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Effect of FACTS Devices STATCOM and SSSC on Wind Farms

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Abstract: - Nowadays, power systems are facing new challenges, such as increasing penetration of renewable energy sources, in particular wind generation, growing demands, limited resources,and competitive electricity markets. Under these conditions, thepower systems has had to confront some major operating problems in voltage regulation, power flow control,transient stability, and damping of power oscillations, etc. Flexible AC transmission system (FACTS) devices can be a solution to these problems. This paper investigates the application of FACTS devices on a 12-bus multimachine benchmark power system including a large wind farm. A STATCOM and an SSSC are added to this power network to provide dynamic voltage control for the wind farm, dynamic power flow control for the transmission lines, relieve transmission congestion and improve power oscillation damping and transient stabilit

I. INTRODUCTION

Power Generation and Transmission is a complex process, requiring the working of many components of the power system in tandem to maximize the output. One of the main components to form a major part is the reactive power in the system. It is required to maintain the voltage to deliver the active power through the lines. Loads like motor loads and other loads require reactive power for their operation. To improve the performance of ac power systems, we need to manage this reactive power in an efficient way and this is known as reactive power compensation. There are two aspects to the problem of reactive power compensation: load compensation and voltage support. Load compensation consists of improvement in power factor, balancing of real power drawn from the supply, better voltage regulation, etc. of large fluctuating loads. Voltage support consists of reduction of voltage fluctuation at a given terminal of the transmission line. Two types of compensation can be used: series and shunt compensation. These modify the parameters of the system to give enhanced VAR compensation. In recent years, static VAR compensators like the STATCOM have been developed. These quite satisfactorily do the job of absorbing or generating reactive power with a faster time response and come under Flexible AC Transmission Systems (FACTS). This allows an increase in transfer of apparent power through a transmission line, and much better stability by the adjustment of parameters that govern the power system i.e. current, voltage, phase angle, frequency and impedance.

II. REACTIVE POWER

Reactive power is the power that supplies the stored energy in reactive elements. Power, as we know, consists of two components, active and reactive power. The total sum of active and reactive power is called as apparent power. In AC circuits, energy is stored temporarily in inductive and capacitive elements, which results in the periodic reversal of the direction of flow of energy between the source and the load. The average power after the completion of one whole cycle of the AC waveform is the real power, and this is the usable energy of the system and is used to do work, whereas the portion of power flow which is temporarily stored in the form of magnetic or electric fields and flows back and forth in the transmission line due to inductive and capacitive network elements is known as reactive power. This is the unused power which the system has to incur in order to transmit power. Inductors (reactors) are said to store or absorb reactive power, because they store energy in the form of a magnetic field. Therefore, when a voltage is initially applied across a coil, a magnetic field builds up, and the current reaches the full value after a certain period of time. This in turn causes the current to lag the voltage in phase Capacitors are said to generate reactive power, because they store energy in the form of an electric field. Therefore when current passes through the capacitor, a charge is built up to produce the full voltage difference over a certain period of time. Thus in an AC network the voltage across the capacitor is always charging. Since, the capacitor tends to oppose this change; it causes the voltage to lag behind current in phase.

In an inductive circuit, we know the instantaneous power to be:

$$p = V_{max} I_{max} \cos \omega t \cos(\omega t - \theta)$$

$$p = \frac{V_{max} I_{max}}{2} \cos\theta \,(1 + \cos 2\omega t) + \frac{V_{max} I_{max}}{2} \sin\theta \sin 2\omega t$$

The instantaneous reactive power is given by:

$$\frac{V_{max} I_{max}}{2} \sin\theta \sin 2\omega t$$

Where:

p = instantaneous power

V_{max} = Peak value of the voltage waveform

I_{max} = Peak value of the current waveform

ω = Angular frequency

= $2\pi f$ where f is the frequency of the waveform.

t = Time period

θ = Angle by which the current lags the voltage in phase

From here, we can conclude that the instantaneous reactive power pulsates at twice the system frequency and its average value is zero and the maximum instantaneous reactive power is given by: $Q = |V|\,|I| \sin\theta$

The zero average does not necessarily mean that no energy is flowing, but the actual amount that is flowing for half a cycle in one direction, is coming back in the next half cycle. A flexible alternating current transmission system (FACTS) is a system composed of static equipment used for the AC transmission of electrical energy. It is meant to enhance controllability and increase power transfer capability of the network. It is generally a power electronics-based system. It is a new integrated concept based on power electronic switching converters and dynamic controllers to enhance the system utilization and power transfer capacity as well as the stability, security, reliability and power quality of AC system interconnections. The term FACTS describes a wide range of controllers, many of which incorporate large power electronic converters, that can increase the flexibility of power systems making them more Controllable. Some of these are already well established while some are still in the research or development stage.

III. STATCOM

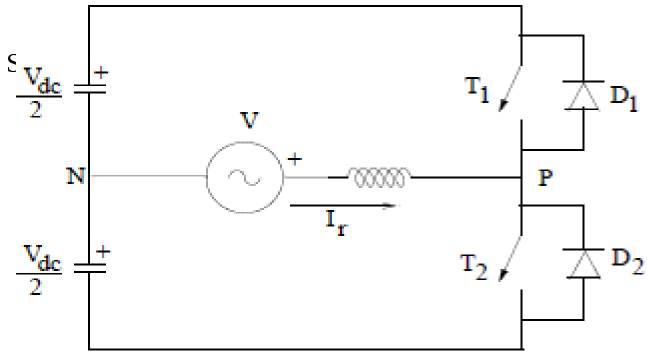
STATCOM is shunt connected static compensator developed as an advanced static VAR compensator where a voltage source convertor (VSC) is used instead of the controllable reactors and switched capacitors. Although VSCs require self-commutated power semiconductor devices such as GTO, IGBT,IGCT, MCT, etc (with higher costs and losses) unlike in the case of variable impedance type SVC which use thyristor devices, there are many technical advantages of a STATCOM over a SVC

ADVANTAGES OF STATCOM

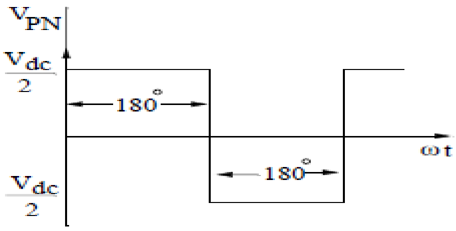
(a) Faster response
(b) Requires less space as bulky passive components (such as reactors) are eliminated
(c) Inherently modular and re locatable
(d) It can be interfaced with real power sources such as battery, fuel cellor SMES (superconducting magnetic energy storage)
(e) A STATCOM has superior performance during low voltage condition as the reactive current can be maintained constant (In a SVC, the capacitive reactive current drops linearly with the voltage at the limit (of capacitive susceptance). It is even possible to increase the reactive current in a STATCOM under transient conditions if the devices are rated for the transient overload. In a SVC, the maximum reactive current is determined by the rating of the passive components – reactors and capacitors.

A STATCOM is comparable to a Synchronous Condenser (or Compensator) which can supply variable reactive power and regulate the voltage of the bus where it is connected.

IV. SINGLE PHASE STATCOM

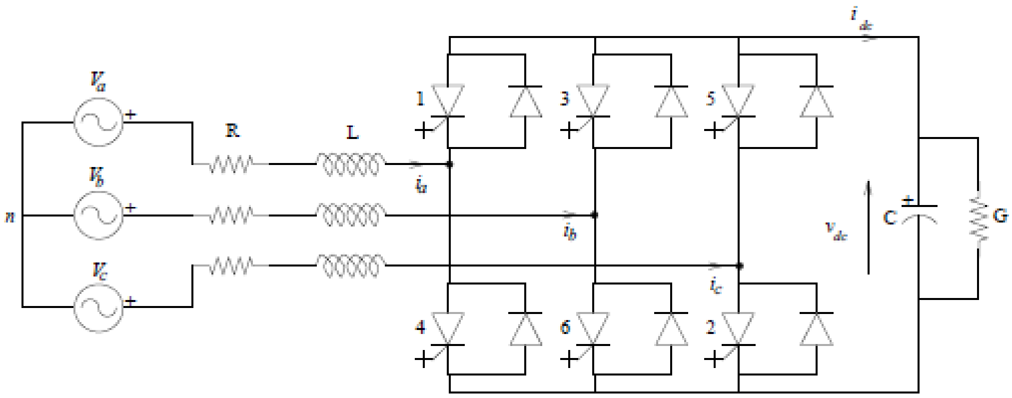


T1 and T2 (based on say GTOs) are switched on and o® once in a cycle. The conduction period of each switch is 180and care has to be taken to see that T1 is o when T2 is on and vice versa. The diodes D1 and D2enable the conduction of the current in the reverse direction. The charge on the capacitors ensure that the diodes are reverse biased. The voltage wave form across PN is shown in Fig . The voltage VP N = Vdc/2 when T1is conducting (T2 is OFF) and VP N = -Vdc/2 when T2 is conducting (and T1 is 0)

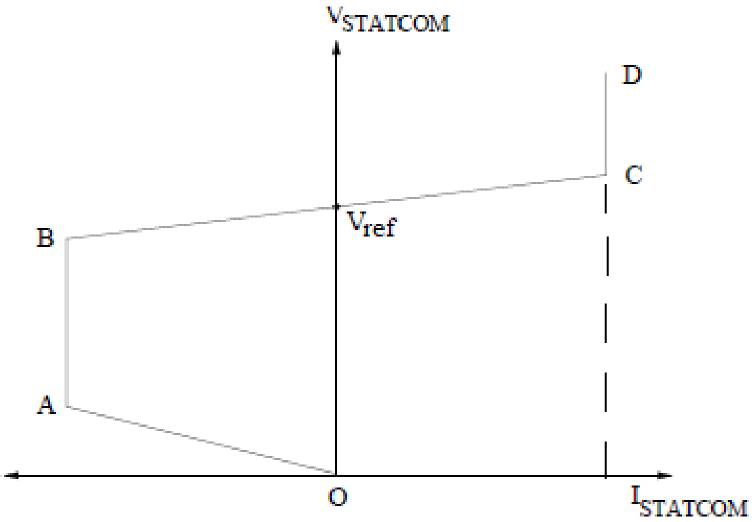


The losses in the STATCOM are neglected and STATCOM is assumed to be purely reactive. As in the case of a SVC, the negative current indicates capacitive operation while positive current indicates inductive operation. The limits on the capacitive and inductive currents are symmetric The positive slope BC is provided for the V-I characteristic to(i) prevent the STATCOM hitting the limits often and (ii) to allow parallel operation of two or more units. The reference voltage (Vref) corresponds to zero current output and generally, the STATCOM is operated close to zero .

V. SIX PULSE CIRCUIT



The basic building block of a high power GTO based STATCOM is a six pulse circuit It is a device connected in derivation, basically composed of a coupling transformer, that serves of link between the electrical power system (EPS) and the voltage synchronous controller (VSC), that generates the voltage wave comparing it to the one of the electric system to realize the exchange of reactive power. In 1991, the world's first commercial transmission system STATCOM (at the time known as SVG for Static Var Generator) was installed at the Inuyama substation of The Kansai Electric Power Company in Japan, for the objective of improving power system and voltage stabilization. It has been successfully operating for nearly 9 years.



Control characterstics of STATCOM

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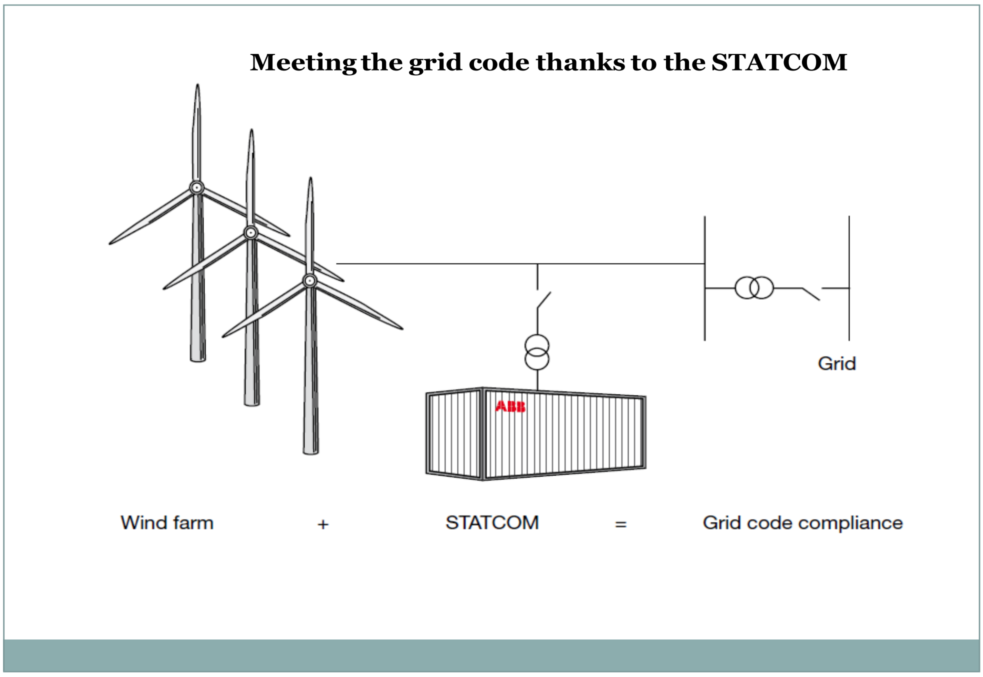
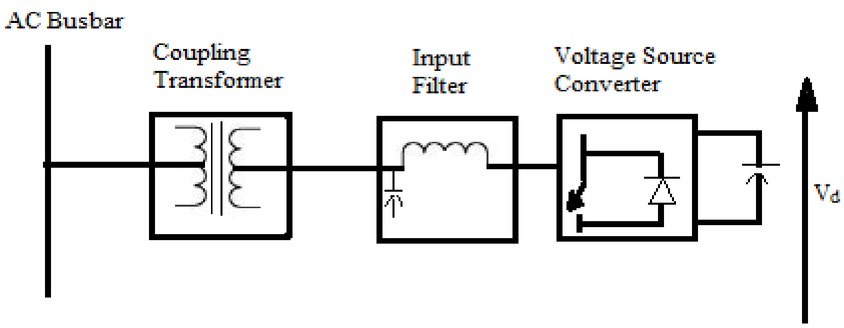
VI. STATCOM INSTALLATION





As discussed in the earlier chapter, we use a STATCOM for transmission voltage control by shunt compensation of reactive power. Usually, STATCOM consists of a coupling transformer, a converter and a DC capacitor, as shown in the figure below.

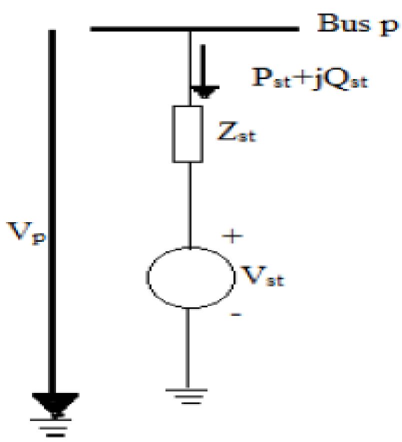


Fig 4.2

VII. COMPENSATION TECHNIQUES

The principles of both shunt and series reactive power compensation techniques are described below:

1.2.1 Shunt compensation

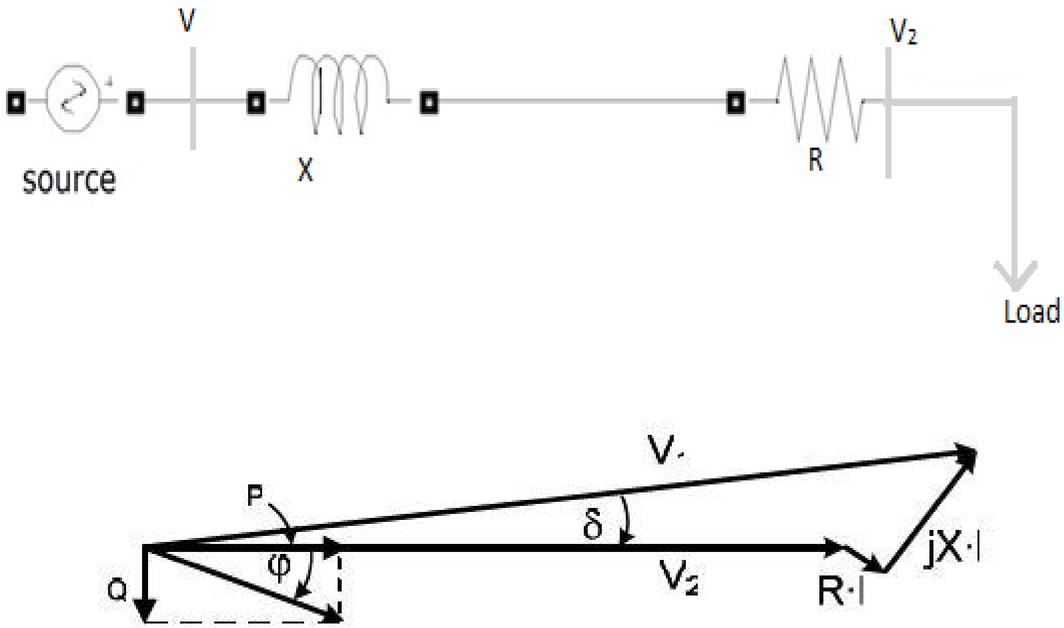


Fig 1.1

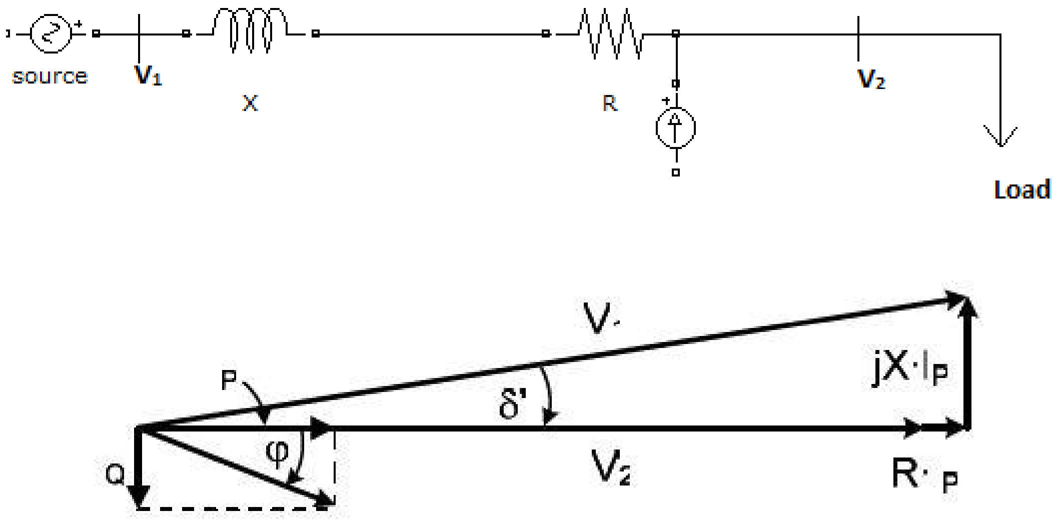


Fig 1.2

The figure 1.1 comprises of a source V1, a power line and an inductive load. The figure 1.1 shows the system without any type of compensation. The phasor diagram of these is also shown above. The active current Ip is in phase with the load voltage V2. Here, the load is inductive and hence it requires reactive power for its proper operation and this has to be supplied by the source, thus increasing the current from the generator and through the power lines. Instead of the lines carrying this, if the reactive power can be supplied near the load, the line current can be minimized, reducing the power losses and improving the voltage regulation at the load terminals. This can be done in three ways: 1) A voltage source. 2) A current source. 3) A capacitor.

In this case, a current source device is used to compensate Iq, which is the reactive component of the load current. In turn the voltage regulation of the system is improved and the reactive current component from the source is reduced or almost eliminated. This is in case of lagging compensation. For leading compensation, we require an inductor. 15 Therefore we can see that, a current source or a voltage source can be used for both leading and lagging shunt compensation, the main advantages being the reactive power generated is independent of the voltage at the point of connection.

1.2.2 Series compensation

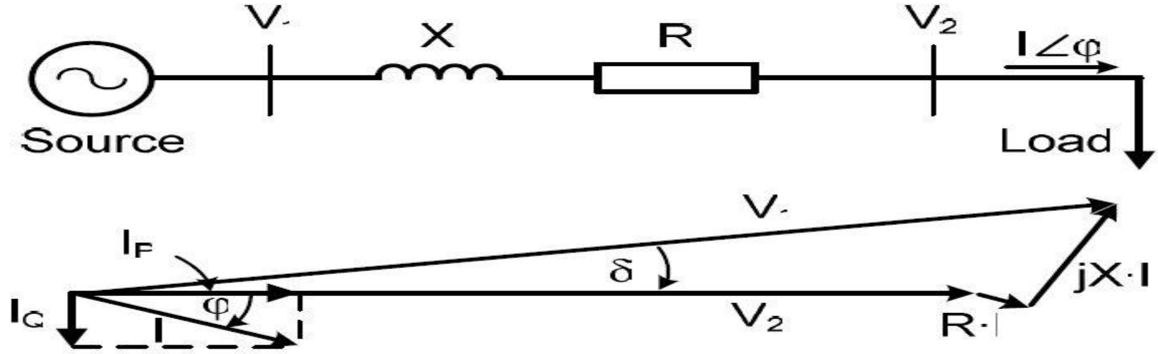


FIG 1.3

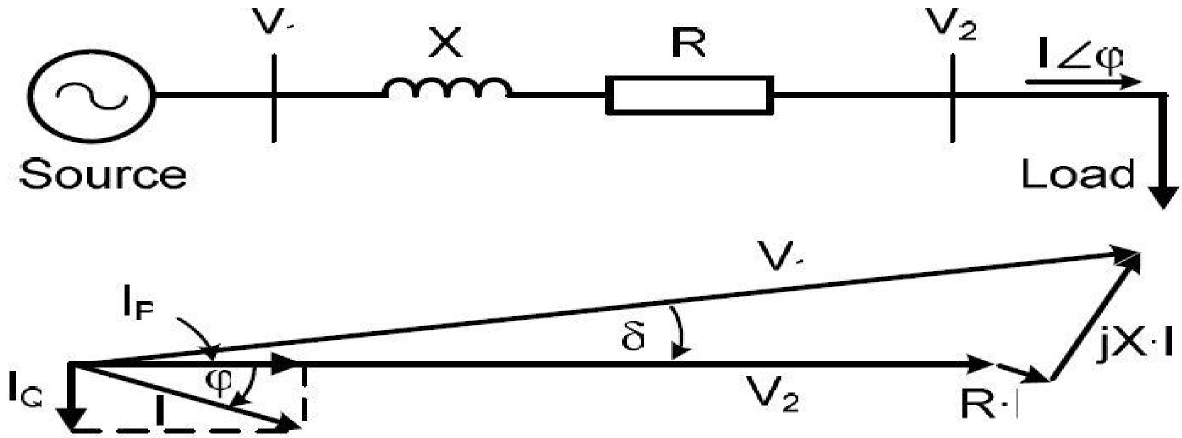


FIG1.4

Series compensation can be implemented like shunt compensation, i.e. with a current or a voltage source as shown in figure 1.4. We can see the results which are obtained by series compensation through a voltage source and it is adjusted to have unity power factor at V2. However series compensation techniques are different from shunt compensation techniques, as capacitors are used mostly for series compensation techniques. In this case, the voltage Vcomp has been added between the line and the load to change the angle V2'. Now, this is the voltage at the load side. With proper adjustment of the magnitude of Vcomp, unity power factor can be reached at v2

VIII. FACTS DEVICES USED

Flexible AC transmission system or FACTS devices used are:

1) VAR generators.

a) Fixed or mechanically switched capacitors.
b) Synchronous condensers.
c) Thyristorized VAR compensators.
(i) Thyristors switched capacitors (TSCs).
(ii) Thyristor controlled reactor (TCRs).
(iii) Combined TSC and TCR.
(iv) Thyristor controlled series capacitor (TCSC).

2) Self Commutated VAR compensators.

a) Static synchronous compensators (STATCOMs).
b) Static synchronous series compensators (SSSCs).
c) Unified power flow controllers (UPFCs).
d) Dynamic voltage restorers (DVRs).

IX. NEED FOR REACTIVE POWER COMPENSATION.

The main reason for reactive power compensation in a system is: 1) the voltage regulation; 2) increased system stability; 3) better utilization of machines connected to the system; 4) reducing losses associated with the system; and 5) to prevent voltage collapse as well as voltage sag. The impedance of transmission lines and the need for lagging VAR by most machines in a generating system results in the consumption of reactive power, thus affecting the stability limits of the system as well as transmission lines. Unnecessary voltage drops lead to increased losses which needs to be supplied by the source and in turn leading to outages in the line due to increased stress on the system to carry this imaginary power. Thus we can infer that the compensation of reactive power not only mitigates all these effects but also helps in better transient response to faults and disturbances. In recent times there has been an increased focus on the techniques used for the compensation and with better devices included in the technology, the compensation is made more effective. It is very much required that the lines be relieved of the obligation to carry the reactive power, which is better provided near the generators or the loads. Shunt compensation can be installed near the load, in a distribution substation or transmission substation.

X. STATIC SHUNT COMPENSATOR: STATCOM

One of the many devices under the FACTS family, a STATCOM is a regulating device which can be used to regulate the flow of reactive power in the system independent of other system parameters. STATCOM has no long term energy support on the dc side and it cannot exchange real power with the ac system. In the transmission systems, STATCOMs primarily handle only fundamental reactive power exchange and provide voltage support to buses by modulating bus voltages during dynamic disturbances in order to provide better transient characteristics, improve the transient stability margins and to damp out the system oscillations due to these disturbances.

A STATCOM consists of a three phase inverter (generally a PWM inverter) using SCRs, MOSFETs or IGBTs, a D.C capacitor which provides the D.C voltage for the inverter, a link reactor which links the inverter output to the a.c supply side, filter components to filter out the high frequency components due to the PWM inverter. From the d.c. side capacitor, a three phase voltage is generated by the inverter. This is synchronized with the a.c supply. The link inductor links this voltage to the a.c supply side. This is the basic principle of operation of STATCOM

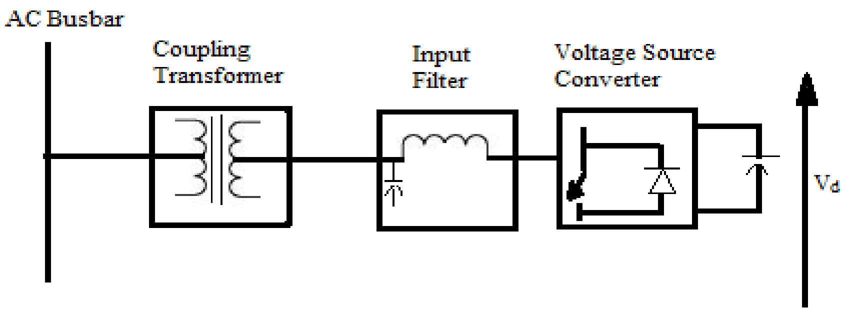


FIG 2.1

For two AC sources which have the same frequency and are connected through a series inductance, the active power flows from the leading source to the lagging source and the reactive power flows from the higher voltage magnitude source to the lower voltage magnitude source. The phase angle difference between the sources determines the active power flow and the voltage magnitude difference between the sources determines the reactive power flow. Thus, a STATCOM can be used to regulate the reactive power flow by changing the magnitude of the VSC voltage with respect to source bus voltage.

2.2 Phase angle control

In this case the quantity controlled is the phase angle δ. The modulation index "m" is kept constant and the fundamental voltage component of the STATCOM is controlled by changing the DC link voltage. By further charging of the DC link capacitor, the DC voltage will be increased, which in turn increases the reactive power delivered or the reactive power absorbed by the STATCOM. On the other hand, by discharging the DC link capacitor, the reactive power delivered is decreased in capacitive operation mode or the reactive power absorbed by the STATCOM in an inductive power mode increases. For both capacitive and inductive operations in steady-state, the STATCOM voltage lags behind AC line voltage ($\delta > 0$).

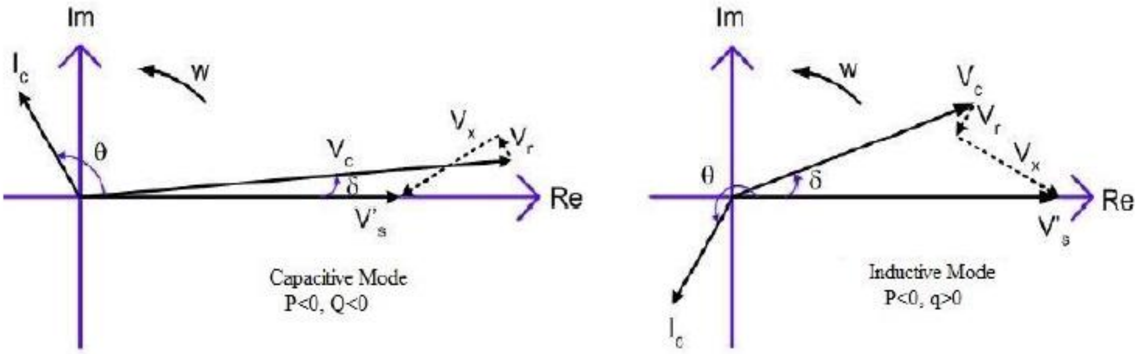


Fig 2.2

By making phase angle δ negative, power can be extracted from DC link. If the STATCOM becomes lesser than the extracted power, Pc in becomes negative and STATCOM starts to deliver active power to the source. During this transient state operation, Vd gradually decreases. The phasor diagrams which illustrating power flow between the DC link in transient state and the ac supply is shown in above Fig. For a phase angle control system, the open loop response time is determined by the DC link capacitor and the input filter inductance. The inductance is applied to filter out converter harmonics and by using higher values of inductance; the STATCOM current harmonics is minimized.

The reference reactive power (Qref) is compared with the measured reactive power (Q). The reactive power error is sent as the input to the PI controller and the output of the PI controller determines the phase angle of the STATCOM fundamental voltage with respect to the source voltage.

XI. PWM TECHNIQUES USED IN STATCOM

Sinusoidal PWM technique

We use sinusoidal PWM technique to control the fundamental line to-line converter voltage. By comparing the three sinusoidal voltage waveforms with the triangular voltage waveform, the three phase converter voltages can be obtained.

The fundamental frequency of the converter voltage i.e. f1, modulation frequency, is determined by the frequency of the control voltages, whereas the converter switching frequency is determined by the frequency of the triangular voltage i.e. fs, carrier frequency. Thus, the modulating frequency f1 is equal to the supply frequency in STATCOM.

The Amplitude modulation ratio, ma is defined as:

$$m_a = \frac{V_{control}}{V_{tri}}$$

Where Vcontrol is the peak amplitude of the control voltage waveform and Vtri is the peak amplitude of the triangular voltage waveform. The magnitude of triangular voltage is maintained constant and the Vcontrol is allowed to vary.

The range of SPWM is defined for 0≤ma≤1 and over modulation is defied for ma>1.

The frequency modulation ratio mf is defined as:

$$m_f = \frac{f_s}{f_i}$$

The frequency modulation ratio, mf , should have odd integer values for the formation of odd and half wave symmetric converter line-to-neutral voltage(VA0). Thus, even harmonics are eliminated from the VA0 waveform. Also, to eliminate the harmonics we choose odd multiples of 3 for mf.

The converter output harmonic frequencies can be given as:

$$f_h = (jm_f \pm k)f_1$$

The relation between the fundamental component of the line-to-line voltage (V_{A0}) and the amplitude modulation ratio m_a can be gives as:

$$V_{A0} = m_a \frac{V_d}{2}, m_a \leq 1$$

From which, we can see that V_{A0} varies linearly with respect to m_a, irrespective of m_f.

The fundamental component converter line-to-line voltage can be expressed as:

$$V_{LL1} = \frac{\sqrt{3}}{2\sqrt{2}} m_a V_d ; m_a \leq 1$$

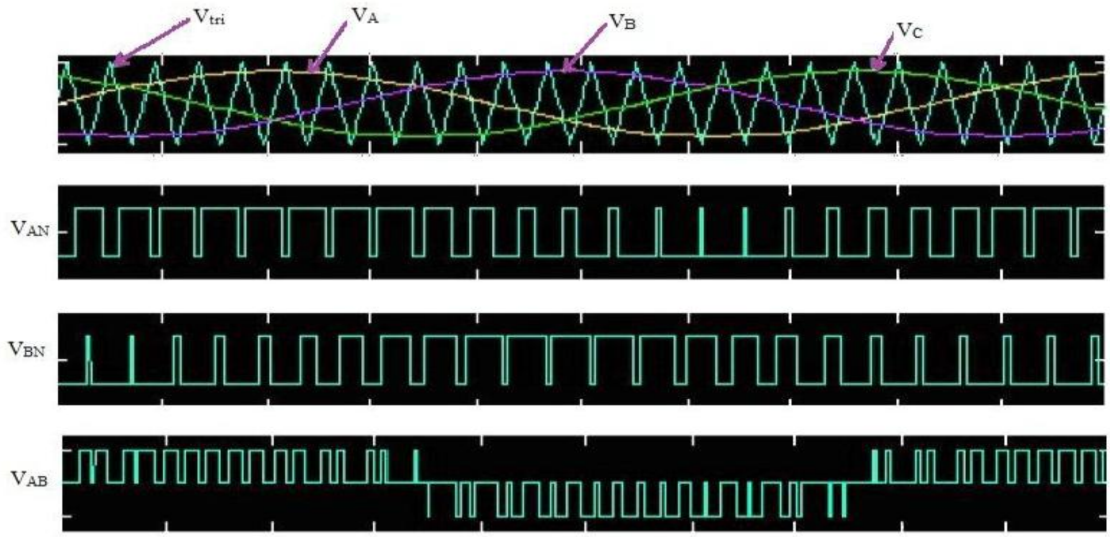


Fig 2.3

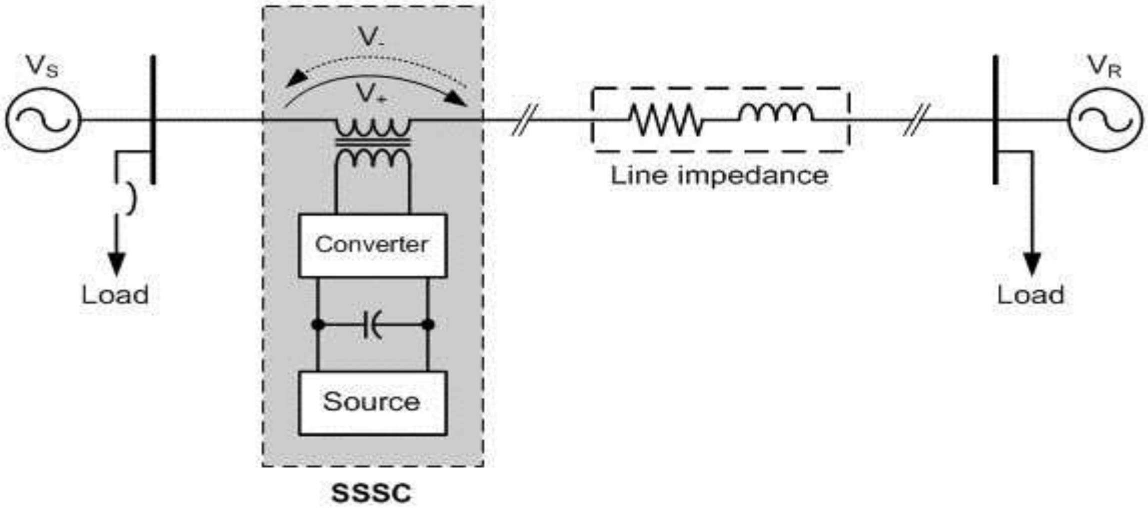
In this type of PWM technique, we observe switching harmonics in the high frequency range around the switching frequency and its multiples in the linear range. From above equation, we can see that the amplitude of the fundamental component of the converter line-to-line voltage is 0.612maVd. But for square wave operation, we know the amplitude to be 0.78Vd. Thus, in the linear range the maximum amplitude of fundamental frequency component is reduced. This can be solved by over modulation of the converter voltage waveform, which can increase the harmonics in the sidebands of the converter voltage waveform. Also, the amplitude of VLL1 varies nonlinearly with ma and also varies with mf in over modulation as given

In a Constant DC Link Voltage Scheme the STATCOM regulates the DC link voltage value to a fixed one in all modes of operation. This fixed value is determined by the peak STATCOM fundamental voltage from the full inductive mode of operation to full capacitive mode at minimum and maximum voltage supply.

Therefore, for $0 \leq ma \leq 1$;

The fundamental voltage is varied by varying ma in the linear range SSSC

The Static Synchronous Series Compensator (SSSC) is a series connected FACTS controller based on VSC and can be viewed as an advanced type of controlled series compensation, just as a STATCOM is an advanced SVC.A SSSC has several advantages over a TCSC such as (a) elimination of bulky passive components { capacitors and reactors, (b) improved technical characteristics (c) symmetric capability in both inductive and capacitive operating modes (d) possibility of connecting an energy source on the DC side to exchange real power with the AC network .



The SSSC when operated with an appropriate DC supply (an energy source and/or sink, or a suitable energy storage) can inject a component of voltage in anti-phase with the voltage developed across the line resistance, to counteract the effect of the resistive voltage drop on the power transmission. The capability of the SSSC to exchange both active and reactive power makes it possible to compensate for the reactive and resistive voltage drops, maintaining a high effective X/R ratio independently of the degree of series compensation

XII. ADVANTAGES OF SSSC

Due to the continuous voltage injection and in combination with a properly structured controller,

1. It is possible to control the power factor of connected loads
2. In the interconnected distribution network topologies, the additional voltage with its controllable magnitude and phase, van be used to work on the power flows.
3. It can also help to cover the capacitive reactive power demand if cable networks, which is higher than in aerial lines, mainly during low load periods that cause inadmissible load elevations;
4. It balances loads in interconnected distribution networks, providing a balanced system;
5. It reduces the harmonics caused because of the use of distributed electrical generation pants at a distribution network level, by active filtering by injecting voltage with the converter at the load side.

By addition of FACTS devices STATCOM AND SSSC in wind farm reactive power compensation in transmission line can be obtained and low frequency oscillations can be damped.

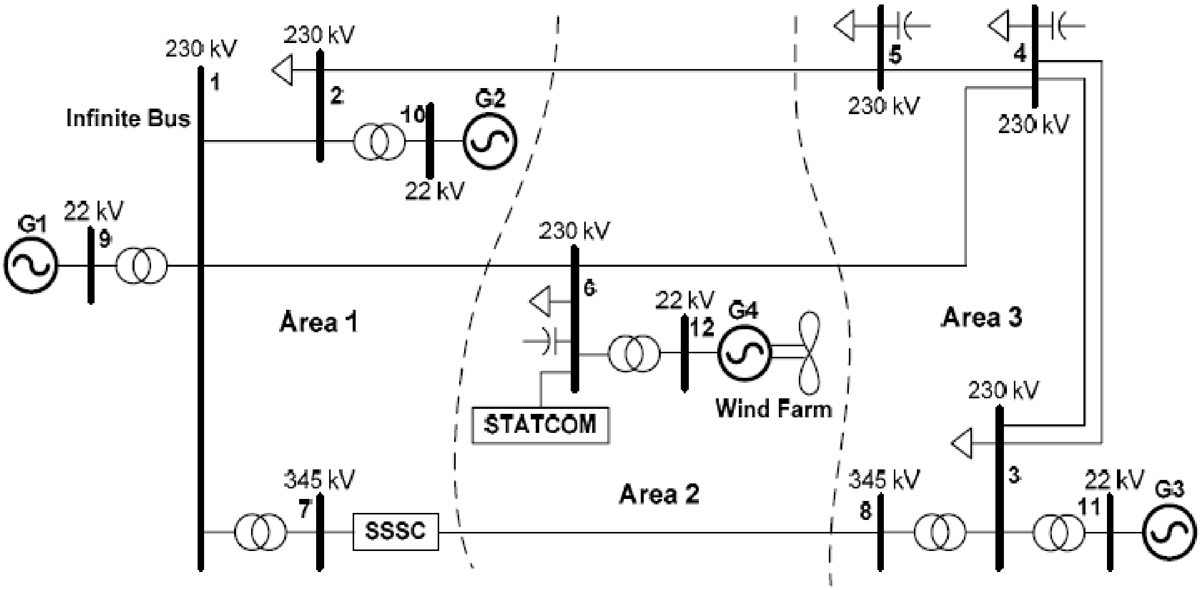


Figure shows single line diagram of 12 bus power system incorporated with large wind farm , STATCOM and SSSC

- Above figure consists of 4 machine 12 bus power system in Which various FACTS devices are used.
- Above system consists of six 230 kv buses and two 345 kv buses and four 22 kv buses.
- Above diagram consists of 3 goegraphical areas A1, A2, A3. A1=power generation area. A2= area located between generation area and load center. A3=load center 500kms away from area 1
- STATCOM is placed at bus 6 to provide steady state as well as transient state voltage support for wind farm. This makes wind farm to generate power even at disturbances occurred due to grid continuously.
- loss of generation in area 3 and overloading of line 1-6 can be prevented by using SSSC
- With suitably designed damping controller SSSC is mainly used for damping frequency oscillations.

G1=3phase infinite source
G2, G3=conventional generators

XIII. ACKNOWLEDGMENTS

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