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Research Article

Performance of Facts Devices to Improve Power Quality and Application of Static Synchronous Compensator

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Abstract: This study presents the study of configuration, working, controller of the fundamentals of the STATCOM and significant function of each custom power devices. Flexible Ac Transmission Systems (FACTS) controller achieves fast control response time as well as providing better control than conventional control. However, Static Synchronous Compensator (STATCOM) could be seen as one of the key Flexible Ac Transmission Systems (FACTS) devices which are based on the Voltage Source Converter (VSC) technology. The capacitive and inductive compensation could be provided by the controller and could as well control output current over the rated maximum capacitive or inductive range without depending on the ac system voltage.

Keywords: Configuration, controller, FACTS device application, STATCOM, structure

INTRODUCTION

One of the most common power quality problems is Voltage sag. A voltage sag is a reduction in the RMS voltage in the range of 0.1 to 0.9 p.u., (retained) for duration greater than half a mains cycle and less than 1 min and a voltage swell is an increase in the RMS voltage in the range of 1.1 to 1.8 p.u., for a duration greater than half a main cycle and less than 1 min (IEEE Standard 519-1992, 1993). Voltage sags caused by faults, increased load demand and transitional events such as large motor starting. And voltage swell is caused by system faults, load switching and capacitor switching. A voltage interruption is the complete loss of electric voltage Interruptions can be short duration (lasting less than 2 min) or long duration. There are different ways to mitigate voltage dips, swell and interruptions in distribution systems. Power Quality systems could be seen as the nonlinear systems which have a wide range of operating conditions and time with variations in configurations and parameters. Flexible Ac Transmission Systems (FACTS) have been developed towards the improvement of the performance of weak ac systems and enhancement of the transmission capabilities over long ac lines. The three states of the power system where FACTS controllers could be used include the steady state, transient and post transient steady states. Studies have established that FACTS devices can regulate the active and reactive power as well as the voltage-magnitude (Hingorani, 1995; Baghaee *et al*., 2008; Mori *et al*., 1993). The dynamic application of FACTS controllers were in the areas of transient stability improvement, oscillation damping (dynamic stability) and voltage stability enhancement. It is a known fact that shunts impedance, series impedance, voltage, current and phase angle could be controlled by the FACTS controller (Shahgholian *et al*., 2010; Sankar and Ramareddy, 2008). Figure 1 shows that FACTS devices can be divided into three categories, mechanical switches, voltage source converter and hybrid device. FACTS controllers could be divided into four categories (Hingorani and Gyugy, 2000; Mathur and Varma, 2002; Sze *et al*., 2003). Four types of controller are there in facts controller include the series controllers, shunt controllers, combined series-shunt controllers and combined series-series controllers. The series controllers include Thyristor Controls Series Capacitor (TCSC) (Duffey and Stratford, 1989; Litzenberger and Lava, 1994; Jovcic and Pillai, 2005) it is suitable for voltage and angle stability applications and power flows can be discuses: (Canizares and Faur, 1999; Kumar *et al*., 2007; Martins and Lima, 1990; Piwko, 1987) Fig. 2.

And Static Synchronous Series Compensator (SSSC) is one of the most recent FACTS devices for power transmission series compensation. The theory of operation of SSSC and its control fundamentals are presented extensively in literature (El-Zonkoly, 2008; Hatziadoniu and Funk, 1996; Sen, 1998; Amin, 1999). Figure 3 shows the basic diagram of the SSSC and its equivalent representation.

While the shunt controller include the Static Var Compensator (SVC) (Amin, 1999; Taylor, 1999; Miller, 1982), STATCOM (Shahgholian *et al*., 2008; Gyugyi *et al*., 1990; Sen, 1999) and STATCOM with

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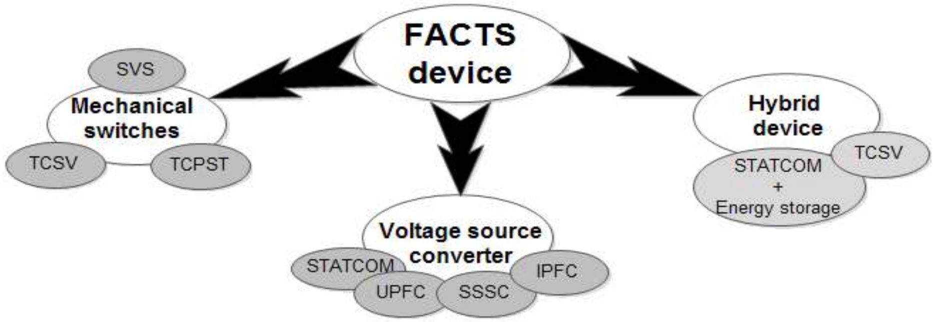


Fig. 1: Classification of FACTS devices

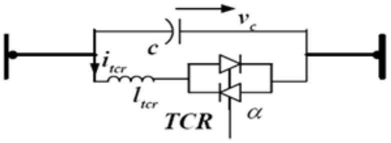
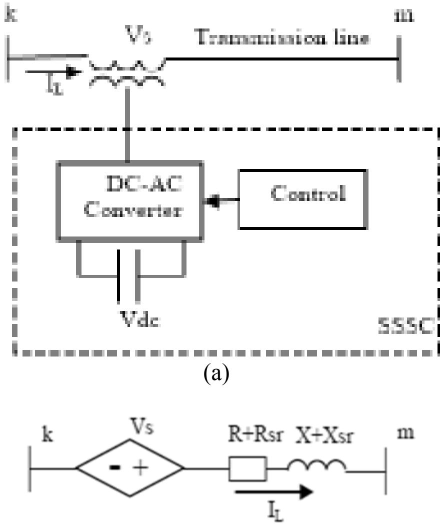


Fig. 2: TCSC model



(a)

(b)

Fig. 3: Basic diagram of the SSSC and its equivalent representation (a) simplified diagram of SSSC, (b) model of transmission line m-kinds installed with SSSC device

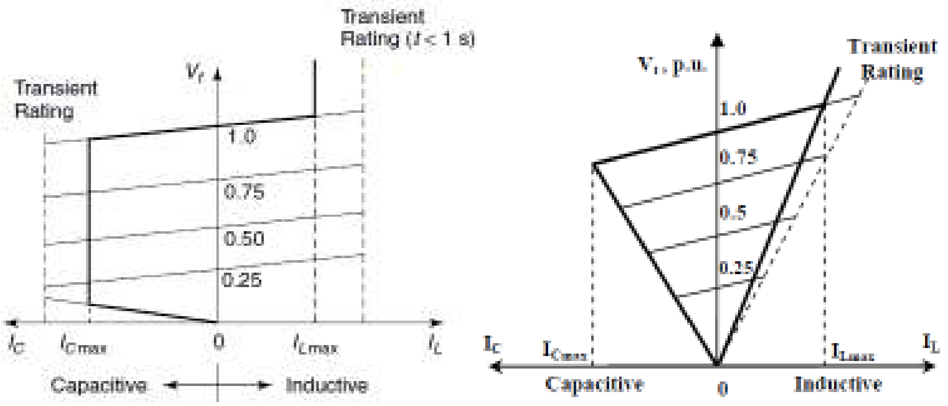
energy-storage system (Kuiava *et al*., 2009) the other categories of FACTS controllers are combined series-shunt controllers which include Unified Power Flow Controller (UPFC) is One of the more intriguing and potentially most versatile class of FACTS device is the Unified Power Flow Controller (UPFC) (Schauder *et al*., 1998; Yoke and Youyi, 1997; Collins *et al*., 2006; Hingorani and Gyugyi, 2000) whereas the combined series-series controllers include Interline Power Controller (IPFC) (Hingorani and Gyugyi, 2000; Mishra *et al*., 2002; Gyugyi *et al*., 1999; Sood, 2002). Many researchers have been conducted on the availability of modelling, simulation, operation and control fundamental of the FACTS devices. The two ways through which simulation of FACTS controllers could be done are:

- Detailed calculations in 3 phase systems
- Steady state and stability analyses (Povh, 2000)

In this study Park *et al*. (2008) Proposed statcom as a current injection model of FACTS controllers is adopted to study dynamical stability of power system that can easily be applied to the linear and non-linear analysis and adopt to any sort of VSI kind of FACTS controllers regardless to type of models. A study to compared the effects of four FACTS controllers using Eigen values analysis in power system small signal angle stability shown in Sood (2002), Povh (2000), Park *et al*. (2008) and Castro *et al*. (2004). Shunts FACTS devices are used to control transmission voltage, power flow, reduce reactive losses and damping of power system fluctuations for high power transfer levels. STATCOM is a type of dynamic reactive power compensating, which has been developed in last few years. In order to utilize STATCOM in high voltage networks and improve its output power quality simultaneously, are highly recommended.

MATERIALS AND METHODS

Characteristic of shunt devices: The classification of the Shunt FACTS devices are based on two categories which include variable impedance of STATCOM model and switching converter SVC model. Figure 2 showed the voltage-current characteristic of STATCOM and SVC. The linear operating range showed that there are some similarities between the voltage-current characteristic and functional compensation capability of the STATCOM and SVC. Static Synchronous Compensator (STATCOM) is essentially an alternating voltage source behind a



(a) (b)

Fig. 4: V-I terminal characteristic of the shunt controllers (a) STATCOM, (b) SVC

coupling reactance (Hingorani and Gyugyi, 2000; Mathur and Varma, 2002). Its unique V-I characteristic illustrated in Fig. 4 shows that the STATCOM can be operated over its full output current range even at very low system voltage levels. This capability is particularly useful for situations in which the STATCOM is needed to support the system voltage during and after faults. Static Var Compensator (SVC) is essentially composed of Thyristor Switched Capacitor (TSC) and Thyristor Controlled Reactor (TCR) connected in parallel to control the voltage at the point of connection to the power system, by adjusting their susceptances to supply or absorb reactive power (Hingorani and Gyugyi, 2000; Mathur and Varma, 2002). The V-I characteristic of the SVC illustrated in Fig. 4 shows that depending on the operating point, the SVC reactance varies. The slope of the line connecting operating point and origin. Once the maximum capacitive output limit of the SVC is reached, the SVC operates as a fixed capacitor. At this condition, the maximum obtainable capacitive current decreases linearly and the generated reactive power decreases as a square of the system voltage. Thus, the minimum value of the capacitive reactance is when the SVC reaches its maximum capacitive rating limit. Any further reduction in voltage will only reduce the output rating retaining a constant reactance.

The STATCOM has advantages over the SVC based on its reduction in size and its much faster response and also moving beyond the limitation of bus voltage which could be as a result of the elimination of ac capacitor banks and reactors. The STATCOM could also serve as a controllable current source beyond the limitation of bus voltage without changing the network structure parameters. One of the control objectives of the SVC is the maintenance of a desired voltage at the high-voltage design helps in making STATCOM to have limitation in its enhanced transfer system as well as short time overloaded capability and also helps in significantly improving its dynamic behavior especially in the interconnected power systems. The STATCOM does not use capacitor or reactor banks for the production of reactive power as was the case in SVC but it is different due to its provision of faster response that is beyond the limitation of bus voltage when compared with the SVC. The supply of the required reactive current by the STATCOM could be at low values of bus voltage whereas the reactive current capability of SVC and the limitations in its sustenance could decrease linearly thereby recording decrease in bus voltage. Even at low system voltage, the STATCOM should be able to produce full capacitive output current thereby making it to be highly effective in improving the transient stability.

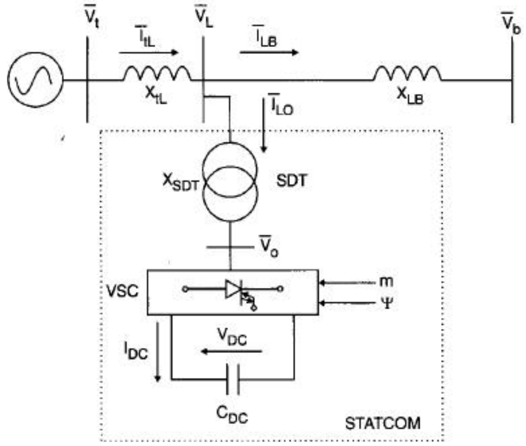
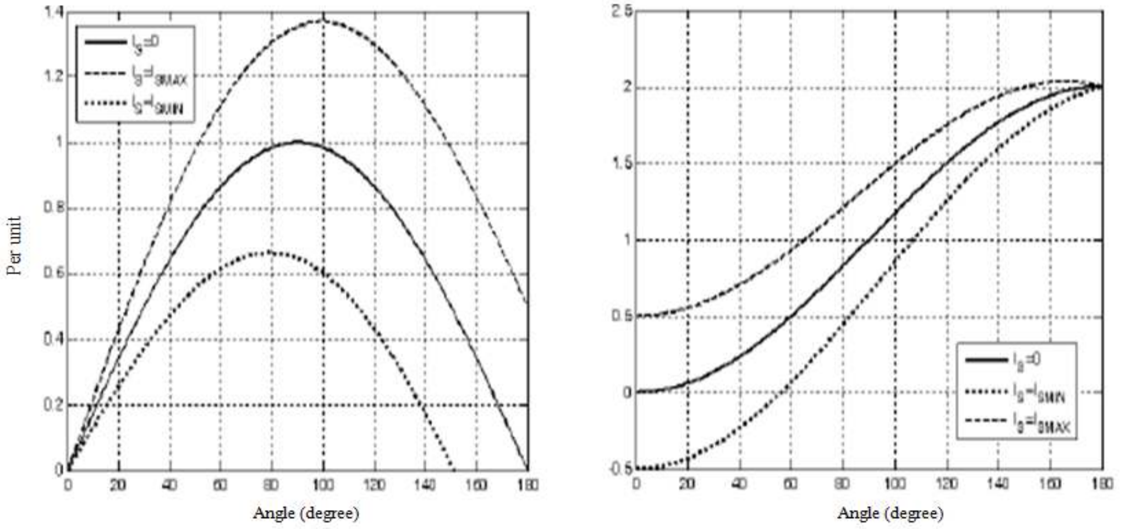


Fig. 5: Schematic diagram of STATCOM

Performance and STATCOM system configuration: The developed dynamic reactive power compensator was named STATCOM based on its steady state operating regime which replicates the operating characteristics of a rotating synchronous compensator without the mechanical inertia. In principle, STATCOM is a controlled reactive power source which aids in provision of voltage support through generation of reactive power at the point of common coupling without seeking for the large external reactors or capacitor banks connections. Figure 5 (Baghaee



(a) (b)

Fig. 6: (a) Power angle characteristic in active (b) reactive power

et al., 2008; Sode-Yome and Mithulananthan, 2004) showed the configuration of a STATCOM connected to bus M of a transmission line. The configuration of STATCOM should basically consists of a Step-Down Transformer (SDT) with a leakage reactance XSDT, a three-phase Voltage Source Converter (VSC) and a dc capacitor but the STATCOM is assumed to be based on Pulse Width Modulation (PWM) converters (Kanojia and Chandrakar, 2009). There is fundamental difference between the operations of STATCOM and Conventional (SVC)

The principle of STATCOM operation entails that the basic objective of a VSC is to produce a sinusoidal ac voltage with minimal harmonic distortion from a dc voltage (Taylor, 1999; Van de Peer *et al*., 2000; Sen, 1999; Mithulananthan *et al*., 2003) for the normal operation of the PWM inverter, the dc voltage across the dc capacitor (CDC) of the STATCOM is always controlled to be constant. The function of the dc capacitor is the establishment of balance in the energy between the input and output during the dynamic change of the var output. However, whenever the compensator supplies only reactive power, the active power provided by the dc capacitor becomes zero. This invariably means that the capacitor does not change its voltage. More so, whenever the voltage magnitudes are equal, the reactive power exchange becomes zero as well. This shows that the capacitor size is mainly determined by the ripple input current encountered with the particular converter design. It has been established that the production of a set of controllable three-phase output voltages with the frequency of the ac power system is being provided by the charged capacitor C_{DC} which helps in providing a dc voltage to the converter (Molina *et al*., 2006). The current from the dc is mainly a ripple of magnitude and smaller than the current from the ac line. In this presentation, the series inductance L_S is seen to be responsible for the leakage of the transformer whereas the R_S represents the active losses of the inverter and transformer. However, the R_{DC} represents the sum of the switching losses which occurs in the inverter and power losses encountered in the capacitor. The maximum current recorded in STATCOM is supplied by the difference in voltage between the converter terminal voltage and the power system voltage as a result of the phase reactance.

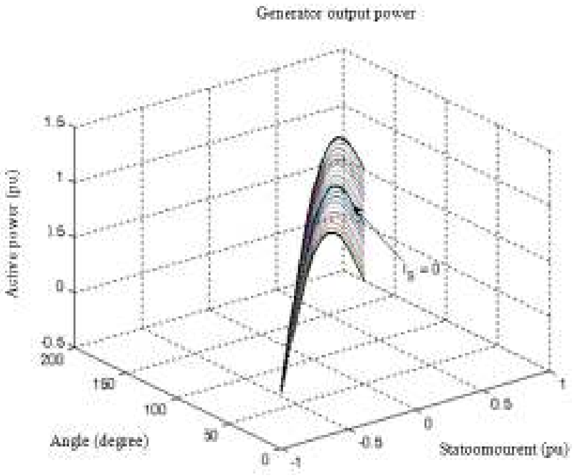


Fig. 7: STATCOM current effect and output active power of generator angle

When there are steady state conditions and the losses were ignored, the exchange of active power and the dc current becomes zero. Figure 6 and 7 show the power-angle curves of the machine for three cases which includes the STATCOM operating at its full

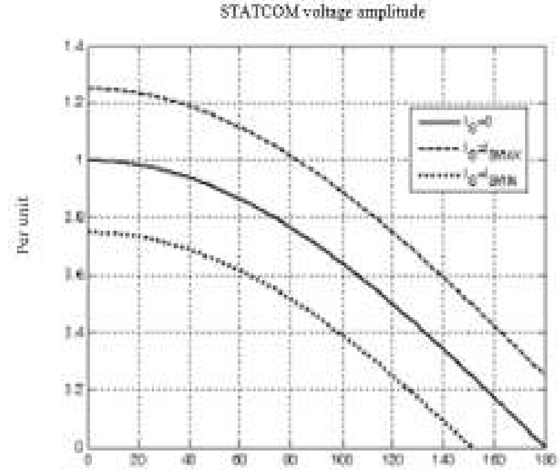


Fig. 8: Amplitude of STATCOM bus voltage

capacitive rating (I_S = = I_SMAX), at full inductive rating (I_S = I_SMIN) and without the STATCOM (I_S = = 0) (Mahdavian and Shahgholian, 2010; Haque, 2005).

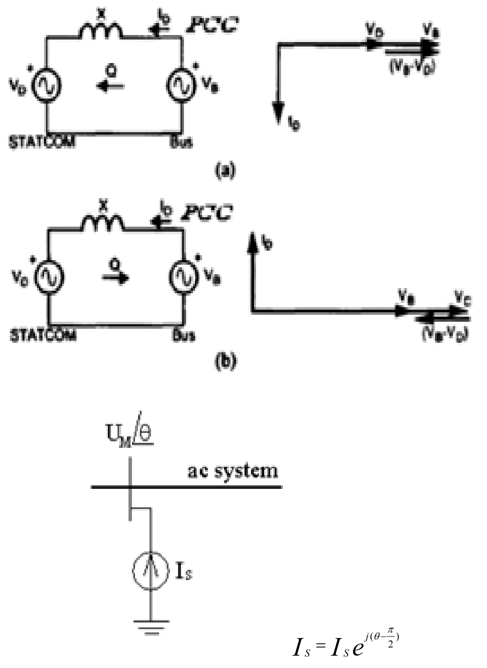
Furthermore, Fig. 8 (Mailah *et al*., 2008; Hingorani and Gyugyi, 2000) shows the amplitude of STATCOM bus voltage for three cases. In practice, it was observed that the STATCOM can operate anywhere which includes operating between the two curves. It can be observed that for a given δ, the value of P_E can be controlled by adjustingI_S.This invariably means that under strongly reduced voltage conditions, the reactive current I_S can be set within its maximum capacity and inductive limits (Hingorani and Gyugyi, 2000; Haque, 2004a, b, 2005; Song and Johns, 1999), In configuration of STATCOM using hybrid multi-inverters with potential, it was proposed that the harmonic contents of output voltage/current would be less than the conventional STATCOM (Fukuda and Li, 2006).

Optimal location of facts devices: Different FACTS devices and differences in their locations have variations in their advantages. The amount of local load, the location of the devices and their types and sizes, improvement stability, the line loading and system initial operating conditions is being determined by the optimization of location of the FACTS devices (Gerbex *et al*., 2003; Panda and Patel, 2009; Panda and Patel, 2007; Panda and Padhy, 2008). There are several established methods through which the optimal locations of FACTS devices could be found in both vertically integrated and unbundled power systems. It was proposed that an algorithm could find the best location for the FACTS devices in multi-machine power systems using genetic algorithm (Gerbex *et al*., 2003; Panda and Patel, 2009; Panda and Patel, 2007; Panda and Padhy, 2008; Cai *et al*., 2004), However, the three criteria which were considered for FACTS optimal allocations include the availability of the transfer capability criterion, steady state stability criterion and economic criterion (Yu and Lusan, 2004). There is consideration for an alternative model that can optimize the placement of FACT devices based on multiple time periods with losses. Additionally, there is another proposition for the optimal location of a shunt FACT device being investigated for an actual line model of a transmission line having series compensation at the centre to get the highest possible benefit (Sharma *et al*., 2007).

RESULTS AND DISCUSSION

Application of STATCOM: Helps in improving the static and dynamic voltage stability of the bus on power system as well as keeping the voltage of the electric network in the receivable operating mode (Chao and Yao, 2007; Elsamahy *et al*., 2011) STATCOM could be seen a voltage sourced converter based shunt FACTS device which could enhance the power system damping through the injection of the controllable reactive power into the system (Al-Baiyat, 2005). More studies emphasized that STATCOM is an active device which can be used to inject both real and reactive power to the system in a very short time as it equally has the ability to improve the damping and voltage profiles of the system. The STATCOM which has energy storage system such as Superconducting Magnetic Energy Storage (SMES) and Battery Energy Storage System (BESS) can control both the reactive and the active power thereby making provision for more flexible power system operation. It was categorically stated in many studies that typical applications of STATCOM are Low Frequency Oscillation (LFO) damping (Mishra *et al*., 2000; Mori *et al*., 1999) dynamic compensation and stability improvement (Wang, 1999), enhancement of transient stability (Torabian and Hooshmand, 2009), voltage flicker control, damping of sub synchronous oscillations in EHV series compensated systems (Keshavan and Prabhu, 2001; Abido, 2005) and power quality improvement (Mailah *et al*., 2008).

Modelling of shunt inverter (STATCOM): The selection of the models for power system components should be according to the proposed system of the study. STATCOM could be explained as a multiple input and multiple output variables. Studies maintained that there are several distinct models which have been proposed to represent STATCOM in static and dynamic analysis (Mahdavian and Shahgholian, 2010; Keshavan and Prabhu, 2001). It was discovered that shunt inverter or STATCOM is modelled as three-phase multi pulse converter and series inverter (Canizares *et al*., 2003) the assumption based on different models was that voltages and currents are sinusoidal, balanced and operated near fundamental frequency. Three models have been investigated for STATCOM which include proposed model, Explanatory model and average circuit model.



(c)

Fig. 9: STATCOM operation, (a) inductive operation for swell, (b) capacitive operation for sag, (c) mathematical model of STATCOM (Miller, 1982)

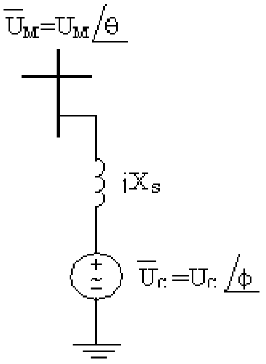


Fig. 10: Equivalent model of the STATCOM

Estimated model:

Proposed technique: In this category of model, the STATCOM is modelled as a reactive current source with a time delay. The injected current of the STATCOM is always in quadrature with its terminal voltage and dose which are devoid of changing the angle of the voltage at connected bus (Mahdavian *et al*., 2009). As can be observed from Fig. 9. The task of the device is to inject the current to the network to correct the voltage at the Point of Common Coupling (PCC) when voltage sag or swell occurs (Giroux *et al*., 2001). Therefore, current controller is more suitable for this kind of device according to its structure and requirements. Current control methods are also faster and have higher dynamic response, compared to voltage control methods since they directly control current of the converter. There are some traditional current control methods such as hysteresis, average current control and peak control method. In this study a new current control method is proposed for STATCOM (Fig. 9). When the STATCOM operates in capacitive mod, the inject d current can be expressed as:

Explanatory model of shunt devices: The static power converters are nonlinear in nature and consequently generate harmonics into the supply. Ideally, the inverter output voltage is the phase which has the voltage at the common connection point. The VSC converters and dc voltage U_{DC} are into a controllable ac output voltage $U_C(t)$ at fundamental frequency with rapidly controllable amplitude (U_c) and phase angle θ_c which is behind the leakage with neglecting harmonics is:

$$u_c(t) = u_c \sin(\omega t - \theta_c) \tag{1}$$

The relationship between STATCOM ac voltage $\overline{U}_C$ and U_{DC} is:

$$U_C = K M_R U_{DC} \angle \theta_C \tag{2}$$

Figure 10 showed the equivalent model of the STATCOM. The two control signals which can be applied to the STATCOM are magnitude control (M_R) and the phase angle which is defined by PWM (θ_c), whereas the M_R is a factor that relates the dc voltage to the peak voltage on the ac side. The modelling of STATCOM is likened to a VSC behind a SDT by a first order differential equation. If modulation ratio of $M_R$is defined by PWM, then the voltage current relationships in the STATCOM should be expressed as:

$$\frac{d}{dt}u_{DC} = \frac{K M_R}{C_{DC}} = (I_{sd}\, SOS\, \theta_C + I_{sd} \sin \theta_C) - \frac{U_{DC}}{R_{DC}} \tag{3}$$

A situation where I_{sd} and I_{sq} are components of STATCOM current where k is the ratio between ac voltage and dc voltage depending on the inverter structure (Song and Johns, 1999) (Fig. 10). Average circuit Model in d_q reference frame: This model which was based on the d_q representation is derived from the stationary and synchronous frame of reference (Blasko and Kaura, 1997). This model is used for studying the VSC and the dynamics of the control loops. The circuit equivalent of STACOM in d_q synchronous frame is given in Fig. 11, where ω is rotation speed, S_D and S_Q are d-axis and q-axis synchronous reference frame inverter switching function, U_{cd} and U_{cq} d-axis and q-axis are synchronous reference frame source voltage, i_q and i_d are synchronous reference frame STATCOM

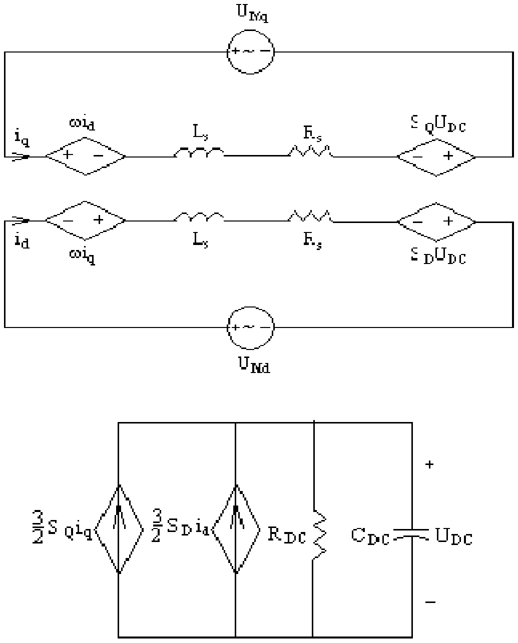


Fig. 11: The circuit equivalent of STATCOM in d_q reference frame (Yoke and Youyi, 1997)

current (Haque, 2005; Shahgholian *et al*., 2009) R_s and L_s are the line resistance and inductance, respectively.

Application of STATCOM for damping control, strategies: STATCOM can improve power system stability through the damping power oscillations as recent reports showed that there are various control approaches for damping controller of the STATCOM that is a nonlinear system. Design of dynamic is categorically used for steady state, transient stability and Eigen value studies. However, a STATCOM application has a complete control system which basically consists of two main parts namely the external and internal controls. The external control depends on the power system network to which the STATCOM is connected whereas the internal control mainly depends on the VSC topologies. An ideal internal control should instantaneously respond to a given command which is generated by the corresponding external controller (Sirisukprasert *et al*., 2003). Damping controllers which is devised for STATCOM towards improving the dynamic of power systems can be classified into two namely continuous and discontinuous controls. The controllers on the basis of design and analytic approach can be divided in to three main parts which include the linear, non-linear and empirical controllers. Studies maintained that:

- Linear include lag-lead controllers, conventional PID controllers (Shahgholian *et al*., 2009). The linear quadratic regulators and pole assignment (Eshtehardiha *et al*., 2007; Lee and Sun, 2002).
- Nonlinear include the adaptive compensation method and fuzzy controller (Faisal *et al*., 2007; Qu and Chen, 2002).
- Empirical include the Tabu search algorithm (Pothiya *et al*., 2006) and genetic algorithm (Sirisukprasert *et al*., 2003).

It was discovered that the performance of nonlinear controller depends on the location of fault and the STATCOM (Eshtehardiha *et al*., 2007). However, the design of a fixed parameter robust STATCOM controller for a high order multi-machine power system could be achieved through a H_∞ based graphical loop-shaping procedure by embedding a particle swarm (Kondo *et al*., 2002).

CONCLUSION

General review of classification of FACTS controller devices are presented in this study. STATCOM is a flexible ac transmission system device which could be connected as a shunt to the network for the purpose of generating or absorbing reactive power. (STATCOM) as a compensating device has been widely proposed for power quality and network stability improvement. It can improve network stability; power factor, power transfer rating and can avoid some disturbances such as sags and swells. An important factor for STATCOM effectiveness in sag mitigation is its sag detection method and the simulation results have demonstrated the superiority of the proposed sag detection algorithm to be utilized in the STATCOM.

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