to the power grid system. However, the generated power from renewable energy source is always fluctuating due to environmental conditions. In the same way, wind power source injection into an electric grid affects the power quality due to the fluctuation nature of the wind and the comparatively new types of its generators panel. One way to introduce power system control is by applying controller known as FACTS (Flexible AC Transmission System) controllers. STATCOM (Static Synchronous Compensator) and SSSC (Static Synchronous Series Compensator) is one of the FACTS controllers and can be introduced to the power system to regulate terminal voltage and to improve system's stability and power quality. The FACTS devices (STATCOM and SSSC) control scheme for the grid connected with wind energy generation system is simulated using MATLAB/PSAT in power system block set. By using IEEE 14 bus power system network, the effectiveness of STATCOM and SSSC are tested by applying the controller at the critical location of the power system.

ABSTRAK

Dalam sistem grid kuasa, matlamat utama adalah untuk menghantar kuasa dengan kualiti kuasa dan faktor kuasa yang tinggi, ekonomi dan risiko yang rendah daripada kegagalan sistem. Permintaan kuasa dan beban yang semakin meningkat terutama beban bukan linear membuat rangkaian sistem kuasa menjadi kompleks untuk dikendalikan dan sistem menjadi tidak selamat dengan aliran kuasa besar tanpa kawalan yang mencukupi. Sumber-sumber tenaga boleh diperbaharui, yang dijangka menjadi sumber tenaga alternatif berpotensi tinggi, boleh membawa cabaran baru apabila disambung kepada sistem grid kuasa. Walau bagaimanapun, kuasa yang dijana daripada sumber tenaga boleh diperbaharui adalah sentiasa berubah-ubah disebabkan oleh keadaan alam sekitar. Dengan cara yang sama, sumber kuasa angin yang disuntik ke dalam grid elektrik akan menjejaskan kualiti kuasa kerana disebabkan ketidakstabilan angin dan panel penjana yang baru. Salah satu cara ialah dengan memperkenalkan sistem kawalan kuasa dengan fungsi pengawal dikenali sebagai pengawal FACTS (Fleksibel Sistem Penghantaran AC). STATCOM (Static Synchronous Compensator) and SSSC (Static Synchronous Series Compensator) adalah salah satu pengawal FACTS yang digunakan di dalam sistem kuasa untuk mengawal voltan terminal dan untuk meningkatkan kestabilan sistem serta kualiti kuasa. Kawalan peranti FACTS (STATCOM dan SSSC) untuk grid bagi sistem penjanaan tenaga angin disimulasi menggunakan MATLAB / PSAT dalam sistem kuasa set blok. Dengan menggunakan IEEE 14 bus rangkaian sistem kuasa, keberkesanan STATCOM dan SSSC diuji dengan menggunakan pengawal di lokasi sistem kuasa yang kritikal.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Centralized power generation system faces a shortage of main energy sources (fossil fuels). Length of the transmission line is one of the main causes of electrical power losses. Therefore, the emphasis on the integration of renewable energy systems to the grid, able to lead to energy efficiency and emission reduction. With the increase of the renewable energy penetration to the grid, power quality of the medium to low voltage power transmission system is becoming a major area of interest.

Most of the integration of renewable energy systems to the grid performed with the aid of power electronic converters. The main purpose of the power electronic converter is to integrate distributed generation to the grid power factor standards. However, high switching frequency inverter can inject additional harmonics to the system, creating major power quality problems if not carried out correctly [1].

Custom Power Devices (CPD) like Shunt Active Power Filter (STATCOM or SVC), Series Active Power Filter (SSSC or TCSC), Combination of series and shunt Active Power Filter, (UPFC) are the latest development of interfacing devices between distribution supply and consumer appliances to overcome voltage/current disturbances and improve the power quality by compensating the reactive and harmonic power generated or absorbed by the load. Solar and wind are the most promising distributed generation sources and their penetration level to the grid is also on the rise. Although the benefits of distributed generation includes voltage support,

diversification of power sources, reduction in transmission and distribution losses and improved reliability, power quality problems are also of growing concern [2].

The development of hybrid Custom Power Devices (CPD) in the power systems in grid is another solution to fix the issue of power quality and power stability especially in power factor. This system will be able to detect, analyze and respond to various perturbations for main energy source and renewable energy source by integrating intelligent devices, advance control methods and digital telecommunications on electrical bus networks.

This concept is the outcome of advanced technology and regulation from various stakeholders who are concerned with demand-side management and increased usage of Renewable Energy Source (RES). This system development is underway and is expected to be dynamic, reliable, flexible, diverse and fully controlled. This new scenario will enable power operators to maximize the power quality, such as in Total Harmonic Distortion (THD_i), Power Factor (PF), current and voltage balancing. Further, this system meets environmental targets and enables the power system to become more flexible to support plug-in distributed generation.

1.2 Problem Statement

Nowadays, the increasing of power demand and loads especially non linear loads making the power system network become more complex to operate. The system becomes insecure with large power flows without adequate control. To overcome these issues, a hybrid system; combination main energy source, renewable energy source and Custom Power Devices (CPD) should be created and applied in the power grid. Then the system should be injected with Flexible AC Transmission System (FACTS) controllers to improve their power quality, power factor and voltage stability. Ideally, these new controllers should be able to control voltage level and improve system's stability by applying at the critical location.

Figure 1.1: Example of control system topology [1].

1.3 Research Hypothesis

In the power system, power factor plays a very important role because it can affect the total cost of electricity. The higher the power factor, the higher the efficiency, thus was providing significant cost savings. Many advantages will be gained if the power factor in power systems increases, which can reduce energy and distribution costs; lower distribution losses in the electricity system; higher voltage regulation and better quality. In addition, improved power factor will increase the efficiency of the equipment and help the equipment lasts longer, at the same time reduce the electricity costs. So, the Custom Power Devices (CPD) should be researched to overcome this problem.

1.4 Project Objectives

This project will be implemented based on the main objectives as expressed below:

- i. To develop novel method to analyze the positioning tolerances of the CPD and the posterior application of that method to the CPD.
- ii. To conceptualize the technically and economically optimal realization of future large scale CPD.

- iii. To propose a model to evaluate parabolic troughs of a functioning prototype to test and validate the model.
- iv. To form new criteria and development of new methods for coordinating control of CPD.

1.5 Project Scopes

This project will be conducted under the scope of review set out below:

- i. To develop novel method to analyze the positioning tolerances of the CPD and the posterior application of that method to the CPD by MATLAB/PSAT software.
- ii. To conceptualize the technically and economically optimal realization of future large scale CPD by using FACTS controllers.
- iii. To propose a model to evaluate parabolic troughs of a functioning prototype to test and validate the model by using IEEE 14-bus test system.
- iv. To form new criteria and development of new methods for coordinating control of CPD by using STATCOM, SSSC and UPFC.

The main goal of this project is to improve the power quality and efficiency of power grid system especially in power factor while reducing the losses.

1.6 Report Outline

Chapter 1 contained about overviewed of overall of this project, objective of doing this project, scope of project description, and the problem statement regarding to this research.

Chapter 2 consist of basic information and literature review that been read. It contains of review of the technical paper written by expertises that have been taken from website and also books. Literature review is crucial for every thesis not only to support the proposed title but also for guidelines and references on the conducted thesis.

Chapter 3 represent about the analysis approach that involve in this research. It also included the procedures and the tools that used in the analysis which is MATLAB/PSAT.

Chapter 4 states the result and the analysis made from the research and the discussion during the research done. Every result from the simulation are stated, analyzed and explained briefly.

Chapter 5 contains the project discussions and conclusion of overall project by state the final result that gained from the project. Future recommendations also stated in order to improve this project in the future undertakings.



CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the basic information and working principle of the FACTS controllers would be discussed. It would also include brief overview of the power flow analysis. Lastly, the reviews of related work would also be included.

2.2 Power Flow

Power flow study, also known as load-flow study, is an important tool involving numerical analysis applied to a power system. A power flow study usually uses simplified notation such as a one-line diagram and per-unit system, and focuses on various forms of AC power (i.e.: voltages, voltage angles, real power and reactive power). It analyzes the power systems in normal steady-state operation. A number of software implementations of power flow studies exist.

In addition to a power flow study, sometimes called the base case, many software implementations perform other types of analysis, such as short-circuit fault analysis, stability studies (transient & steady-state), unit commitment and economic load dispatch analysis. In particular, some programs use linear programming to find the optimal power flow, the conditions which give the lowest cost per kilowatthour delivered.

Power flow or load-flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. The principal information obtained from the power flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line.

Load flow studies are performed using computer software that simulates actual steady-state power system operating conditions, enabling the evaluation of bus voltage profiles, real and reactive power flow and losses. Conducting a load flow study using multiple scenarios helps ensure that the power system is adequately designed to satisfy the performance criteria. A properly designed system helps contain initial capital investment and future operating costs. Load flow studies are commonly used to investigate:

- i. the component or circuit loading
- ii. the bus voltage profiles
- iii. the real and reactive power flow
- iv. the power system losses
- v. the proper transformer tap settings

The goal of a power flow study is to obtain complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions. Once of this information is known, real and reactive power flow on each branch as well as generator reactive power output can be analytically determined.

Due to the nonlinear nature of this problem, numerical methods are employed to obtain a solution that is within an acceptable tolerance. The solution to the power flow problem begins with identifying the known and unknown variables in the system. The known and unknown variables are dependent on the type of bus. A bus without any generators connected to it is called a Load Bus. With one exception, a bus with at least one generator connected to it is called a Generator Bus. The exception is one arbitrarily-selected bus that has a generator. This bus is referred to as the Slack Bus [3].

For assessing the impact of the STATCOM, SSSC and UPFC in controlling the grid voltage, power flow study is necessary. Moreover, in the planning stage, to determine the ratings of the STATCOM, SSSC and UPFC, among others, repeated load flow studies are carried out. Also, in a stability study, load flow solution is required to establish the initial operating point. Thus, power flow studies are indeed one of the most fundamental studies necessary to be carried out before implementing any STATCOM, SSSC and UPFC in a power system.

2.3 Introduction to FACTS Controllers

Flexible AC Transmission System (FACTS) is a power electronic based system that provides control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability [4]. There are 3 types of FACTS controller, which are namely shunt, series and shunt-series.

The shunt connected FACTS controllers could be used to improve the voltage profile of a specific bus, improve the transient stability and power oscillation damping. Some examples of the shunt connected FACTS controllers are Static VAR Compensator (SVC) and the Static Synchronous Compensator (STATCOM) [5].

The series connected FACTS controller could improve the voltage stability limit, increase the transient stability margin, power oscillation damping and sub-synchronous oscillation damping [6]. Some examples of the series FACTS controllers are Thyristor Switched Series Capacitor (TSSC), Thyristor-Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC).

The shunt-series connected FACTS controller provides multifunctional flexibility required to solve many of the problems facing by the power delivery industry. Some examples of shunt-series connected FACTS Controllers are Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) [7].

2.3.1 Theory of FACTS Controllers

The shunt connected FACTS controller utilizes the basic principle of the steady state transmittable power and the voltage profile along the line could be controlled by appropriate reactive shunt compensation. When connected to an ac power source, capacitors generate while the reactors (or inductors) absorb the reactive power. These

VAR generator and absorber would be used with mechanical switches for controlling the VAR generation and absorption [8]. There are three types of shunt connected FACTS controllers actually, in which there are called variable impedance (or reactance to be exact) type, switching converter type and the hybrid type.

The series connected FACTS controller uses the basic principle of the cancellation of a portion of the reactive line impedance could increase the transmittable power. This is due to the fact that AC power transmission over long lines was primarily limited by the series reactive impedance of the line. The series capacitive compensation basically to decrease the overall effective series transmission impedance from the sending end to the receiving end [8, 9].

In series connected FACTS controllers, there are divided into two types, namely the variable impedance type series compensator and switching converter type series compensator. The main concepts of the series connected FACTS controller are actually quite similar to the shunt connected FACTS controller, except for the series compensator, is a reciprocal of the shunt compensator [8, 9].

For the combinational shunt-series connected FACTS Controllers combines the main principles of the shunt and series connected FACTS Controllers. It able to control, simultaneously or selectively, all the parameters affecting the power flow in the transmission line, that are impedance, voltage and the phase angle [10].

2.3.2 Operation and Control of FACTS Controller

All of FACTS controllers have a converter based which is Voltage-Source Converters (VSC). A basic building block of any VSC is the three phase converter bridge. One is commonly known configuration for a three phase bridge is shown in Figure 2.1. The bridge has two DC terminals indicated by “+” sign and “-” sign in the Figure 2.1 and three AC terminals “~” in the mid points of the converter legs. By controlling the states of switches in the legs we can produce arbitrary voltage waveforms at the AC terminals.

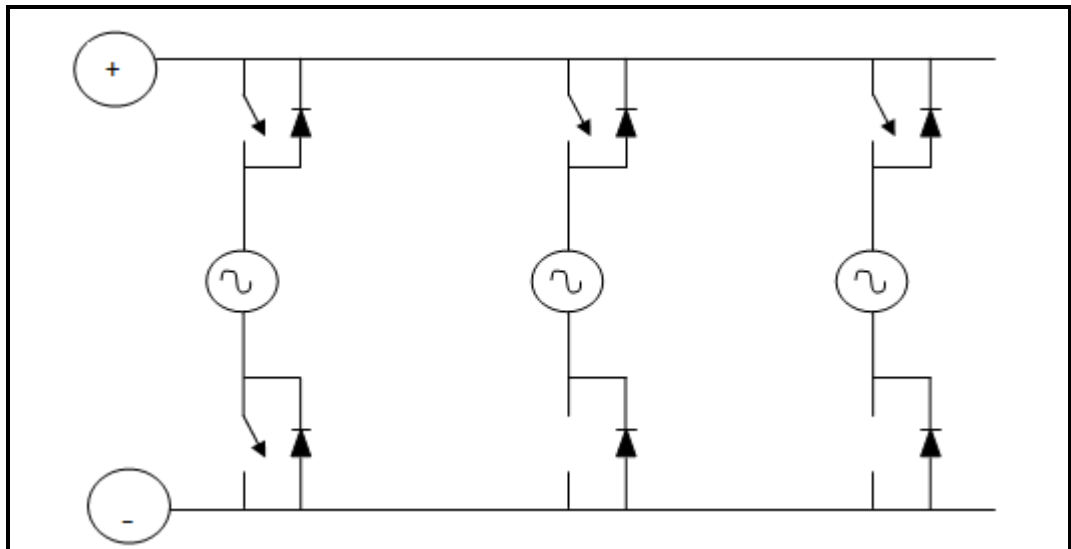


Figure 2.1: A three phase converter bridge-the basic building block of a Voltage Source Converters [8].

When a VSC is interfaced to a transmission system it has to operate at the line frequency and to produce a balanced set of sinusoidal voltages. Therefore, a VSC coupled to the transmission system has only two control degrees of freedom; it can vary the magnitude and the phase angle of its output voltage relative to the system voltage [8].

These two control degrees of freedom can be mapped to exchange active and reactive power with the transmission system. The amount of exchanged reactive power is limited only by the current capacity of the converter switches, while the active power coupled to (from) the line has to be supplied from (delivered to) the DC terminals, as shown symbolically in Figure 2.2 [8].

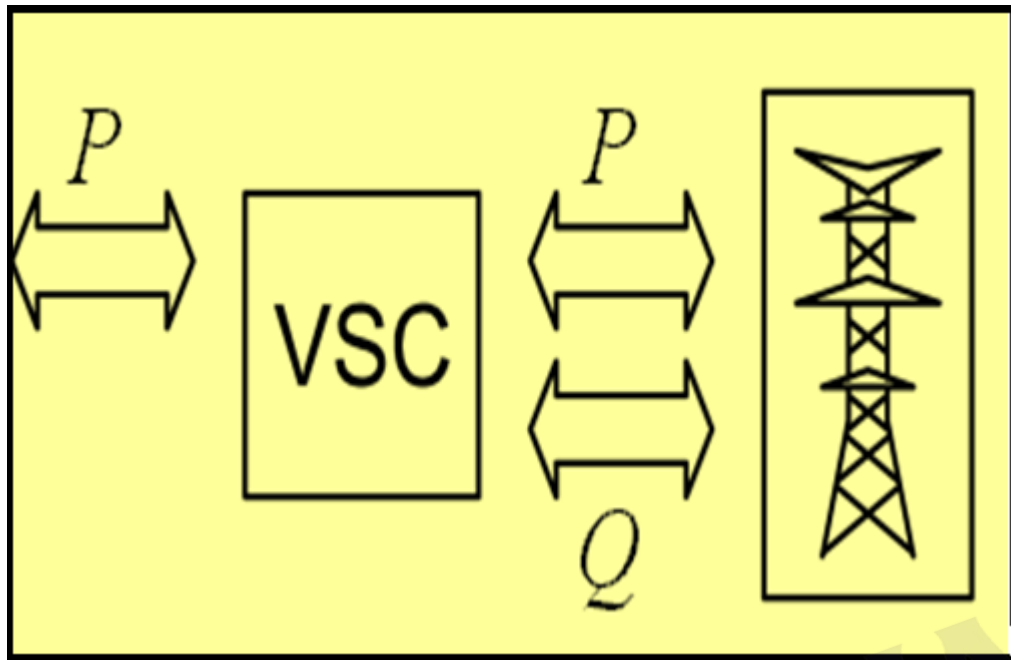


Figure 2.2: A VSC interfaced to a transmission line- P and Q exchange [8].

Among the main functions of FACTS devices that can enhance the flexibility and increase the security of a power system are phase shifting; which is realized by injecting a voltage in series into the power system, voltage support by means of shunt device and line impedance adaption by means of series devices.

2.4 Introduction to STATCOM

STATCOM (Static Synchronous Compensator) or known as ASVG (Advanced Static Var Generator) is a solid-state voltage source inverter that is coupled with a transformer and connected to a transmission line. A STATCOM injects an almost sinusoidal current, of variable magnitude, at the point of connection. It is based on the principle that a voltage-source inverter generates a controllable AC voltage source behind a transformer-leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network. The function of a STATCOM model is based on how it's regulating the reactive current flow through it. This property is useful for regulating the line voltage [4, 5, 8, 11]

2.4.1 Function of STATCOM

A STATCOM is basically a DC-AC voltage source inverter with an energy storage unit, usually a DC capacitor and operates as a controlled Synchronous Voltage Source (SVS) connected to the line through a coupling transformer as shown in Figure 2.3 [4, 8].

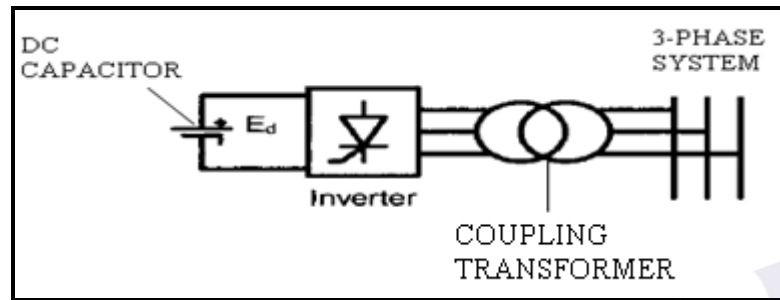


Figure 2.3: Schematic configuration of STATCOM diagram [8].

The STATCOM is a shunt reactive power compensating electronic device that generates AC voltage, which intern causes a current of variable magnitude at the point of connection. This injected current is almost in quadrature with the line voltage, thereby emulating an inductive or a capacitive reactance at the point of connection with the transmission line. The functionality of the STATCOM model is verified by regulating the reactive current flow through it. This is useful to generate or absorb reactive power for regulating the line voltage of the bus where the STATCOM is connected [4, 5, 8, 13].

2.4.2 Operation of STATCOM

The principle of control reactive power via STATCOM is well known that the amount of type (capacitive or inductive) of reactive power exchange between the STATCOM and the system can be adjusted by controlling the magnitude of STATCOM output voltage with respect to that of system voltage. When Q is positive, the STATCOM supplies reactive power and when the Q is negative, the STATCOM absorbs reactive power from the system. Reactive power generation was achieved by charging and discharging the energy storage capacitor [4, 5, 8, 13]. The reactive power supplied by the STATCOM is given by this equation.

$$Q = \frac{V_{STATCOM} - V_S}{X} V_S \quad (2.1)$$

Where:

Q = Reactive power.

$V_{STATCOM}$ = Magnitude of STATCOM output voltage.

V_S = Magnitude of system voltage.

X = Equivalent impedance between STATCOM and the system.

Figure 2.4 demonstrates a simplified diagram of the STATCOM with an inverter voltage source, E and a tie reactance, X_{tie} connected to an ac system with voltage source, V_{th} and a Thevenin reactance, X_{th} . When the converter voltage is greater than the system voltage, the STATCOM “sees” an inductive reactance connected at its terminal. Hence, the system “sees” the STATCOM as a capacitive reactance and the STATCOM is operating in a capacitive mode. The current flows from the STATCOM to the AC system, and the device generates reactive power. In this case, the system draws capacitive current that leads by an angle of 90° the system voltage, assuming that the converter losses are equal to zero [14, 15].

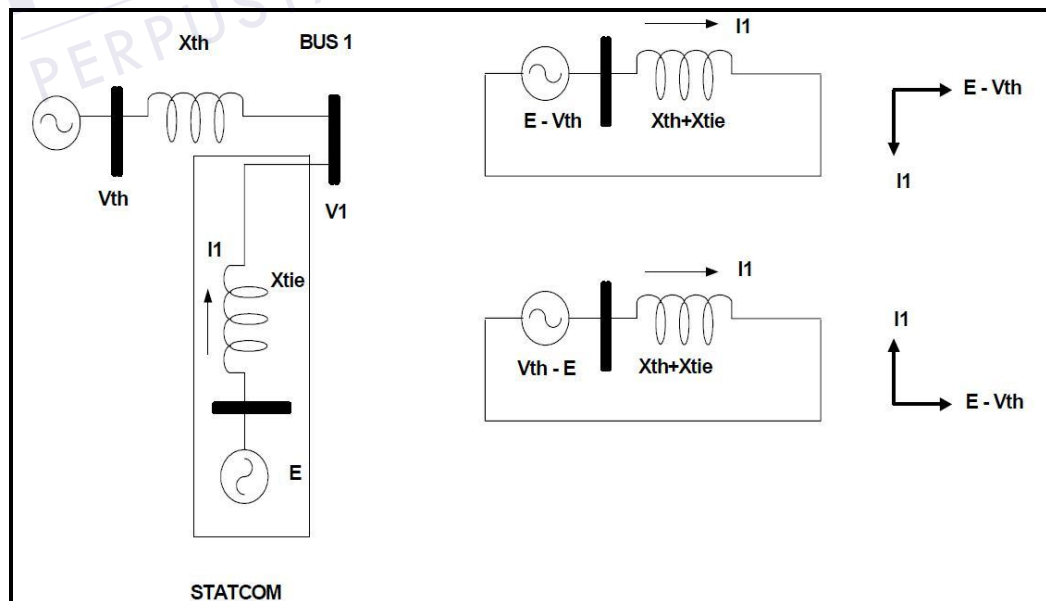


Figure 2.4: A static synchronous compensator operated in inductive and capacitive mode diagram [14].

2.4.3 Circuit Configuration of STATCOM

For STATCOM, there are two types of circuit configuration which are multipulse converter and multilevel converter. Both of these types have different circuit connection and different operation

In the multipulse converter, the 3-phase bridges are connected in parallel on the DC side as shown in Figure 2.5. The bridges are magnetically coupled via a zigzag transformer. The transformer is usually arranged in order to make the bridges appear in series viewed from the AC sides. Each windings of the transformer is phase shifted. This is to eliminate selected harmonics and produce a multipulse output voltage. Pulse Width Modulation (PWM) is applied to improve the harmonics content, at the expense of higher switching and snubber loss, plus reduced the fundamental of var rating [14, 15, 16].

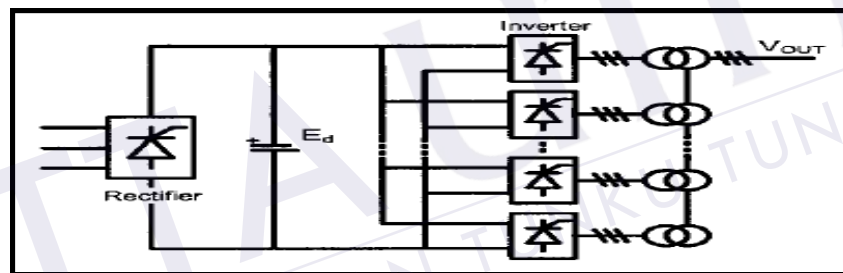


Figure 2.5: Multipulse converter diagram [16].

Figure 2.6 shows the multilevel converter configuration consists of three different configurations which are Diode-clamped converter, Flying Capacitor Converter and Cascade Converter. A cascade converter is constructed by standard H-bridges in series. Apart from other designs, cascade multilevel converter eliminates clamping diode, flying capacitors or zigzag transformer. Thus, it's requires least components used and low cost are involved. Larger dc-side capacitors are required compared to the diode clamped and flying capacitor converter under balanced condition but it provides separate phase control to support significant voltage unbalance [14, 15, 16, 17].

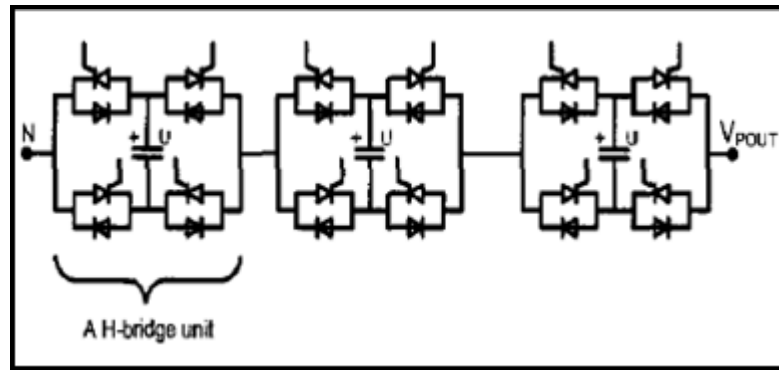


Figure 2.6: Cascade multilevel converter diagram [16].

2.4.4 Advantages of STATCOM

STATCOM has many advantages over the other compensators. The advantages of STATCOM can be summarized such as:

- i. It has short term overload capability of ~20%
- ii. It requires 15-35% less MVA rating than SVC to deliver same level of performance for the system steady state power transfer, dynamic voltages support, and transient stability performance.
- iii. It can act as voltage source in stating other converter based equipment.
- iv. It can be used together with other type of compensations equipment.
- v. It does not require large harmonic filter.

The other advantages are STATCOM has a dynamic performance far exceeding the other var compensators. The overall system response time of STATCOM can reach 10ms or less. STATCOM has the ability to maintain full capacitive output current at low system voltage, which it makes STATCOM become more effective than SVC in improving the transient stability.

Compare to other compensator, STATCOM can easily realize redundancy design, which brings a higher reliability. STATCOM also has a smaller installation space [16, 17, 18].

2.5 Introduction to SSSC

The SSSC is generally connected in series with the transmission line with the arrangement as shown in Fig 2.3. The SSSC comprises a coupling transformer, a magnetic interface, voltage source converters (VSC) and a DC capacitor. The coupling transformer is connected in series with the transmission line and it injects the quadrature voltage into the transmission line.

The magnetic interface is used to provide multi-pulse voltage configuration to eliminate low order harmonics. The injected voltage of the coupling transformer V_s is perpendicular to the line current I_L [4, 8].

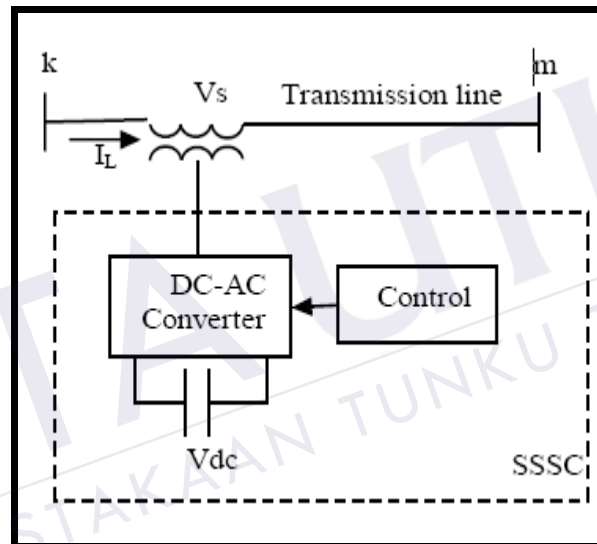


Figure 2.7: Simplified diagram of SSSC [8].

The SSSC is in principle a synchronous voltage source, which is typically connected in series with a transmission circuit to provide line compensation. This controllability is achieved by using a controllable interface between the dc voltage source (typically a capacitor) and the ac system. The series capacitive compensation basically to decrease the overall effective series transmission impedance from the sending end to the receiving end. The relationship characterizes the power transmission over a single line is:

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