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Power flow and transient stability modelling of a 12-pulse Statcom

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ABSTRACT - Due to the arising liberalization and deregulation of the electric energy market, the demand on AC-transmission system are steadily growing. Therefore, more sophisticated ac-system controllers are highly needed. This paper is focusing on one of these topologies, i.e the two-levels voltage source inverter static compensator (Statcom), which is an interesting high power circuit for transmission applications. A steady state and transient stability models with GTO thyristors are proposed. Simulations are carried out in a 9 bus, 3 machines AC system. The proposed model is suitable for power system studies that require accurate representation as transient stability and voltage stability.

Key words: Statcom, power flow, transient stability, Facts controller, pwm **.**

1. Introduction

The development and use of Flexible AC Transmission System (FACTS) controllers in power transmission systems had led to many applications of these controllers to improve the stability of power networks. Many studies have been carried out and reported in the literature on the use of these controllers in a variety of voltage and angle stability applications, proposing diverse control schemes and location techniques for voltage and angle oscillations control. Reference [1] provides details of the mathematical derivation of control equations and the control algorithms used in two possible cases, depending on the dc voltage control. The authors in [2] present an approach for the dynamic control of voltage-sourced converter (VSC) based FACTS controllers, which uses a linear multi-variable approach based on state space theory. Modelling and control of the system were carried out in a synchronous d-q frame. In [3], the authors use the work presented in [4] to discuss the use of a Pulse Width Modulation (PWM) based control system to control over-currents caused by an unbalanced single-phase fault placed at the ac bus where the STATCOM is connected.

The current paper concentrates on describing in detail adequate STATCOM model for these types of studies, based on an energy balance criterion. The proposed model allow to accurately and reliably represent a STATCOM for angle stability studies using power flow, steady state and transient stability programs, as the model allows for an appropriate representation of the typical control limits for this controller. For the model to be accurate, it is important to represent the losses of the controller (P_{loss}), as discussed below; previously proposed models in [5] do not consider this issue.

Moreover, the STATCOM model was included into a realistic test system as opposed to the usual two-bus STATCOM tests systems found in the literature. The results for the stability of a 9 bus test system are presented and thoroughly analyzed.

2. Statcom models

The STATCOM device is the static counterpart of the rotating synchronous condenser but it generates/absorbs reactive power at a faster rate. In principle, it performs the same voltage regulation function as the classical SVC but in a more robust manner. Unlike the SVC, its operation is not impaired by the presence of low voltages (IEEE/CIGRE, 1995). It goes on well advanced energy storage facilities, which open the door for a number of new applications, such as energy markets and network security (Dewinkel & Lamorce, 1993).

The schematic representation of the STATCOM considered in this paper and its equivalent circuit are shown in Fig.1.

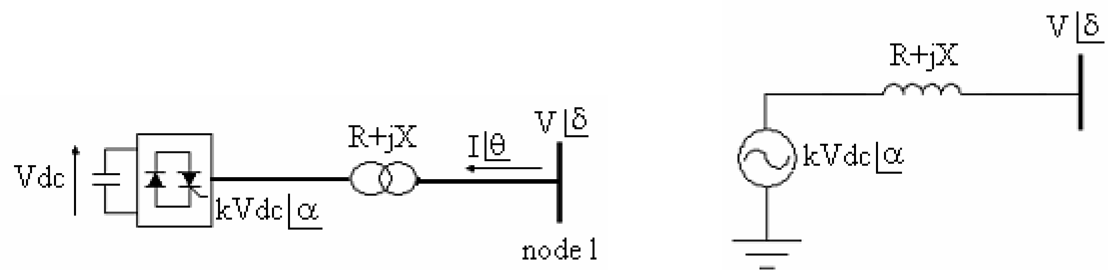

Fig.1 : STATCOM and its equivalent circuit

Fig.2 shows a typical 12-pulse STATCOM arrangement. Two six-pulse converters are connected in parallel on the same dc bus and interconnected in series through step down transformers on the ac side. The first one is connected with a wye-wye transformer and the second one with a wye-delta transformer. The delta-connected secondary of the second transformer must have $\sqrt{3}$ times the turns compared to the wye-connected secondary. If the output voltage of one converter is shifted by 30° with respect to the output voltage of the other converter and if the primary sides of the transformers are connected in series, the total output voltage on the ac side will be the sum of the individual voltages in each transformer. In this manner, it is possible to eliminate low order harmonics.

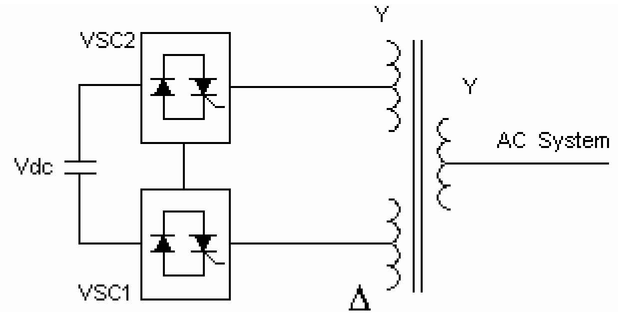

Fig.2 : schema of the 12-pulse STATCOM

The instantaneous STATCOM output voltage for phase a can be computed as:

$v_a = a_1 v_{a,Y} + a_2 \frac{v_{a,\Delta}}{\sqrt{3}}$, where a_1 and a_2 are the voltage ratios of the corresponding inverter transformers while $v_{a,Y}$ and $v_{a,\Delta}$ are the output voltages of the wye-wye and wye-delta connected converters respectively. The current flowing in each converter is the same, scaled by the transformer ratio, as the current being drawn from the ac system by the STATCOM.

On the other hand the magnitude of the fundamental component of the converter output voltage is given by kV_{dc}, where V_{dc} represents the voltage across the capacitor. If a magnitude control is used and for a 12-pulse inverter, using some PWM scheme, $k = \sqrt{\frac{3}{8}}m$ where m is the modulation index.

α is the angle of the STATCOM fundamental output voltage.

$V \angle \delta$ is the voltage of the bus where the STATCOM is connected.

$Y = \frac{1}{R + jX} = G + jB$ represents the step down transformer admittance.

The STATCOM has the ability to either generate or absorb reactive power by suitable control of the inverter voltage with respect to the voltage of the node where the STATCOM is connected, say node *l* (Fig.1). The reactive power injection at the ac bus has the form:

$$Q = V^2 B - kV_{dc} VB\cos(\delta - \alpha) + kV_{dc} VG\sin(\delta - \alpha)) \tag{1}$$

If V>kVdc then Q becomes positive and the STATCOM absorbs reactive power. On the other hand, Q becomes negative if V<kVdc and the STATCOM generates reactive power.

2.1. STATCOM Power Flow Modelling [6]

In power flow studies the STATCOM may be represented in the same way as a synchronous condenser (IEEE/CIGRE, 1995) which in most cases is the model of a synchronous generator with zero active power generation. A more flexible STATCOM power flow model is presented in this paper. It adjusts the voltage source magnitude and phase angle using Newton's algorithm to satisfy a specific voltage magnitude at the point of connection with the ac network:

$$kV_{dc}\angle\alpha = kV_{dc}(\cos\alpha + j\sin\alpha) \tag{2}$$

It should be pointed out that maximum and minimum limits will exist for kV_{dc} which are a function of the STACOM capacitor ratings.

The expression of the real power supplied by the ac system to the STATCOM to charge the capacitor and to compensate the switching and snubbers losses is given by

$$P = \frac{|V|.kV_{dc}}{X}\sin(\delta - \alpha) \tag{3}$$

In practice, this quantity is small and α will be kept close to δ ($\delta - \alpha \approx 1 \div 4^{\circ}$).

The node at which the STATCOM is connected is represented as a PV node, which may change to a PQ node in the event of limits being violated. Contrary to the SVC, the STATCOM is represented as a voltage source for the full range of operation, enabling a more robust voltage support mechanism. An alternative way to model the STATCOM in a Newton-Raphson power flow algorithm is described in this section. It is a simple and efficient model based on the use of a variable voltage source, which adjusts automatically in order to achieve a specified voltage magnitude.

The active and reactive powers injected by the source may be derived using the complex equation

$$S = kV_{dc}.I^* = kV_{dc}.Y^*(kV_{dc} - V^*) \tag{4}$$

Taking the variable source voltage to be $kVdc\angle\alpha$, and after performing some complex operations, the active and reactive powers for the shunt converter are derived as follow:

$$\begin{aligned} P &= kV_{dc}{}^2 G - kV_{dc}V(G\cos(\alpha-\delta) + B\sin(\alpha-\delta)) \\ Q &= -kV_{dc}{}^2 B - kV_{dc}V(G\sin(\alpha-\delta) - B\cos(\alpha-\delta)) \end{aligned} \tag{5}$$

Based on these equations, the linearized STATCOM equation is given below:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial kV_{dc}} & \frac{\partial P}{\partial \alpha} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial kV_{dc}} & \frac{\partial Q}{\partial \alpha} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta kV_{dc} \\ \Delta\alpha \end{bmatrix} \tag{6}$$

At the end of iteration (i), the variable voltage magnitude kV_{dc} is updated :

$$kV_{dc}{}^{(i+1)} = kV_{dc}{}^{(i)} + \Delta kV_{dc}{}^{(i)}$$

Then the STATCOM is connected to the 9 bus ac system (Fig.6) and must maintain the voltage magnitude at node 8 at 1 p.u. The power flow solution leads to the following results:

Node	Nodal Voltage	Voltage Magnitude	Injected power
1	1.04	1.04	0.7164 + j0.2704
2	1.0117 + j0.1653	1.0251	1.6300 + j0.067
3	1.0216 + j0.0834	1.0250	0.8500 – j 0.109
8	1.0158 + j0.0129	1.0159	-1.0000 – j0.3500

Table 1: Nodal voltages and injected powers without STATCOM

In tables 1 and 2 we have reported only the results for the nodes of some interest.

The supplementary real power (≈ 0.0041p.u) needed by the STATCOM to charge its capacitor and compensate the switching losses is supplied by generator 1 which is modelled as a slack bus.

On the other hand a large amount of reactive power (≈ 0.3234 p.u) is absorbed by the STATCOM to regulate bus 8 voltage at 1 pu (table 2).

Node	Nodal Voltage	Voltage Magnitude	Injected power
1	1.04	1.04	0.7205 + j0.3282
2	1.0110 + j0.1687	1.0250	1.6300 + j0.2355
3	1.0215 + j0.0850	1.0250	0.8500 – j0.0342
8	0.9921 + j0.0147	1.0	-1.0019 – j0.6734

Table 2: Nodal voltages and injected powers with STATCOM connected at node 8

2.2. Transient stability model [7,8,9]

The STATCOM model proposed here is based on the power balance equation:

$$P_{ac} = P_{dc} + P_{loss} \tag{7}$$

which basically represents the balance between the controller's ac power P_{ac} and dc power P_{dc} under balanced operation at fundamental frequency. For the models to be accurate, it is important to represent the losses of the controllers (P_{loss}).

The transient stability model of the STATCOM with PWM voltage control is depicted in Fig.3.

The DC circuit is described by the following differential equation, in term of the voltage Vdc on the capacitor:

$$\frac{dV_{dc}}{dt} = \frac{P}{CV_{dc}} - \frac{V_{dc}}{CR_c} - \frac{R(P^2 + Q^2)}{CV^2V_{dc}} \tag{8}$$

The power injection at the AC bus has the form:

$$\begin{aligned} P &= V^2G - kV_{dc}VG\cos(\delta - \alpha) - kV_{dc}VB\sin(\delta - \alpha) \\ Q &= -V^2B + kV_{dc}VB\cos(\delta - \alpha) - kV_{dc}VG\sin(\delta - \alpha) \end{aligned} \tag{9}$$

Most of the variables are explained in Fig.3. The term $1/R_c$ is used to model the switching inertia of the converter due to the electronic switches and their snubber circuits.

The current circulating between the STATCOM and the ac system can be expressed in the dq frame as:

$$I = i_q + ji_d \tag{10}$$

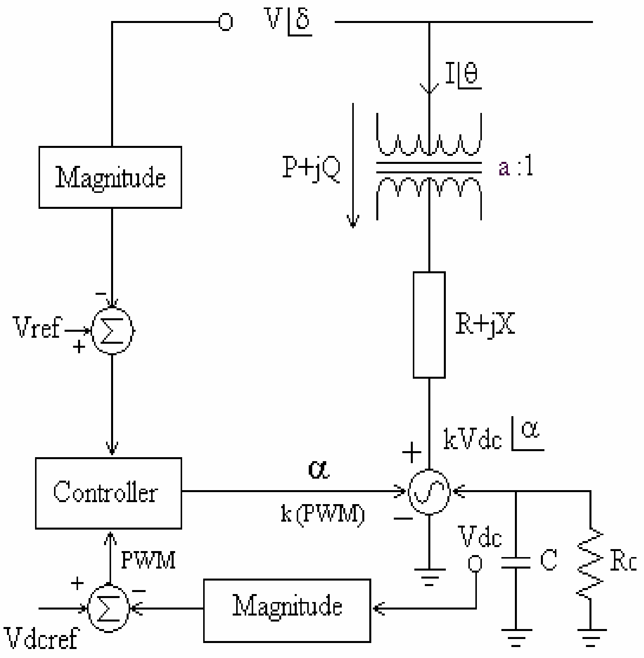

Fig.3 : Transient stability model of the STATCOM

In the dq frame the currents equations of the STATCOM are time invariant and are given by:

$$\frac{di_d}{dt} = -\frac{R\omega_0}{X} i_d - \omega_0 i_q + \frac{\omega_0 k \sin\alpha}{X} V_{dc}$$
$$\frac{di_q}{dt} = \omega_0 i_d - \frac{R\omega_0}{X} i_q + \frac{\omega_0 k \cos\alpha}{X} V_{dc} \quad (11)$$

where ω_0 represents the synchronous frequency of the ac system.

Real and reactive currents are defined mathematically as:

$$i_P = i_d \sin\delta + i_q \cos\delta$$
$$i_R = i_d \cos\delta - i_q \sin\delta \quad (12)$$

By this convention, positive i_R implies the STATCOM is in inductive region (absorbs reactive power) while negative i_R implies it is in the capacitive region.

The control of reactive current is necessary because the STATCOM current is not only dependent on the firing angles of the GTOs but on parameters of the rest of the system as well. The control of reactive current has an advantage that the current limits can be incorporated in the controller itself. The real current i_P is used to maintain capacitor at a constant voltage.

The kind of control selected is the amplitude control (control type 1). For this purpose a basic PWM voltage control is obtained regulating the amplitude of m as defined by the following equation (Fig.4):

$$\frac{dm}{dt} = \frac{K_d}{T_2}\left[-m + \frac{K}{K_d}(V_{ref_{ac}} - Vmac)\right] - \frac{K_a T_1}{T_2 T_{mac}}(K_{mac}V - V_{mac}) \qquad (13)$$

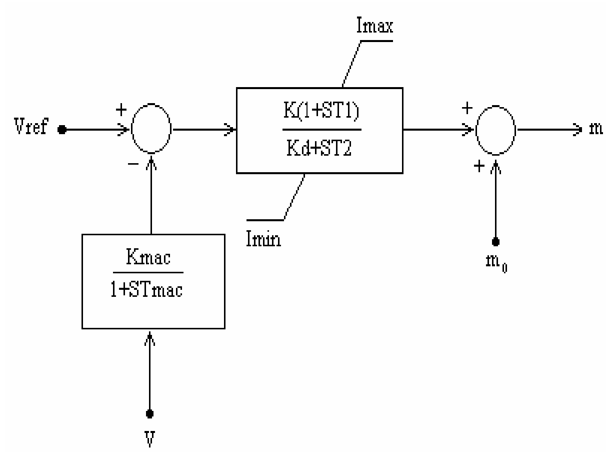

Fig.4: STATCOM voltage control block diagram

In the same manner real power flow from the ac system to the STATCOM is regulated by controlling angle α as defined by the following equation (Fig.5):

$$\frac{d\alpha}{dt} = \left(\frac{K_p}{T_{mdc}} - K_I\right)V_{mdc} + K_I V_{ref_{dc}} - \frac{K_p K_{mdc}}{T_{mdc}}V_{dc} \qquad (14)$$

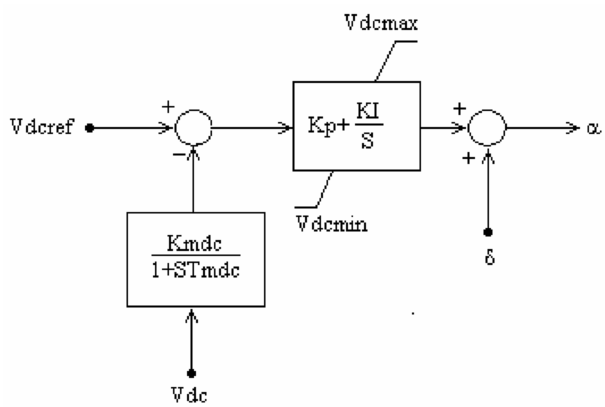

Fig.5: STATCOM amplitude control block diagram

K and K_d are the gain and the integral deviation of the voltage control respectively.

K_p and K_i are the proportional and integral gains for the α control.

T_1 and T_2 are transient time constant and time constant of the voltage control.

Finally, two low by-pass filters are considered for both the AC and DC voltage measurements, with the following equations:

$$\frac{dV_{mac}}{dt} = (-V_{mac} + K_{mac}V)/T_{mac} \\ \frac{dV_{mdc}}{dt} = (-V_{mdc} + K_{mdc}V_{dc})/T_{mdc} \tag{15}$$

K_{mac} and K_{mdc} are the gains of the ac and dc measurements respectively while T_{mac} and T_{mdc} are the time delays of the same measurements.

The phase angle α determines the active power P flowing into the controller and hence the charging and discharging on the capacitor. The amplitude control for the state variable α is reported in Fig.5. The limits on α are automatically computed imposing the following system:

$$P = \frac{V^2{}_{dc}}{R_C} + RI^2 \\ V_{dc} = V_{ref_{dc}} \\ V = V_{ref} \\ P = V^2G - \sqrt{3/8}V_{dc}VG\cos\alpha - \sqrt{3/8}V_{dc}VB\sin\alpha \tag{16}$$

from which it can be obtained:

$$\cos\alpha = \frac{bc}{a^2+b^2} \pm \sqrt{\left(\frac{bc}{a^2+b^2}\right)^2 - \frac{c^2-a^2}{a^2+b^2}} \\ where \\ a = -\sqrt{3/8}V_{ref_{ac}}V_{ref_{dc}}B \\ b = -\sqrt{3/8}V_{ref_{ac}}V_{ref_{dc}}G \\ c = V^2{}_{ref_{ac}}G - \frac{V^2{}_{ref_{dc}}}{R_C} - RI^2 \tag{17}$$

Then, the limits for α are computed imposing in the previous equations the limits $I_{\max}$ and $I_{\min}$ of the current I ($I_{\max} = 1.2$ and $I_{\min} = 0.8$).

The STATCOM data are stored in Table 3. All data are calculated on a 100MVA / 230kV base on the AC side.

$V_{ref_{dc}}$	1.040	K_p	100
$V_{ref_{ac}}$	1.000	K_i	20
R	0.010	K_{mac}	1
X	0.015	K_{mdc}	1
R_C	600	$T_1(s)$	0.001
X_C	0.0143	$T_2(s)$	0.05
K_a	200	$T_{mac}(s)$	0.001
K_d	10	$T_{mdc}(s)$	0.001

Table 3: STATCOM data

The base voltage on the DC side is determined by

$$V_{dc_{base}} = \left(\sqrt{2} / (\sqrt{3}k) V_{ac_{base}} \right) \tag{18}$$

Hence the per unit capacitor value is given by

$$C(pu) = 1 / (\omega C Z_{base}) \tag{19}$$

where $$Z_{base} = \frac{\left(230.10^3\right)^2}{100.10^6} = 529\Omega \tag{20}$$

The voltage control characteristics of the STATCOM will be represented by the following equation:

$$V - V_{ref} \pm X_{SL} I = 0 \tag{21}$$

where V is the voltage at the bus being controlled, V_{ref} is the desired voltage setting, I is the STATCOM current and X_{SL} stands for the controller droop.

Connecting the STATCOM to the electrical system leads to a change in the initial condition values. We have depicted in Table 4 the initial values of different parameters with and without STATCOM. We have considered only the generator 1 which is a slack bus. In the dq frame the generator parameters are:

$E'\angle\delta_G = (E'_q + jE'_d)\angle\delta_G$ is the generator transient internal voltage. (22)

$I_G = I_q + jI_d$ is the current supplied by the generator. (23)

$Vt = V_q + jV_d$ is the generator terminal voltage. (24)

P is the real power supplied by the generator.

Parameters	Without Statcom	With Statcom
δ_G	$0.06258\ rad$	$0.06262\ rad$
I_q	0.67124	0.67168
I_d	−0.30257	−0.35831
V_q	1.03796	1.03796
V_d	−0.06504	−0.06509
E'_q	1.05636	1.05975
E'_d	−0.02423	−0.02425
P	0.716	0.7205

Table 4: Generator 1 parameters

The major changes are in concern with the current component in the direct axis, I_d, and the real power P. This is due to the fact that the active power needed by the STATCOM, for charging the capacitor and compensating its switching losses, is supplied by generator 1 which has been modelled as a slack bus.

3. SIMULATION AND RESULTS

The test system used for our simulations is depicted in Fig.6. It is the WSCC 3-machine, 9-bus system and is extracted from [10]. The STATCOM is connected to the bus 8 .

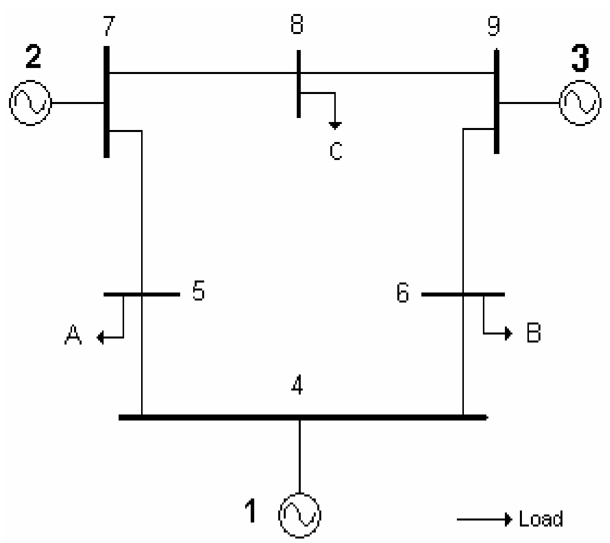

Fig.6: AC test system

After modelling the STATCOM, the ability of the system to maintain a stable operation condition under large perturbations is typically studied.

A severe disturbance is simulated by applying a three phase fault at the end of line 5-7, near bus 7 at t = 0.5s . The fault is cleared at t = 0.583s by disconnecting the faulted transmission line.

$R_{fault} = 2.4e-3pu \quad and \quad X_{fault} = 2.4e-3pu$ are the fault resistance and the fault inductance respectively.

The STATCOM remains operative during the duration of the fault as shown in the next figures.

The protection scheme temporarily reduces the var capacity by keeping the angle α between limits when the STATCOM output ac current reaches it maximum preset value. As soon as the current resumes the allowed value the angle α is free to change in response to system voltage changes (Fig.7).

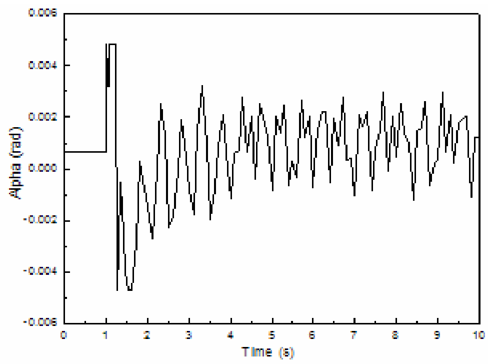

Fig.7: Variations of angle α

Observe that the dc voltage increases from 1.04 pu at 0.5 s then to 1.04006 pu and finally decreases at 1.04 pu at 0.583, consequently increasing the STATCOM ac output voltage according to the equation $V_{statcom} = \sqrt{3/8}mV_{dc}$ (Fig.8). The STATCOM control circuit allows the increase in V_{dc} from its rated voltage of 1.04 pu to 1.04006 pu. Beyond this value the dc capacitor should be protected by keeping the control output angle α at its maximum value $\alpha_{\max}$ (0.0048 rad). The modulation index m is changing according to the equation previously mentioned, maintaining the voltages at Bus 7 and Bus 8 at their reference values (Fig.9).

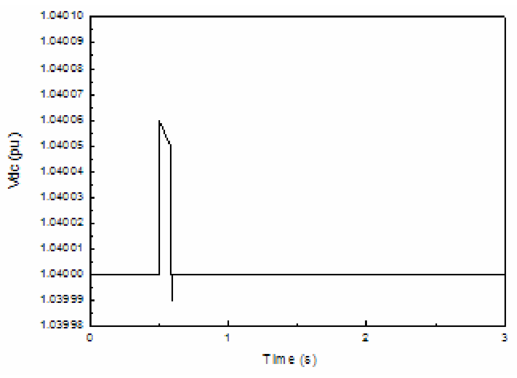

Fig.8:Voltage at dc bus

Typically, the modulation index control would be ”faster” than the phase angle control, as there is a significant charging and discharging inertia of the capacitor due to its relative large value, whereas the modulation index has an immediate effect on the output voltage of the controller.

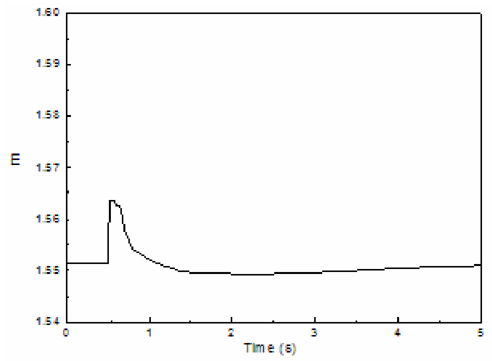

Fig.9: variations of modulation index

The control limits of the controller are simulated by determining the values of the modulation index m and phase angle α corresponding to the current and DC voltage limits, respectively, by solving the steady state equations of the converter.

During the fault, the voltage at Bus 7 falls almost to 48 percent of its pre-set value of 1.01 pu against one percent without STATCOM, while maximum capacitive current is provided by the STATCOM (Fig.10). Therefore, the STATCOM is capable of transiently providing capacitive current in excess to the nominal value. The STATCOM responds to any changes in the AC system within 2 cycles, due to the relatively small transformer reactance, which allows almost instantaneous changes in the STATCOM ac output current to compensate for system voltage variations.

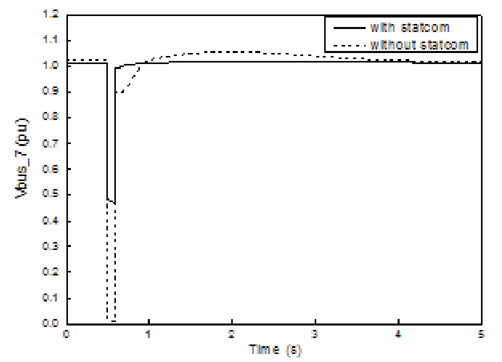

Fig.10: Voltage at bus 7

The shape of the voltage at Bus 8 is depicted in Fig.11. Observe that this voltage does not drop as it was the case with voltage at Bus 7. Therefore, the STATCOM, connected at bus 8, provides a good support for the voltage at this bus by injecting a large amount of reactive power (Fig.12).

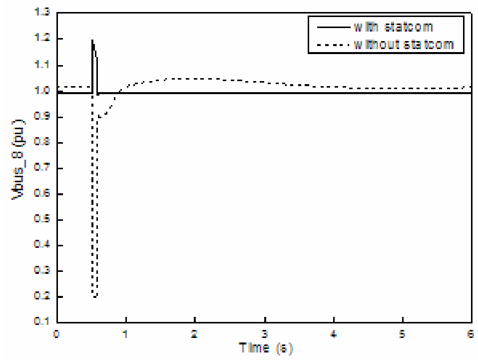

Fig.11: voltage at bus 8

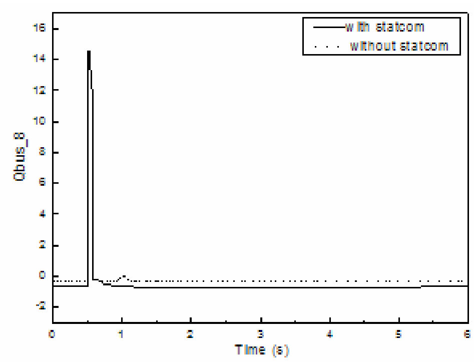

Fig.12: reactive power provided by the statcom at bus 8

The generator 2 is situated near the fault location. During the fault it will accelerate due to the fact that the balance between mechanical power and electrical power is lost (Fig.13).

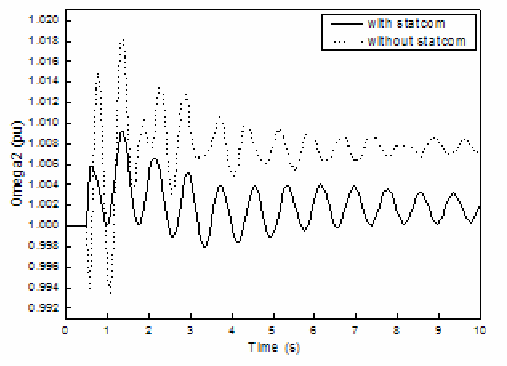

Fig. 13: generator 2 speed variations

Therefore the Automatic Voltage Regulator (AVR) will overexcite the alternator to provide more active power and set up again the power balance (Fig.14 & 15). We can observe that the amplitudes of the generator speed and electrical power are well damped by the STATCOM which absorbs inductive power. It has to be noted that the magnitude of the allowed current is different for inductive and capacitive regions of operation (0.8 and 1.2 respectively).

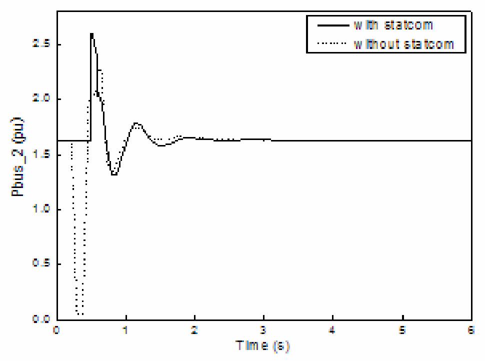

Fig.14: generator 2 active power

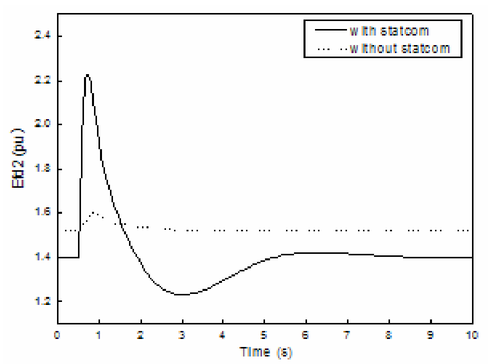

Fig.15: generator 2 excitation voltage

CONCLUSION

The STATCOM transient stability and power flow models proposed in this paper are basically improved versions of models previously proposed in the literature. The results presented and discussed for the WSCC 9-machine test system show how these models can be readily and reliably used for stability studies of power system.

The models discussed here are all based on the assumption that voltages and currents are sinusoidal, balanced, and operate near fundamental frequency. Hence, these models have some limitations, especially when studying large system changes occurring close to FACTS controllers or unbalanced system conditions.

On the other hand the use of the phase control implemented in our model needs a D-Q decomposition but leads to better results.

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