Multi-Shunt VAR Compensation SVC and STATCOM for Enhance the Power System Quality

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Abstract: *Flexible AC Transmission Systems (FACTS) devices can be operating in shunt or series or compound with the power system to compensate the reactive power. By controlling the thyristor valves, it can control on the voltage system and the reactive power to improve the power system quality. The purpose of this paper is to study the effects of varies controllers: SVC and STATCOM. A comparison of the effectiveness of installing reactive power compensators was presented in large-scale power networks. A suitable bus was first identified using modal analysis method. The single Static Var Compensation (SVC) and single Static Synchronous Compensation (STATCOM) were installed separately on the most critical bus. The effects of the installation of different devices on power loss reduction, voltage profile improvement, and voltage stability margin enhancement. This paper discusses the SVC and STATCOM modules for operation and control to compensate the reactive power to enhance the power system quality. Also, this paper shows the using of MATLAB/Simulink software to describe the operation and control steps for the SVC and STATCOM.*

Keywords: Power Quality, SVC, STATCOM, VAR Compensation and Power System.

1. Introduction:

The increasing on the demand power, so the electrical grid extended and classified to generation, transmission and distribution. This extension required to increase the transmission voltage, that's reached now to 1200Kv. To save the system in service, it must to operate with advanced control devices for system stability, high efficiency and reliability, the advanced control techniques can to effect direct for the electrical system to reach the optimize voltage control [1]. Shunt compensation has been used to influence the natural electrical characteristics of transmission lines to increase steady-state transmittable power and control the voltage profile along the line [2]. Providing adequate reactive power support at appropriate locations not only leads to the reduction in power loss and improvement in voltage profile but also solves voltage instability problems. A number of reactive compensation devices have been used by modern electric power utilities for this purpose, and each device has its own characteristics and limitations. At present, utilities aim to achieve this purpose using the most efficient compensation device [3-5]. Traditionally, shunt capacitors are installed in power networks to compensate reactive power and are used for many purposes, such as reducing power loss, improving voltage profile, and increasing the maximum transmitted power in cables and transformers [5].

Among the available reactive compensation devices, shunt flexible AC transmission system (FACTS) devices play an important role in controlling the flow of reactive power to the power network, thereby affecting system voltage fluctuations and stability [6]. Static var compensator (SVC) is the most widely used shunt FACTS device in power networks because of its low cost and good system enhancement performance. It is a shunt-connected static var generator (SVC) or absorber with an adjustable output, which allows the exchange of capacitive or inductive current to provide voltage support. Installed at a proper location, SVC can also reduce power losses [7-8]. Static synchronous compensator (STATCOM) is also a shunt compensator and an important member of the FACTS family, increasingly used in long transmission lines in modern power systems. STATCOMs have various applications in the operation and control of a power system, including power flow scheduling, reducing the number of unsymmetrical components that damp power oscillation, and enhance transient stability [3-8]. This paper focuses on the FACTS devices and the shunt capacitors to safe the stable operation of an autonomous power system. Each SVC and STATCOM device has different characteristics. Therefore, it is important to study their behaviors in order to use them effectively.

2. Reactive power compensation

Firstly, it's important to discusses the active and reactive power. Fig. 1shows the phasor diagram of active, reactive and apparent power. Where, the resistor *R* connected to a three-phase a.c. voltage source will see a current which is in phase with the voltage across this resistor. If an inductance *L* or a capacitance *C* is connected to the same source, the current will be 90° lagging or leading with respect to the voltage. Real power systems represent a combination of *R*, *L* and *C*, which means that voltage and current are usually not in phase [6-10]. The angle between voltage and current is called the phase angle ϕ.

Apparent power *S* is the product of voltage (*U*) and current (*I*) and has the unit volt-ampere [VA].

$$S = \sqrt{3}\ UI \quad \text{[VA]} \tag{1}$$

Like voltage and current, apparent power can also be represented in a phasor diagram as a complex quantity. The real component of this phasor is called active power and the imaginary component is the reactive power. The cosine of the angle between active and apparent power is the power factor cosϕ.

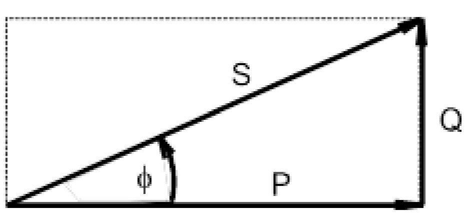

Fig. 1 Phasor diagram of active, reactive and apparent power.

Active power *P* is the product of the voltage and the in-phase (active) component of the current. The active power is measured in watts [W].

$$P = \sqrt{3}\, UI \cos\phi = S \cos\phi \qquad \text{[W]} \tag{2}$$

Reactive power *Q* is the product of the voltage and the watt-less (reactive) component of the current. The unit of the reactive power is volt-ampere reactive [var]. According to IEC Publ. 27-1 the unit abbreviation 'var' should be written in lower-case letters, while all other power unit abbreviations are to be in capital letters [3-8].

$$Q = \sqrt{3}\, UI \sin\phi = S \sin\phi \quad \text{[var]}\ . \tag{3}$$

Reactive power can be either positive or negative, depending on the sign of the phase angle ϕ. By definition, positive reactive power means power consumption and is characteristic for inductive loads such as power converters, reactances and motors. Negative reactive power indicates reactive power generation typical for generators or capacitor banks.

Reactive power compensation, SVCs usually generate the reactive power which is consumed by the load, meaning that positive reactive power of the load is compensated for by negative reactive power of the SVC. It is desired to reduce the remaining reactive power as far as possible in order to reduce the equipment ratings and energy transmission losses.

2.1 Voltage control

Reactive power compensation is often the most effective approach to improve both voltage stability and power transfer capability. Basic means of voltage control are offered through generating units due to the fact that the automatic voltage regulators control field excitation to maintain voltage levels at the terminals of generators. This, however, does not completely control the voltage throughout the system; hence, additional devices have to be used to compensate reactive power [5-11]. One approach for compensating voltage drops in transmission networks is to add substations containing shunt capacitors along the line. The installation of shunt capacitor substations acts in such a way that it breaks the transmission line into shorter segments, with each substation responsible for providing a constant voltage along that segment. Switching the shunt capacitors in and out compensates the voltage along the transmission line [8]. These shunt capacitors have to mechanically be switched on and off; hence, there is usually difficulty when it comes to coordination. Due to this, other, more sophisticated methods of voltage regulation are necessary [6-9]. A load current passing through the series impedances $R+jX$ of transmission lines, cables or transformers creates a voltage drop ΔU across this impedance, causing a voltage difference between the sending end and the receiving end of the transmission system. Without additional measures, the voltage at the receiving end is usually smaller than the voltage at the sending end. This voltage drop can be calculated approximately by applying the following equation:

$$\mathrm{D}U = U_s - U_r \approx RI \cos\alpha + XI \sin\alpha \tag{4}$$

From equation (4) it can be seen that any change in load current I will cause a change in busbar voltage. Very large cyclically varying loads, such as the SPS having a large reactive and active power swing and very short rise times of the pulse, will cause heavy disturbances of the 18 kV and 400 kV busbar voltages, making the operation of the accelerator impossible and disturbing other electrical loads connected to the power network [3-9]. Equation (4) also shows that the reactive power is an excellent means to control the voltage drop and therefore the busbar voltage. Modern SVCs are able to change their reactive power output within 100 ms, making them highly suitable for the voltage control of busbars feeding fast changing or pulsing loads such as electric arc furnaces, rolling mills or particle accelerators.

3. Static Var Compensation (SVC)

Shunt compensation can be used to provide reactive power compensation. Traditional shunt capacitors or the newly introduced FACTS controllers can be used for this purpose. However, FACTS controllers are very expensive compared to shunt capacitors.

A Static Var Compensator (SVC) is a device which compensates for the reactive power of the load connected to a power system. Because of its fast response it can stabilize the busbar voltage even during fast changes of the load. An SVC is usually directly connected to a medium voltage power system. In the past, many SVCs were based on the effect of self-saturation of the iron core of a so-called saturated reactor. Since the end of the seventies, thyristor-controlled SVCs have been available on the market and for a few years one has been able to observe the development of new SVC technologies based on GTO or IGBT semiconductors [6]. The aim of this development is to improve dynamic performance, flicker control and speed of reactive power regulation as well as the reduction of losses which form a major part of the operating costs of such an installation. Fig. 2 shows the SVC design with the power system. SVC is a shunt-connected static var generator/load whose output can be adjusted to exchange capacitive or inductive current to maintain or control a specific power system variable [11–12]. In its simplest form, SVC consists of a thyristor-controlled reactor in parallel with a bank of capacitors. From operational perspective, SVC behaves like a shunt-connected variable reactance, which either generates or absorbs reactive power to regulate the voltage magnitude at the point of connection to the AC network. It is used extensively to provide fast reactive power and voltage regulation support. The thyristor's firing angle control enables SVC to provide an almost instantaneous response speed. As an important component for voltage control, it is usually installed at the receiving node of transmission lines. Fig. 3 shows an SVC that has been considered as a shunt branch with a compensated reactive power QSVC, set by available inductive and capacitive susceptances [5-13].

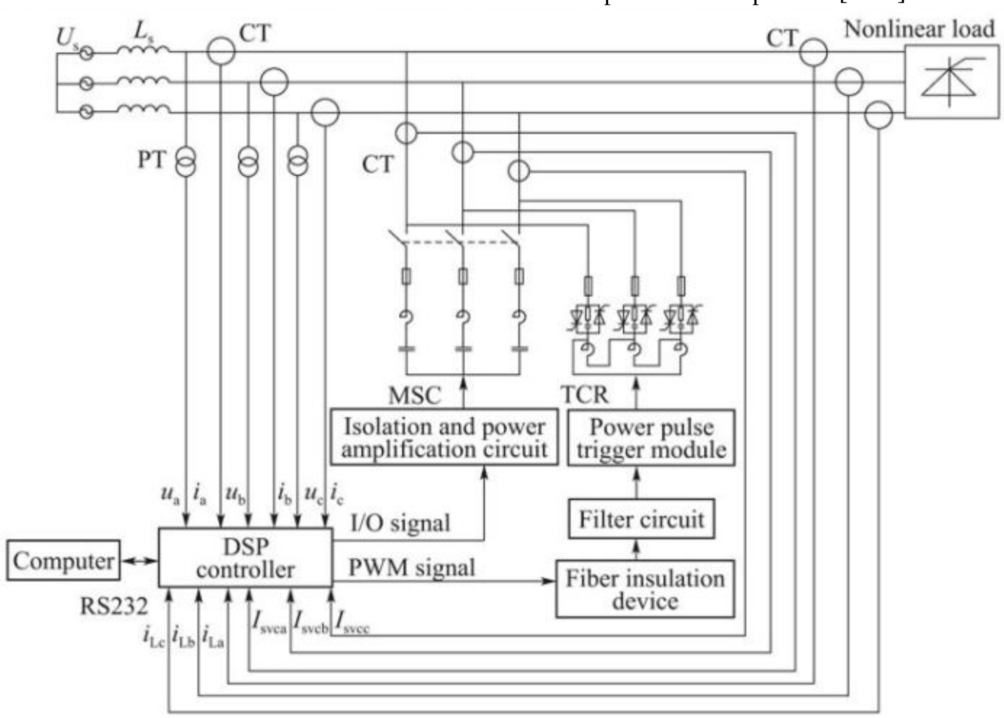

Fig. 2 Static Var Compensation design

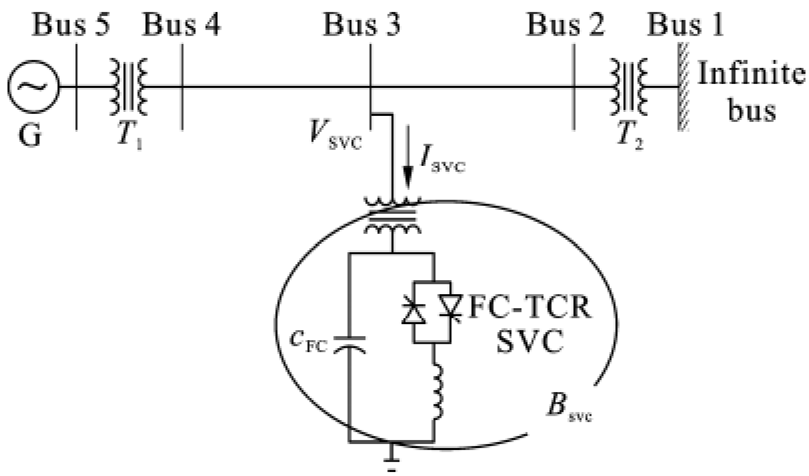

Fig. 3 Circuit diagram of SVC

The main control logic for the firing angle for the thyristor is related to determine the SVC susceptance required in the transmission system, to reach the voltage to the reference value. When there is a discrepancy between the two values, the controller orders changes in the susceptance until equilibrium is attained [6-12]. The general control module is depending on the SVC function of the system voltage Vk and the susceptance B_{SVC} is determined as:

$$I_{SVC} = \mathrm{j}\, B_{SVC}\, V_K \tag{5}$$

In the function for the step-down transformer the susceptance can to determine by:

$$B_{SVC} = \frac{B_\sigma(B_{C1}+B_{C2}+\cdots\ldots\ldots+B_{Cn}+B_{TCR})}{(B_\sigma+B_C+B_{TCR})} \tag{6}$$

where B_σ corresponds to the susceptance of the transformer, B_{TCR} varies from 0 to B_L, the firing angles changes and control from 180◦ to 90◦, B_L consider the susceptance of the reactor and B_C is the susceptance of capacitor bank. Thus, expressions for the maximum and minimum susceptance are determined as:

$$B_{SVC}^{Max} = \frac{B_\sigma(B_{C1}+B_{C2}+\cdots+B_{Cn})}{B_\sigma+B_{C1}+B_{C2}+\cdots+B_{Cn}} \tag{7}$$

$$B_{SVC}^{Min} = \frac{B_\sigma(B_{C1}+B_{C2}+\cdots+B_{Cn}+B_L)}{B_\sigma+B_{C1}+B_{C2}+\cdots+B_{Cn}+B_L} \tag{8}$$

The thresholds of reactive power that can be exchanged to the system are defined as:

$$Q_{SVC}^{Max} = -V_{Max}^2 B_{SVC}^{Min} \tag{9}$$

$$Q_{SVC}^{Min} = -V_{Min}^2 B_{SVC}^{Max} \tag{10}$$

3.1 Simulation SVC for Voltage Regulator

By using MATLAB/Simulink software, we can to simulate the SVC module with the power system. Fig. 4 and Fig. 5 shows the SVC system and control; the SVC is set to Voltage regulation mode with a reference voltage Vref = 1.0 pu. The voltage droop reactance is 0.03 pu/200 MVA, so that the voltage varies from 0.97 pu to 1.015 pu when the SVC current goes from fully capacitive to fully inductive. Double-click the blue block to display the SVC V-I characteristic [4-15].

The Three-Phase Programmable Voltage Source is used to vary the system voltage and observe the SVC performance. Initially the source is generating its nominal voltage (500 kV). Then, voltage is successively decreased (0.97 pu at t = 0.1 s), increased (1.03 pu at t = 0.4 s) and finally returned to nominal voltage (1 pu at t = 0.7 s).

Start the simulation and observe the SVC dynamic response to voltage steps on the Scope. Waveforms are reproduced on the Fig. 6. Where, Trace 1 shows the actual positive-sequence susceptance B1 and control signal output B of the voltage regulator, also shows the actual system positive-sequence voltage V1 and output Vm of the SVC measurement system. Trace 2 shows the compensation Mvar value.

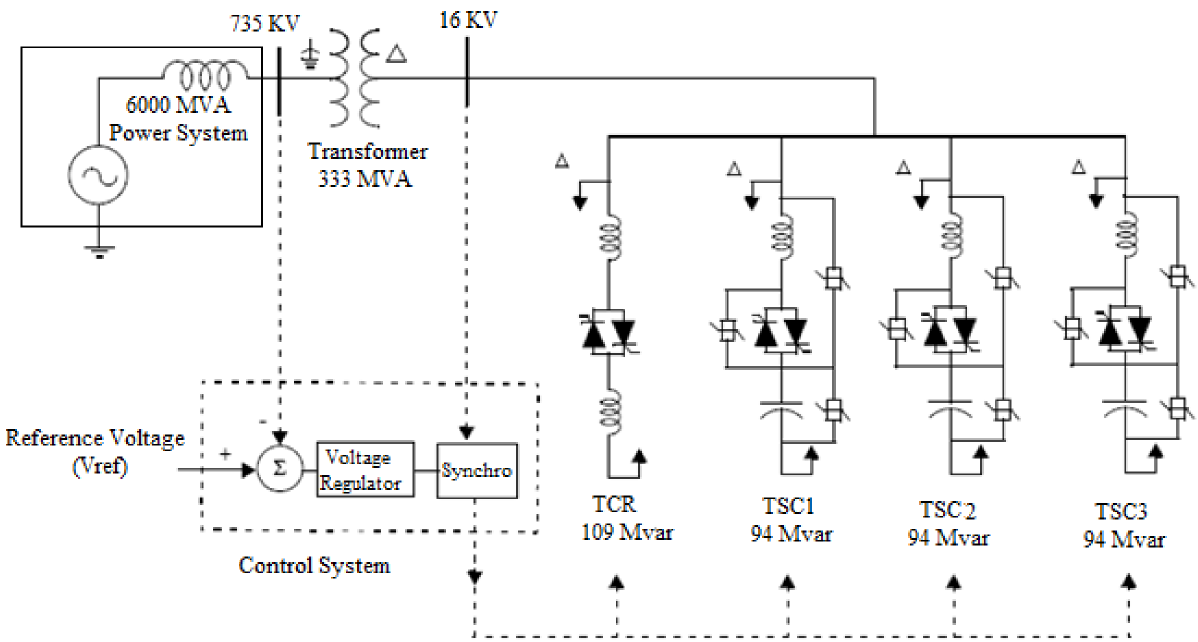

Fig. 4 Single line diagram of SVC connected with power system

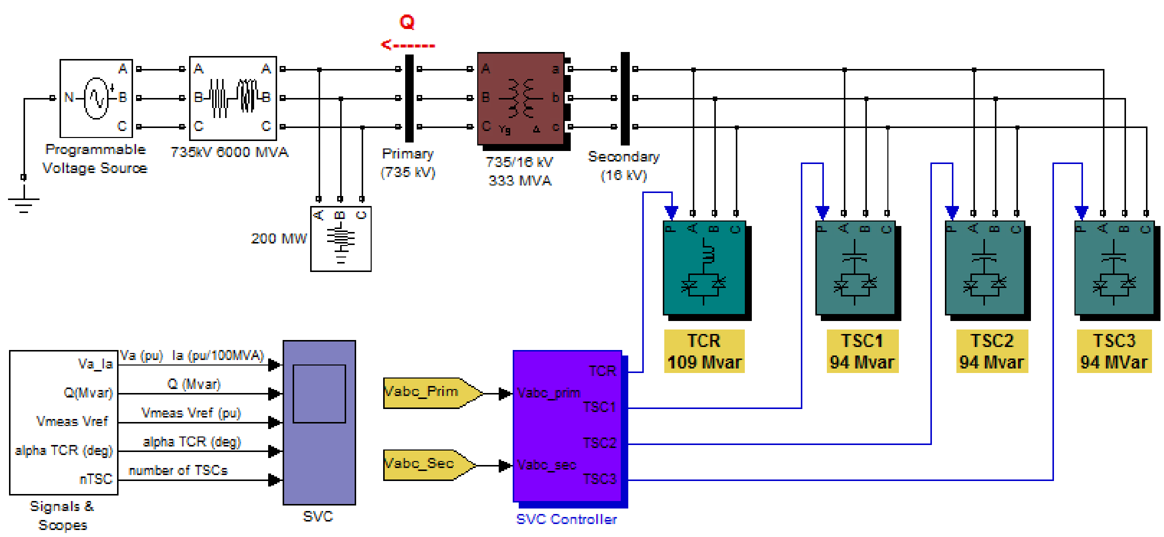

Fig. 5 System simulation by MATLAB/Simulink software

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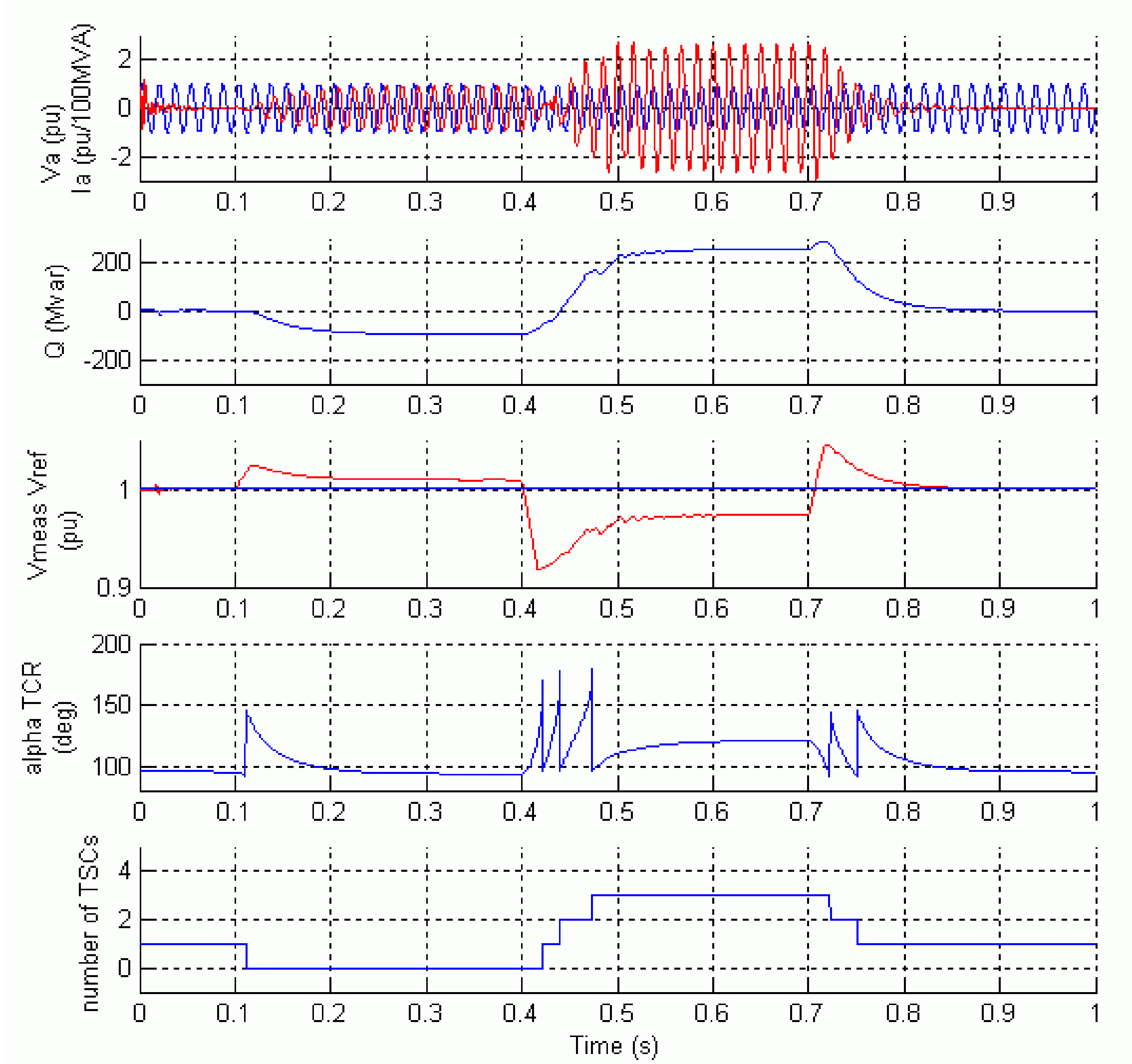

Fig. 6 SVC waveforms steady-state and dynamic response to regulate the voltage

4. STATCOM Operation and Control

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 [7-17]. 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 [8-18]. The link inductor links this voltage to the A.C supply side. This is the basic principle of operation of STATCOM.

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 [7-10]. 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. Fig. 8 shows the phasor diagrams which illustrating power flow between the DC link in transient state and the ac supply.

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) [7-10]. 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. Fig. 9 shows the basic STATCOM design. To simulate the STATCOM equations, it's can represent the shunt voltage source of the three-phase E_{VR}, also, V_K is the magnitude of the bus voltage to determine the reactive power flow, and the V_{VR} is the VSC output fundamental voltage [2-16]. The principle operation of the STATCOM module is given by a source coupled in parallel to the node with series impedance ($Y_{VR} = G_{VR} + jB_{VR}$), the expression current supplied to the bus system as:

$$I_{VR} = Y_{VR}\, E_{VR} - Y_{VR} V_K \tag{11}$$

In addition, the reactive power is expressed as:

$$Q_{VR} = V_{VR}^2 B_{VR} - V_{VR} V_K [G_{VR} \cos(\delta_{VR} - \theta_K) - B_{VR} \sin(\delta_{VR} - \theta_K)] \tag{12}$$

Where, δ_{VR} and θ_K are the voltage phase angles. For $V_{VR} > V_K$, the controller generates reactive power and consumes reactive power when $V_{VR} < V_K$.

4.1 STATCOM simulation

Depending on the power rating of the STATCOM, different technologies are used for the power converter. High power STATCOMs (several hundreds of Mvars) normally use GTO-based, square-wave voltage-sourced converters (VSC), while lower power STATCOMs (tens of Mvars) use IGBT-based (or IGCT-based) pulse-width modulation (PWM) VSC. The Static Synchronous Compensator (Phasor Type) block of the FACTS library is a simplified model, which can simulate different types of STATCOMs. Due to low frequencies of electromechanical oscillations in large power systems (typically 0.02 Hz to 2 Hz), this type of study usually requires simulation times of 30–40 seconds or more [10-18].

The STATCOM model described in this example is rather a detailed model with full representation of power electronics. It uses a square-wave, 48-pulse VSC and interconnection transformers for harmonic neutralization. Fig. 3 Shows the STATCOM module and Fig. 4 Control Circuit on 100 Mvar STATCOM on a 500 kV Power System, this type of model requires discrete simulation at fixed type steps (25 µs in this case) and it is used typically for studying the STATCOM performance on a much smaller time range (a few seconds). Typical applications include optimizing of the control system and impact of harmonics generated by converter [17].

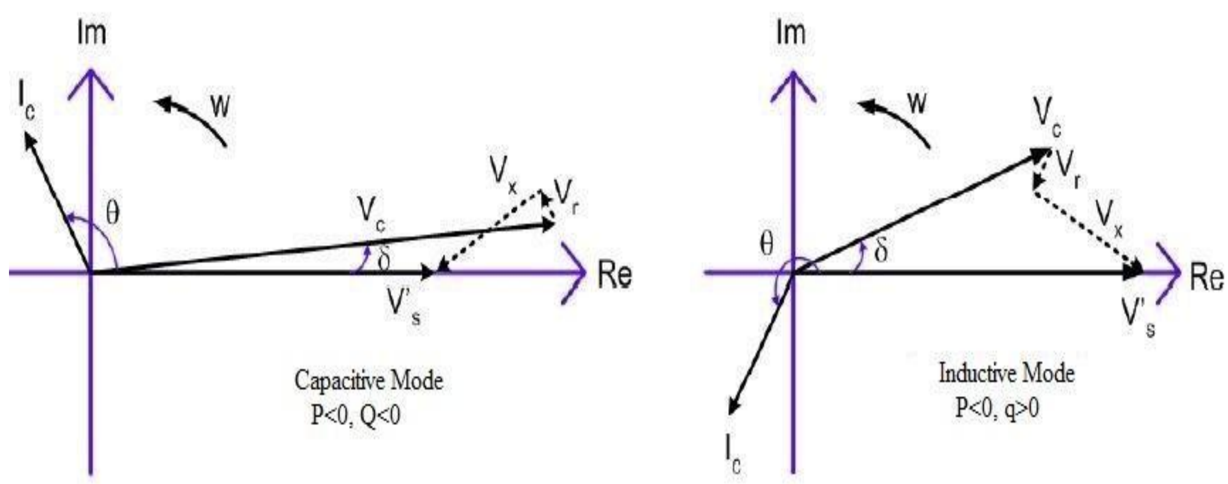

Fig. 8 Phasor diagrams for illustrating power flow between the DC and AC

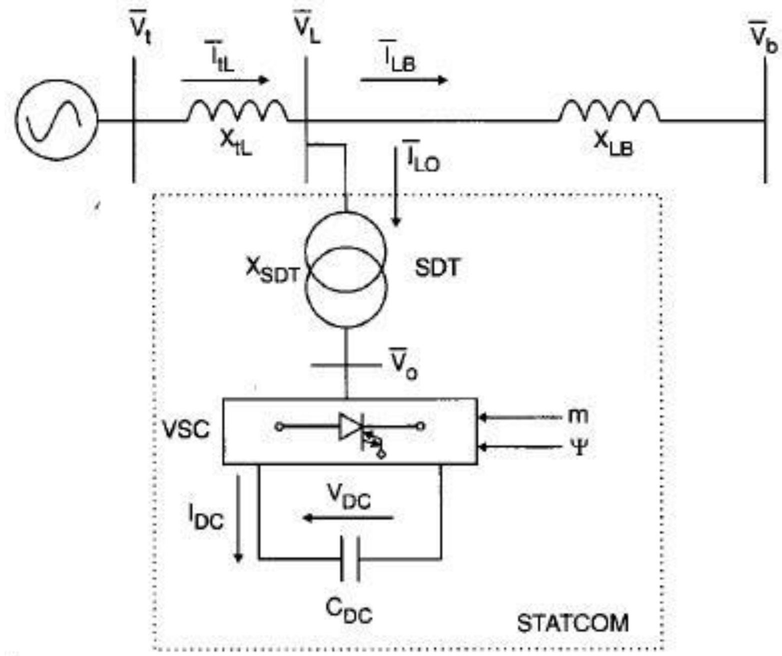

Fig. 9 the basic STATCOM design

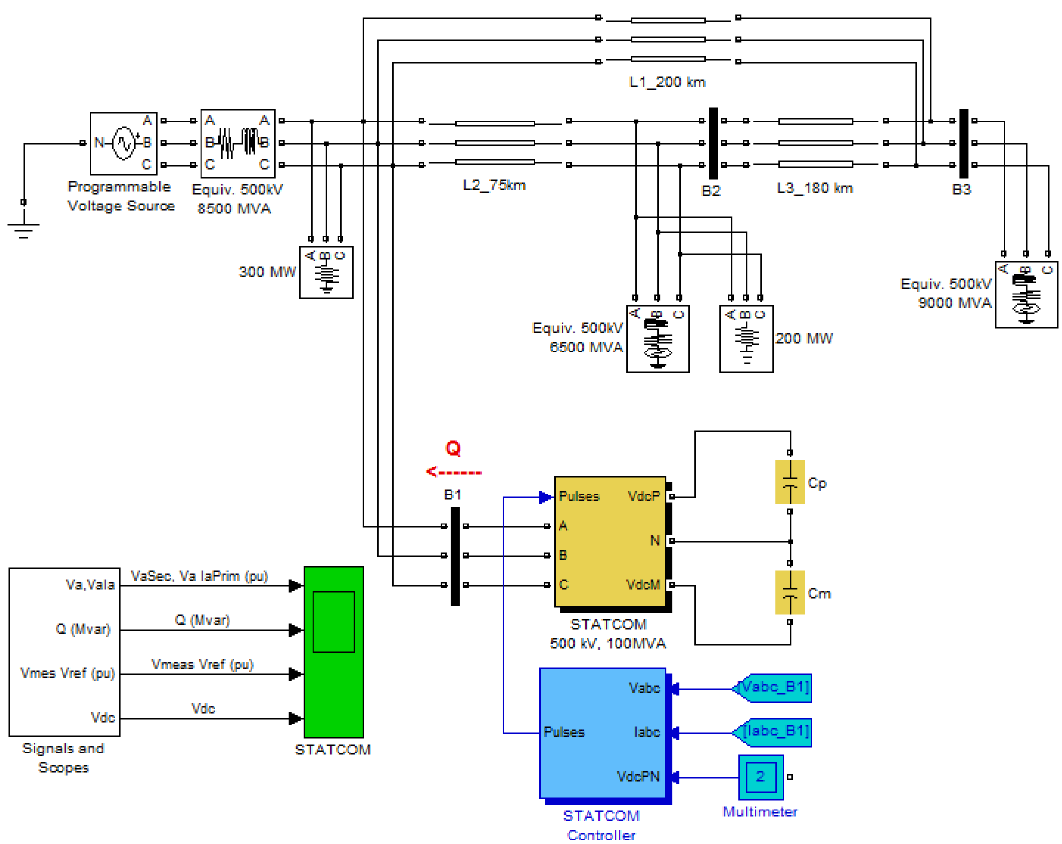

Fig. 10 Model of the 100 Mvar STATCOM on a 500 kV Power System

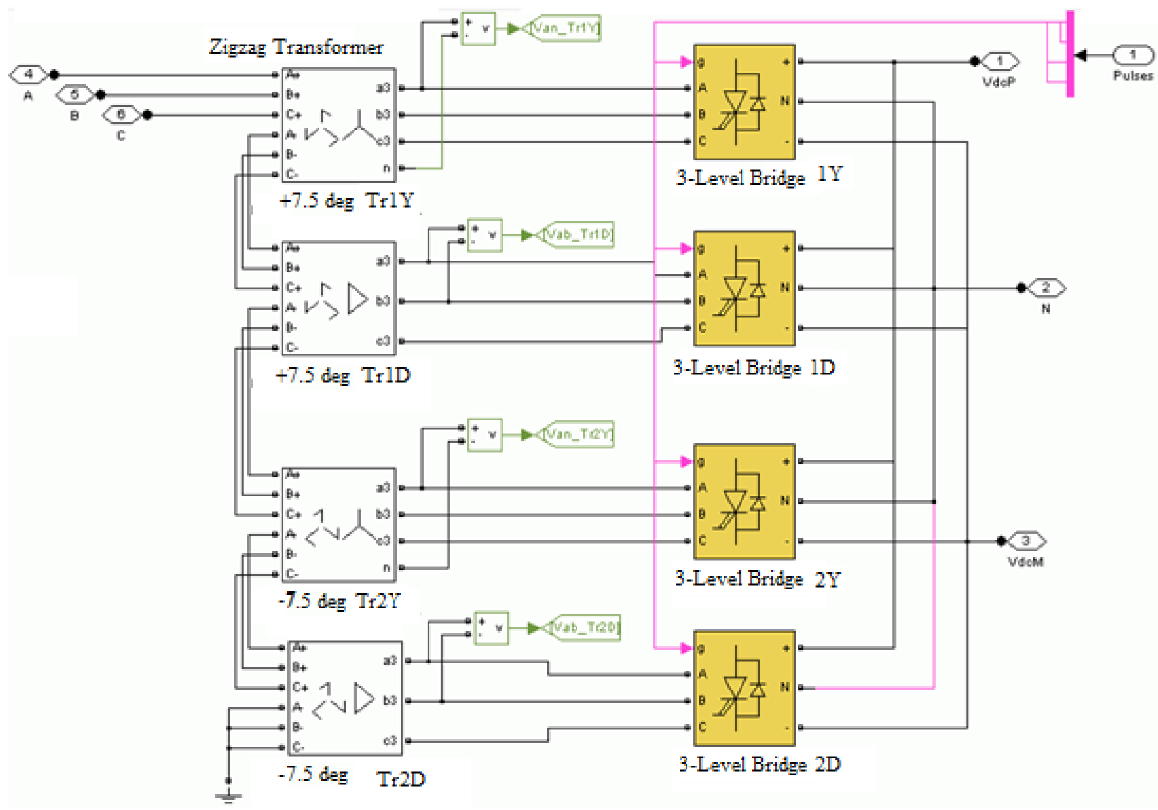

Fig. 11 Control Circuit on 100 Mvar STATCOM on a 500 kV Power System

Except for the 23rd and 25th harmonics, this transformer arrangement neutralizes all odd harmonics up to the 45th harmonic. Y and D transformer secondaries cancel harmonics 5+12n (5, 17, 29, 41,...) and 7+12n (7, 19, 31, 43,...). In addition, the 15° phase shift between the two groups of transformers (Tr1Y and Tr1D leading by 7.5°, Tr2Y and Tr2D lagging by 7.5°) allows cancellation of harmonics 11+24n (11, 35,...) and 13+24n (13, 37,...). Considering that all 3n harmonics are not transmitted by the transformers (delta and ungrounded Y), the first harmonics that are not canceled by the transformers are therefore the 23rd, 25th, 47th and 49th harmonics. By choosing the appropriate conduction angle for the three-level inverter (σ = 172.5°), the 23rd and 25th harmonics can be minimized. The first significant harmonics generated by the inverter will then be 47th and 49th. Using a bipolar DC voltage, the STATCOM thus generates a 48-step voltage approximating a sine wave [15-17].

Fig. 12 shows the waveforms Illustrating STATCOM Dynamic Response to System Voltage Steps. PLL (phase locked loop) synchronizes GTO pulses to the system voltage and provides a reference angle to the measurement system. Measurement System computes the positive-sequence components of the STATCOM voltage and current, using phase-to-dq transformation and a running-window averaging. Voltage regulation is performed by two PI regulators: from the measured voltage Vmeas and the reference voltage Vref, the Voltage Regulator block (outer loop) computes the reactive current reference Iqref used by the Current Regulator block (inner loop). The output of the current regulator is the α angle which is the phase shift of the inverter voltage with respect to the system voltage. This angle stays very close to zero except during short periods of time, as explained below. A voltage droop is incorporated in the voltage regulation to obtain a V-I characteristic with a slope (0.03 pu/100 MVA in this case). Therefore, when the STATCOM operating point changes from fully capacitive (+100 Mvar) to fully inductive (-100 Mvar) the SVC voltage varies between 1-0.03=0.97 pu and 1+0.03=1.03 pu [6-18].

Firing Pulses Generator generates pulses for the four inverters from the PLL output (ω.t) and the current regulator output (α angle). To explain the regulation principle, let us suppose that the system voltage Vmeas becomes lower than the reference voltage Vref. The voltage regulator will then ask for a higher reactive current output (positive Iq= capacitive current). To generate more capacitive reactive power, the current regulator will then increase α phase lag of inverter voltage with respect to system voltage, so that an active power will temporarily flow from AC system to capacitors, thus increasing DC voltage and consequently generating a higher AC voltage. As explained in the preceding section, the conduction angle σ of the 3-level inverters has been fixed to 172.5°. This conduction angle minimizes 23rd and 25th harmonics of voltage generated by the square-wave inverters. Also, to reduce noncharacteristic harmonics, the positive and negative voltages of the DC bus are forced to stay equal by the DC Balance Regulator module. This is performed by applying a slight offset on the conduction angles σ for the positive and negative half-cycles [14-20]. The STATCOM control system also allows selection of Var control mode (see the STATCOM Controller dialog box). In such a case, the reference current Iqref is no longer generated by the voltage regulator. It is rather determined from the Qref or Iqref references specified in the dialog box.

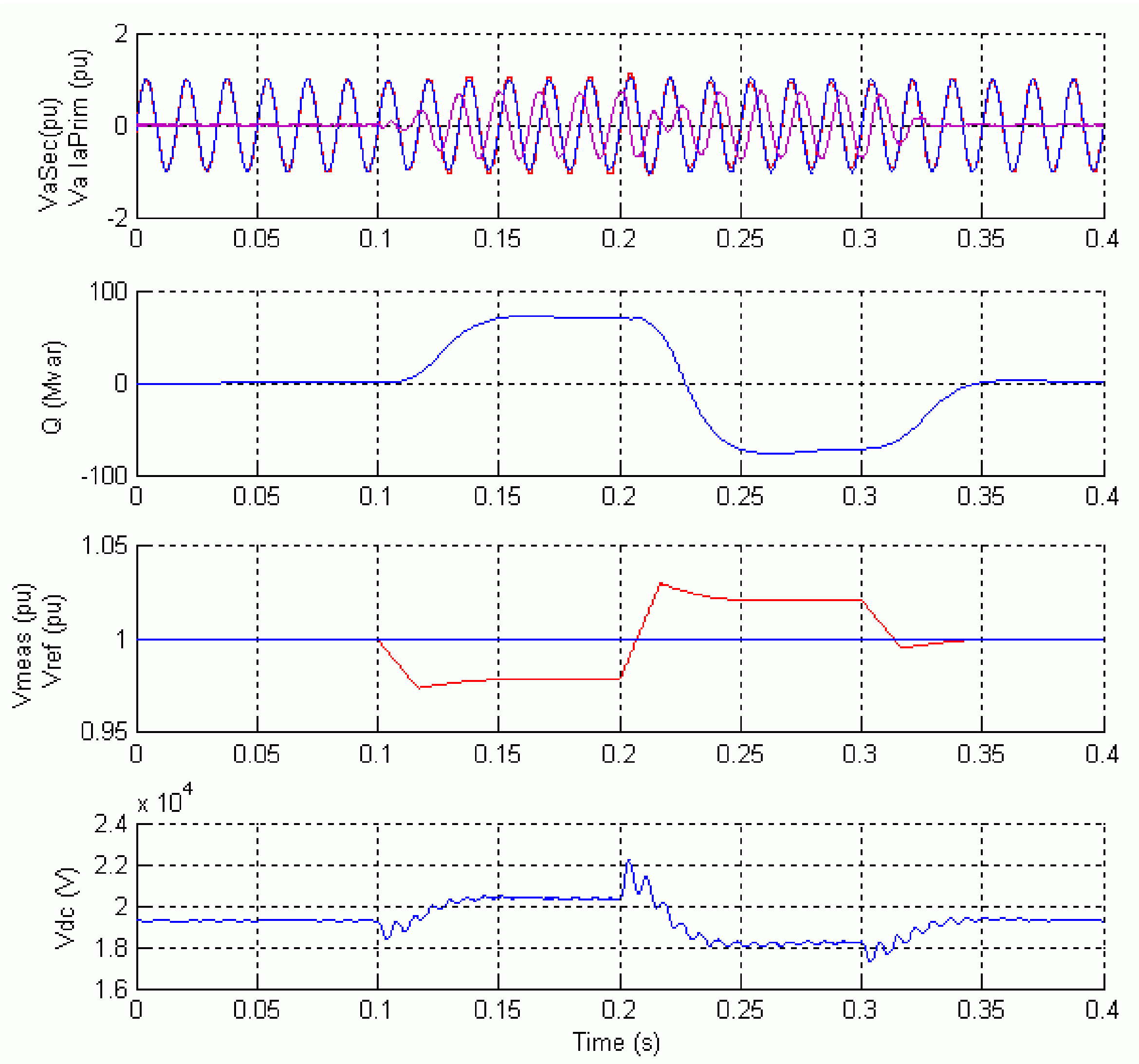

Fig. 12 Waveforms Illustrating STATCOM Dynamic Response to System Voltage Steps

5. Procedure for installing different var compensators

Implementation procedure for installing different var compensators in a power network. The most critical system buses (i.e., buses with large participation factors) considered suitable for shunt var compensator installation are first identified using the modal analysis method. One shunt capacitor, one SVC, and one STATCOM are installed separately on the most critical bus [1]. The total power loss, voltage deviation, and smallest eigenvalue are calculated for each case to compare the effectiveness ofthe capacitor, SVC, and STATCOM on power loss reduction, voltage profile improvement, and voltage stability margin enhancement [19-24]. The comparison and analysis procedures of the effect of the installation of different var compensators on a power system are described as follows:

1) Specify system parameters, such as bus, branch, and generator data;

2) Calculate the Jacobian matrix and eigenvalues for the base system;

3) Calculate eigenvectors and bus participation factors for the smallest eigenvalue;

4) The bus with the largest participation factor is determined and considered suitable for shunt var compensator installation;

6) The power flow program is run to calculate the power loss, voltage deviation, and the eigenvalues for each case;

7) The effectiveness of the shunt capacitor, SVC, and STATCOM on power loss reduction, voltage profile improvement, and voltage stability margin enhancement are compared and analyzed.

6. Conclusions

The technology of FACTS represents an alternative to control. The design and implementation of a control system more efficient for the governors of the machines and for proper control of SVC and STATCOM controllers to improve their response to contingencies of large magnitude are important topics for further research. The Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM) have the ability to provide dynamic compensation to a transmission system. Their speed of response enable increased transient stability margins, voltage support enhancement, and damping of low frequency oscillations. The main operational objective of both FACTS devices is to increase power transmission capability by voltage control at the point of connection of the power network. In this research both controllers are compared by their most important features;

1) The effectiveness of the most commonly used shunt compensation devices such as shunt capacitor, SVC, and STATCOM on power loss reduction, voltage profile improvement, and voltage stability margin enhancement has been compared and analyzed.

2) Overall, the effect of the installation of a single STATCOM in achieving the aforementioned objectives is better than that of a single SVC, and the effect of the installation of a single SVC is better than that of a single shunt capacitor. However, SVC and STATCOM are expensive compared with shunt capacitor.

3) In large-scale test systems, installing only one Var compensation device to achieve all the aforementioned objectives is definitely insufficient. Optimal placement and sizing of multi-var compensators is necessary.

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