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# Dynamic Phase-domain Modelling and Simulation of STATCOM in Large-scale Power Systems

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*Abstract*-- **This paper presents a dynamic model of the Static Synchronous Compensator (STATCOM) in the phase frame reference and rectangular coordinates. The STATCOM is taken to be a Voltage Source Converter (VSC) coupled with a shunt connected transformer to the power system, the equivalent model allows for a direct voltage regulation and its incorporation into an algorithm for the analysis of their contribution to the stability of the SEP's to dynamic phenomena. The tool used for the study is called Dynamic Power Flow. Validation with long-term test large-scale power systems are presented and discussed, which proves to be suitable for this type of dynamic analysis.**

***Index Terms*—STATCOM, Dynamic power flows, large-scale.**

## I. Introduction

Recent power system "black-outs" in North America and Europe have highlighted the vulnerability of today's power networks and has given renewed encouragement to power systems researchers to develop new models and methods with much improved functionality aimed at preventing widespread outages [1-3]. The versatility of the steady-state three-phase power flow algorithm with provisions for FACTS controllers has already been demonstrated in both polar and rectangular co-ordinates [4-5]. Building on these research developments, this paper presents a dynamic model of the STATCOM controller in the phase frame of reference suitable for direct incorporation into a dynamic power flow algorithm.

The STATCOM consists of one Voltage Source Converter (VSC) and its associated shunt-connected transformer whose operational characteristics resemble those of synchronous voltage sources. They behave analogously to synchronous compensators, except that VSC's have no mechanical inertia, and are therefore capable of responding much more rapidly to changing system conditions, they do not contribute short circuit current, they have no moving parts, and they have a symmetric lead-lag capability [4-6]. Theoretically, VSC-based controller can go from full lag to full lead in fractions of a cycle. In the present work, relating to power system long-term dynamic assessment, controllers are modeled to have a quasi-instated response to achieve the set voltage or power to be controlled.

It is important to notice that devices are analyzed from the "black box" viewpoint of operational control of power system rather than internal dynamic control. The STATCOM controller have been developed using simply control systems to enable the basic control capabilities of the device and case studies of power system dynamics using the developed model have been carried out to show its capabilities to help the dynamic power flow problem solved.

## II. Power System Stability

Power System Stability may be defined as the ability that an electric power system has, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with system variables bounded so that system integrity is preserved. Integrity of the system is preserved when practically the entire power system remains intact with no tripping of generators or loads, except for those disconnected by the isolation of the faulted elements or intentionally tripped to preserve the continuity of operation of the rest of the system. A key issue in the control of large-scale power network operation is to maintain stability.

Despite the bulk of literature that the STATCOM has generated, as far as this authors are aware, stability analysis of large-scale power system with embedded STATCOM controllers has not received much research attention, certainly, the phase domain using rectangular coordinates for dynamic power flows analysis have not yet been tackled anywhere.

The first step in the research was the developed of conventional power plant components models in the phase domain. The novelty of the task in hand being the suitability of the transmission network models for large-scale, three-phase dynamic power flow analysis.

## III. Dynamic Modelling Philosophy

Power networks can be modeled as a set of non-linear equations corresponding to active and reactive nodal power injections; these are linearised around a base operating point determined by generation and load powers, and nodal voltages. On the other hand, models of active power plant

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components, such as generators, are described by a set of first order differential equations [7-8]. By suitable combination of both sets of equations the complete power system model, aimed at time response calculations of large-scale power networks, can be reduced to an algebraic-differential initial value problem of the form,

$$\frac{dy}{dt} = F(y,x) \tag{1}$$

$$0 = G(x,y) \tag{2}$$

where $y$ and $x$ are vectors of integrable and non-integrable algebraic variables. In general, $F$ and $G$ are non-linear vector functions and thus the non-integrable network variables cannot be eliminated algebraically. The initial conditions for a stability study are determined by a steady-state power flow solution. Thereafter equations (1) and (2) must be solved simultaneously as a function of time [9].

Consequently the objective of the dynamic power analysis is to solve $y$ and $x$ as a function of time. Set (1) comprises the differential equations of all synchronous generators, since each generator is coupled to the other power plants only through the network, set (1) is a collection of separate subsets. Set (2) comprises network equations and the stator equations of each machine, transformed into the network reference frame. This set of equations is interdependent and therefore the solution technique must provide a simultaneous solution.
The open literature offers a wide range of numerical methods to solve them [9]. The simultaneous approach is where the differential equations are transformed into algebraic equations and combined with the network algebraic equations for all variables to be solved simultaneously. The partitioned solution is the traditional method, used in nearly all-present day industrial programs. In the presented research a Newton-trapezoidal method of integrations has been selected to solve simultaneously differential and static system equations. .

## IV. The Static Synchronous Compensator Controller

The Static Synchronous Compensator (STATCOM or SSC) consists of one VSC and its associated shunt-connected transformer, as illustrated in Fig 1. It is the static counterpart of the rotating synchronous condenser but it generates/absorbs reactive power at a faster rate because no moving parts are involved, it can be used in a similar way to the synchronous condenser to provide dynamic compensation to a transmission system [10]. In principle, it performs the same voltage regulation function as the SVC but in a more robust manner because unlike the SVC, its operation is not impaired by the presence of low voltages. Its speed of response enables increased transient stability margins, voltage support enhancements, and damping of low frequency oscillation.

The schematic representation of the STATCOM and its equivalent circuit are shown in Fig. 1. The equivalent circuit corresponds to the Thevenin equivalent as seen from bus $k$, with a sinusoidal voltage at the bus $k$, of magnitude $V_k$ and phase angles $\theta_k$ and the fundamental component of the STATCOM voltage is taken to be a variable voltage source $\boldsymbol{E}_{vR}$, with magnitude $V_{vR}$ and phase angle $\delta_{vR}$, the superscript $\rho$ is used to denote phases *a, b* and *c*. The three phase voltage generated by the STATCOM is adjusted with little delay by virtue of semiconductor devices switching, under consideration by the rates of frequency and amplitude modulation, $m_a$ and $m_f$, respectively [1,8]. The voltage magnitude, $V_{vR}$, is given maximum and minimum limits, which are a function of the STATCOM capacitor rating. On the other hand, $\delta_{vR}$ may take any value between 0 and $2\pi$ radians.

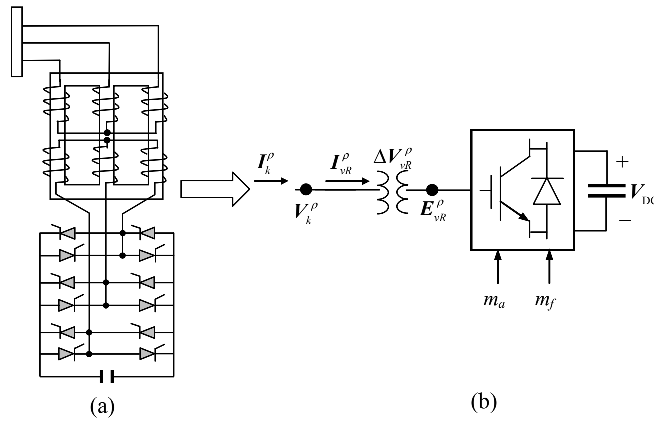


**Fig. 1** STATCOM system: (a) VSC connected to the AC network via a shunt-connected transformer; and (b) STATCOM schematic representation [11]

### A. Dynamic STATCOM model

The main operational objective of the STATCOM is to increase power transmission capability by voltage control at the point of connection of power network. During disturbances and contingencies, the internal voltage source is varied to control the voltage at the bus and contribute to a more stable voltage performance. With reference to the equivalent circuit shown in Fig. 1(b), and assuming three-phase parameters, the dynamic behavior of the compensator in the normal compensating range, is well characterized by the basic transfer function block diagram show in Fig. 2. In standard control mode, the STATCOM is operated as a voltage regulator; when a disturbance occurs and as result, $V_{\text{bus}}$ drops (or rises) the voltage source $V_{vR}$ is adjusted, This enables the set voltage to kept by supplying or absorbing reactive power to the system.

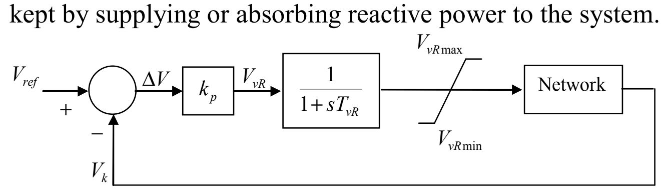


**Fig. 2** STATCOM linear model for voltage magnitude control

The block diagram describes the interaction of variables in a simple model of the STATCOM, where the proportional controller coupled with the STATCOM regulates nodal voltage and maintains the connection error close to zero. The condition is that it behaves as a PV node, i.e. the phase angle of voltage of the STATCOM is in synchronism with the system in CA, then there is no transfer of real power, reactive power is transmitted only to the magnitude of the voltage controlled. The differential equations, state variables and control input parameters can be arrange as follows;

$$\Delta V = V_{\text{ref}} - V_{\text{bus}} \tag{3}$$

$$\frac{d}{dt}V_{vR} = \frac{k\Delta V - V_{vR}}{T_{vR}} \qquad V_{vR\ \min} \le V_{vR} \le V_{vR\ \max} \tag{4}$$

where
$V_{\text{bus}}$ is the nodal voltage magnitude
$V_{vR}$ is the voltage source converter
$T_{vR}$ is the transient time constant
$V_{\text{ref}}$ is the pre-specified reference voltage (magnitude)
$k_p$ is the gain of proportional controller
$s$ is the Laplace operator

### B. Dynamic Power flow STATCOM Modelling

The ordinary differential equation (4) is transformed into an algebraic equation, to be solved simultaneously with the algebraic equations representing the network and the generating plant equations. Applying trapezoidal rule, the algebraic form of the STATCOM differential equation becomes

$$V_{vR(t)} = V_{vR(t-\Delta t)} + \frac{\Delta t}{2}\left[\frac{K_p\left(V_{ref} - V_{k(t)}\right) - V_{vR(t)}}{T_{vR}} + \frac{K_p\left(V_{ref} - V_{k(t-\Delta t)}\right) - V_{vR(t-\Delta t)}}{T_{vR}}\right] \tag{5}$$

Grouping terms together gives

$$F_{(t)}\left(V_{vR}\right) + F_{(t-\Delta t)}\left(V_{vR}\right) + k_{(V_{vR})} = 0 \tag{6}$$

where

$$F_{(t)}\left(V_{vR}\right) = V_{vR(t)} + \frac{\Delta t}{2}\left[\frac{K_p V_{k(t)} + V_{vR(t)}}{T_{vR}}\right] \tag{7}$$

$$F_{(t-\Delta t)}\left(V_{vR}\right) = -V_{vR(t-\Delta t)} + \frac{\Delta t}{2}\left[\frac{K_p V_{k(t-\Delta t)} + V_{vR(t-\Delta t)}}{T_{vR}}\right] \tag{8}$$

$$k_{(V_{vR})} = -\frac{\Delta t K_p V_{ref}}{T_{vR}} \tag{9}$$

It should be noted that equations (8) and (9) are constants. Term relating to time ($t$) is used to derive the terms in the Jacobian matrix to be evaluated in each iteration.

Equation (6) represents an increase in a row and a column in the structure of the Jacobian matrix, with the following elements:

$$\begin{bmatrix} \Delta P_k \\ \Delta E_k^2 \\ \Delta F\left(V_{vR}\right) \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial e_k} & \frac{\partial P_k}{\partial f_k} & \frac{\partial P_k}{\partial V_{vR}} \\ \frac{\partial E_k^2}{\partial e_k} & \frac{\partial E_k^2}{\partial f_k} & 0 \\ \frac{\partial F\left(V_{vR}\right)}{\partial e_k} & \frac{\partial F\left(V_{vR}\right)}{\partial f_k} & \frac{\partial F\left(V_{vR}\right)}{\partial V_{vR}} \end{bmatrix} \begin{bmatrix} \Delta e_k \\ \Delta f_k \\ \Delta V_{vR} \end{bmatrix} \tag{10}$$

where the Jacobian elements relating to the STATCOM to be include are

$$\frac{\partial F\left(V_{vR}\right)}{\partial e_k} = \frac{\Delta t K_p e_k}{2T_{vR}\sqrt{e_k^2 + f_k^2}} \tag{11}$$

$$\frac{\partial F\left(V_{vR}\right)}{\partial f_k} = \frac{\Delta t K_p f_k}{2T_{vR}\sqrt{e_k^2 + f_k^2}} \tag{12}$$

$$\frac{\partial F\left(V_{vR}\right)}{\partial V_{vR}} = 1 + \frac{\Delta t}{2T_{vR}} \tag{13}$$

where $\Delta t$ represent the step of integration, $e$ and $f$, are real and imaginary part of the voltage, respectively.

Terms with the subscript ($t$-$\Delta t$) are calculated using initial values obtained from power flows results and remain constant for the whole of the iterative process at time ($t$), whereas terms with the subscript ($t$) are updated at the end of each iteration step ($it$) using:

$$\left(V_{vR}\right)^{it+1} = \left(V_{vR}\right)^{it} + \left(\Delta V_{vR}\right)^{it} \tag{14}$$

Repetitive solutions at time ($t$) are carried out until changes at each nodal voltage and generators' state variables are less than a prescribed small tolerance, say $1e^{-12}$. Updated values of power flows are obtained for time ($t$) along with a new set of values for the state variables at each generating plant. The new set of state variables is used to obtain an improved solution at time ($t+1$). The whole process is repeated until the maximum time scheduled for simulation is completed, or up to a time when loss of system stability become apparent.

## V. Voltage Magnitude Control Using STATCOM in Dynamic Power Flows

The three-phase dynamic power flow program written in C++ OOP, with the STATCOM model incorporated along with the conventional power networks components has been used to solve a wide range of test power systems with different grades of complexity and sizes, given in each case very robust solution. Solution are achieved in less than nine iteration most of the cases, within one specific tolerance of $1e^{-12}$. The multiphase dynamic power flow is used in order to assess the impact of these controllers on large-scale electric power networks.

### A. Dynamic Power flow STATCOM Modelling

A five-bus network [2] is firstly used to investigate the effectiveness' of the STATCOM model proposed to control the voltage magnitude at the point connected, under a three-phase load trip and single phase transmission line trip.

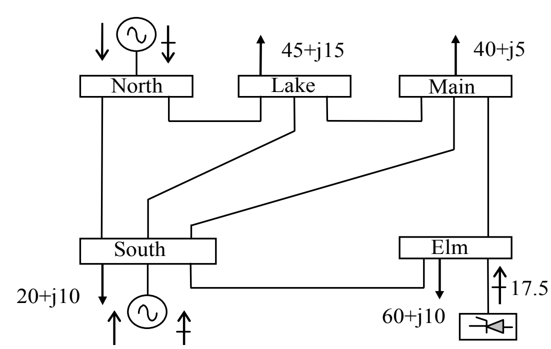


**Fig. 3** Five-bus network

The STATCOM is connected to bus Elm and it is set to maintain the nodal voltage magnitude at one per unit. The objective of this simulation is to show the capability of the controller to keep a constant voltage magnitude at the bus connected and to improvement transient stability. The scenario considered in this simulation is shown on Table 1.

TABLE 1
Scenario of events, five-bus network

| Item | Time [min] | Type of action |
|---|---|---|
| 1 | 17 | Three-phase load at node *elm* is disconnected |
| 2 | 34 | Three-phase load at node *elm* is reconnect |
| 3 | 58 | Phase *a* of line *main-elm* is disconnect |
| 4 | 75 | Phase *a* of line *main-elm* is reconnect |

From the generating plant variables behavior shown in Fig. 4-11, the responses to the scenario both with (a) and without (b) compensation are clearly appreciated. From Fig. 4, it can be seen than disturbance in the line trip have a negligible impact on frequencies fluctuations, but the load trip is a serious disturbance. The system frequency oscillations of ±0.5Hz (a), with compensation are limited to a range of ±0.06Hz (b).

Fig. 5 shows rotor angle difference, it can be notice that the angle of power plant South respect to North decreases significantly with the incorporation of the STATCOM.

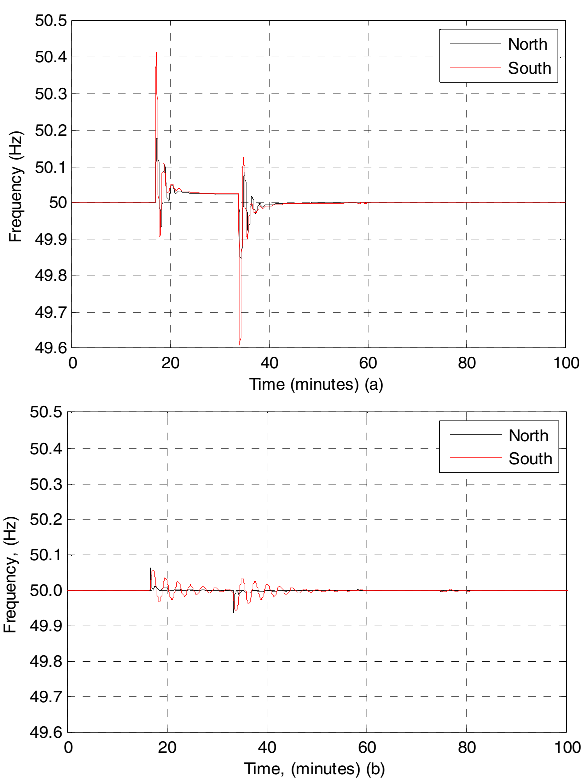


**Fig. 4** Frequency of system: (a) without and (b) with STATCOM embedded

After analyzing Fig. 6-11 it can be notice that mayor changes occur in remains controls of the generation power plant when a STATCOM is present in the network. Even the low pressure steam turbine power, Fig. 11 shows a significant influence of the STATCOM controller.

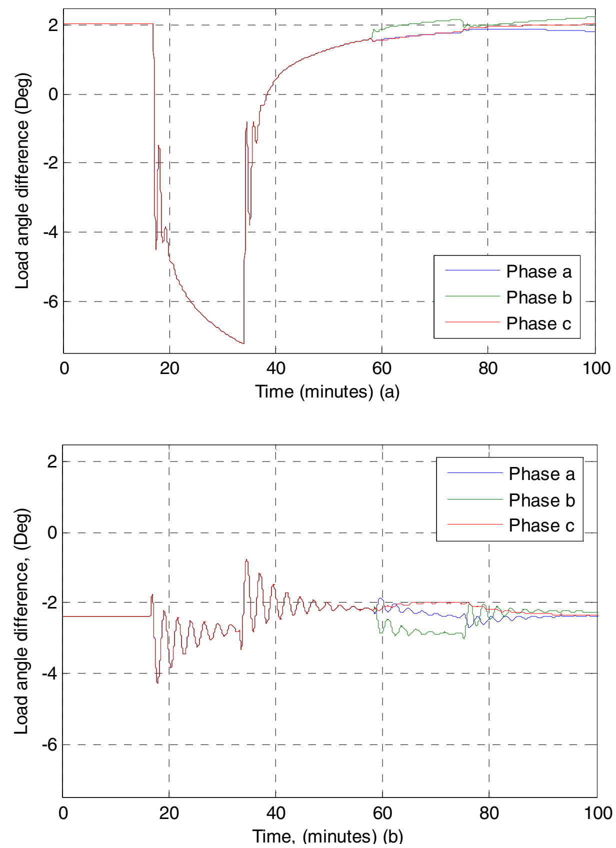


**Fig. 5** Load angle difference: (a) without and (b) with STATCOM embedded

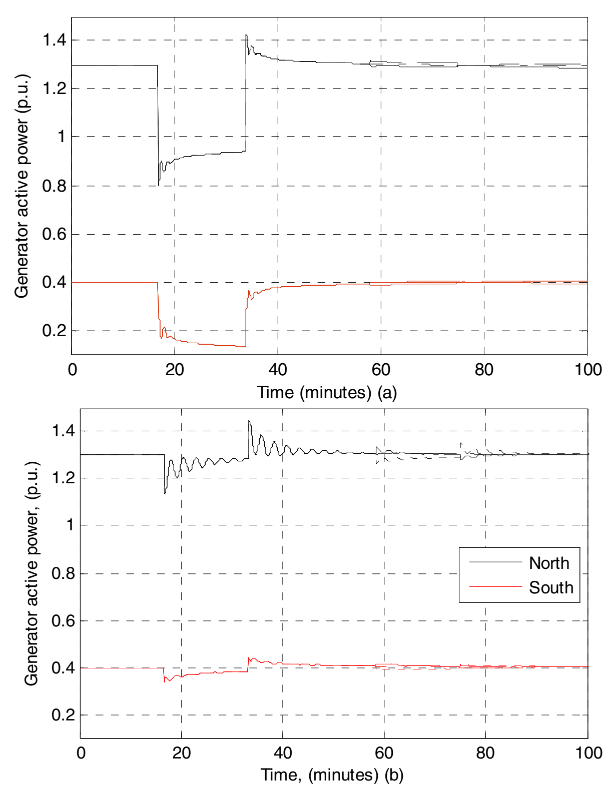


**Fig. 6** Generator active power: (a) without and (b) with STATCOM

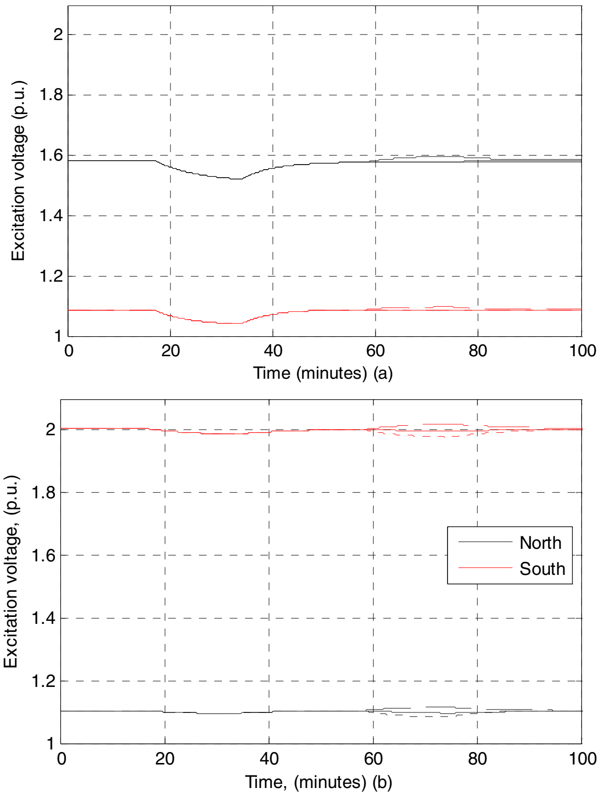


**Fig. 7** Excitation voltage: (a) without and (b) with STATCOM

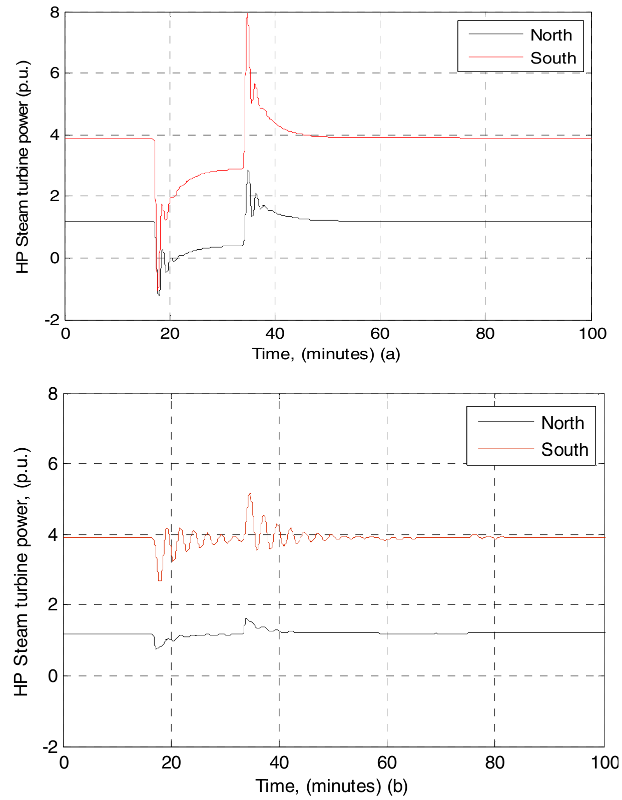


**Fig. 9** HP Steam turbine power: (a) without and (b) with STATCOM

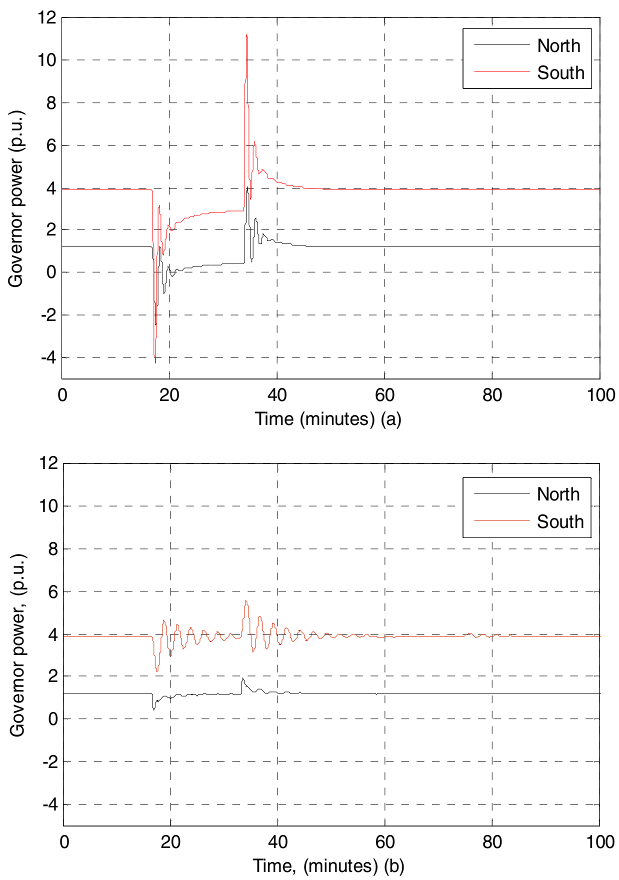


**Fig. 8** Governor power: (a) without and (b) with STATCOM

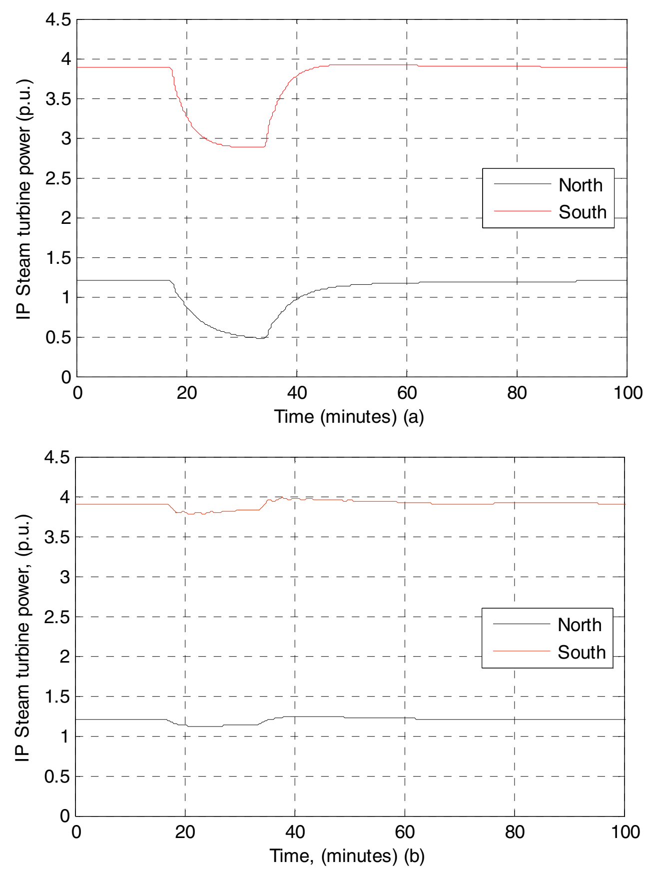


**Fig. 10** IP Steam turbine power: (a) without and (b) with STATCOM

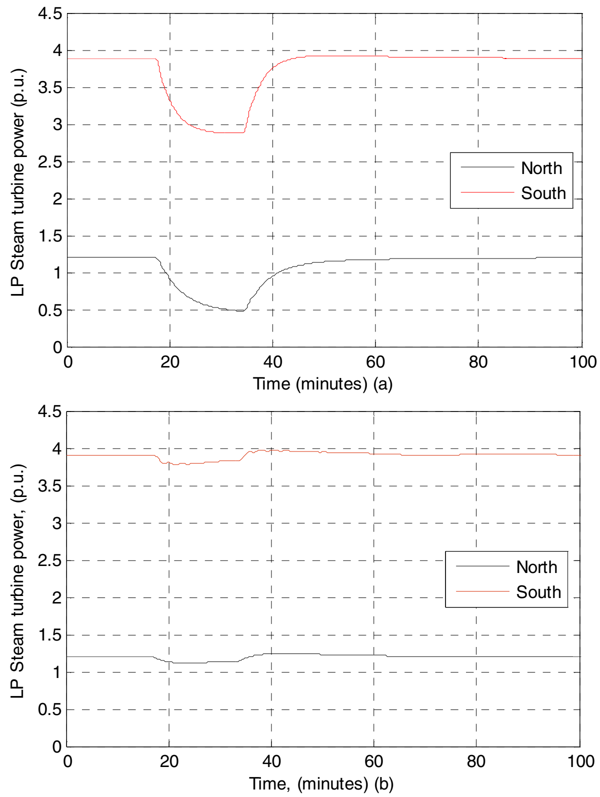


**Fig. 11** LP Steam turbine power: (a) without and (b) with STATCOM

By observing Fig 6 and Fig. 12, it is notice that a three-phase load trip causes a decrease in the generator power out, together with the step increase in nodal voltage magnitude and phase angles. Conversely, a positive effect is notice following reconnection of the three-phase load.

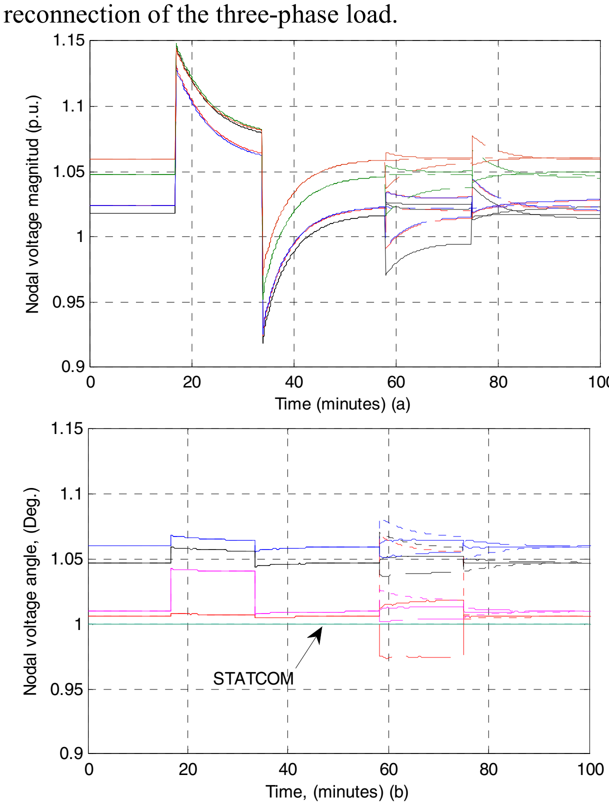


**Fig. 12** Nodal voltage responses of the system (a) without and (b) with STATCOM embedded.

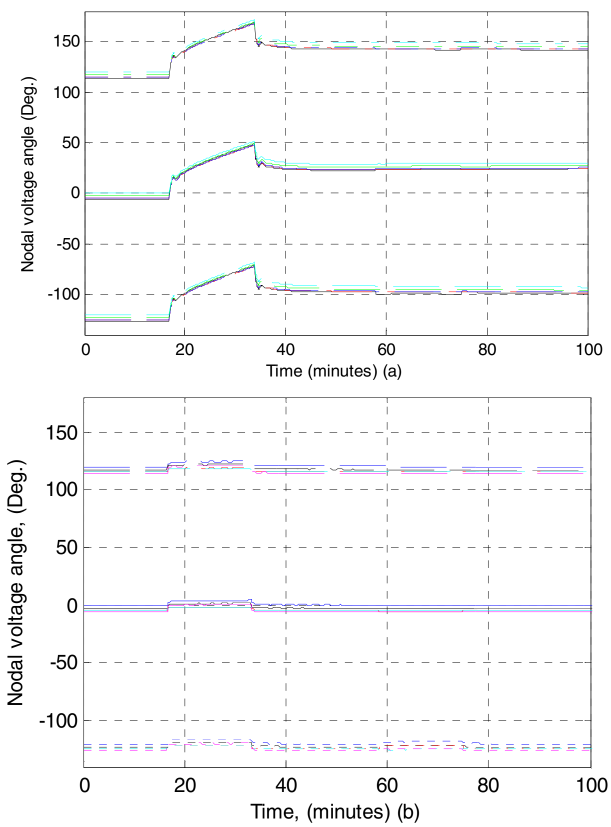


**Fig. 13** Nodal voltage angle: (a) without and (b) with STATCOM

Fig. 12 shows nodal voltage magnitudes, it can be notice that mayor changes occur when the STATCOM is present in the network compared with the case study where no STATCOM is included. For one the voltage magnitude in the STATCOM bus is maintained at its set value of one per unit. Keeping the voltage magnitude at the STATCOM bus at one per unit smooth out the recovery of the system after a disturbance has occurred, moving the system away from the possibility of voltage instability.

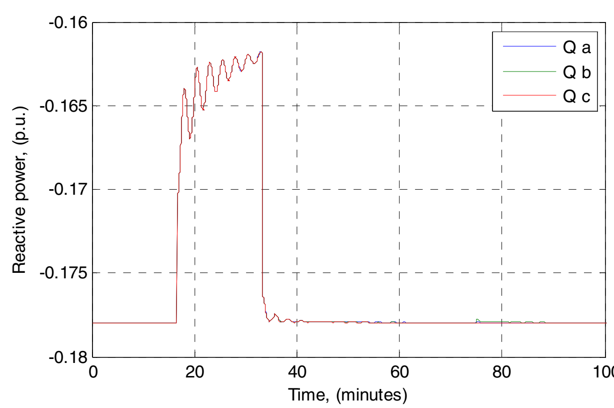


**Fig. 14** STATCCOM reactive power

Results had shown the STATCOM being able to compensate voltage in the AC system supplying reactive power to the power system. Fig. 14 show reactive power injected by the STATCOM at the bus connected in order to control the voltage magnitude at bus.

## *B. 57-bus network numerical example*

Network of 57 nodes is used to investigate to the effectiveness of the STATCOM model to maintain stability following diverse perturbations, shown Table 2. The STATCOM is connected at bus 47 and set to maintain the nodal voltage magnitude at the one per unit. The objective of this simulation is to assess the capability of the controller to keep a constant voltage magnitude at the connecting bus and to improve stability.

TABLE 2
Scenario of events, 57 bus network.

| Item | Time [min] | Type of action |
|---|---|---|
| 1 | 1 | Three-phase load at node 47 is disconnected |
| 2 | 6 | Three-phase load at node 47 is reconnected |
| 3 | 10 | Phase *a* of line 47-48 is disconnect |
| 4 | 15 | Phase *a* of line 47-48 is reconnect |

The simulation results are shown in Fig. 15-18. In this case the system without the STATCOM show instability at time 6 when the three-phase load is reconnected. However when the STACOM is presented in the network, keeping at one per unit the bus where is connected, it reduce the frequency fluctuations during the first swing and the recovery time, allowing for the remains events, Fig. 15.

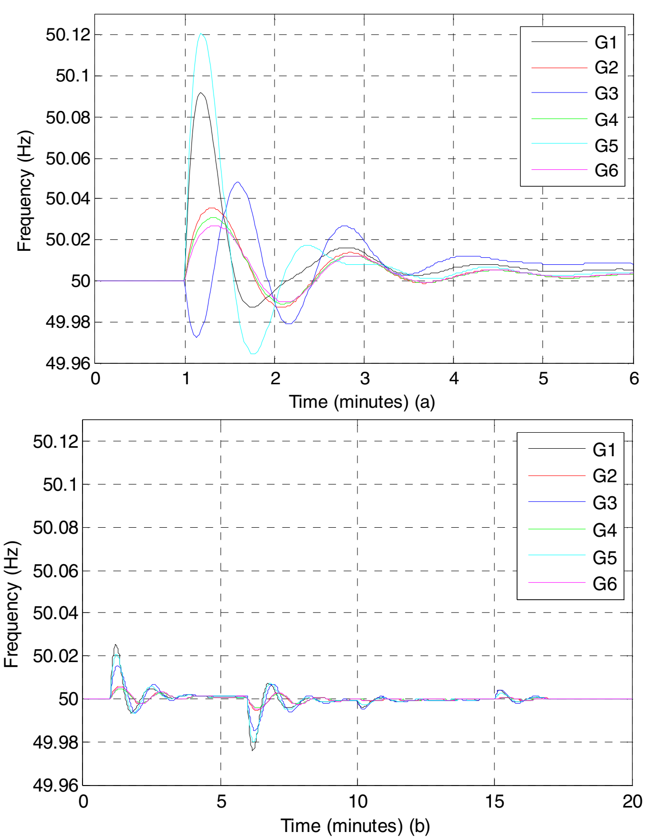


**Fig. 15** Frequency response, (a) without and (b) with STATCOM

Analyses of Fig. 16 show the same situation in the nodal voltages magnitudes when the STATCOM is presented in the network compared with the case where no STATCOM is included.

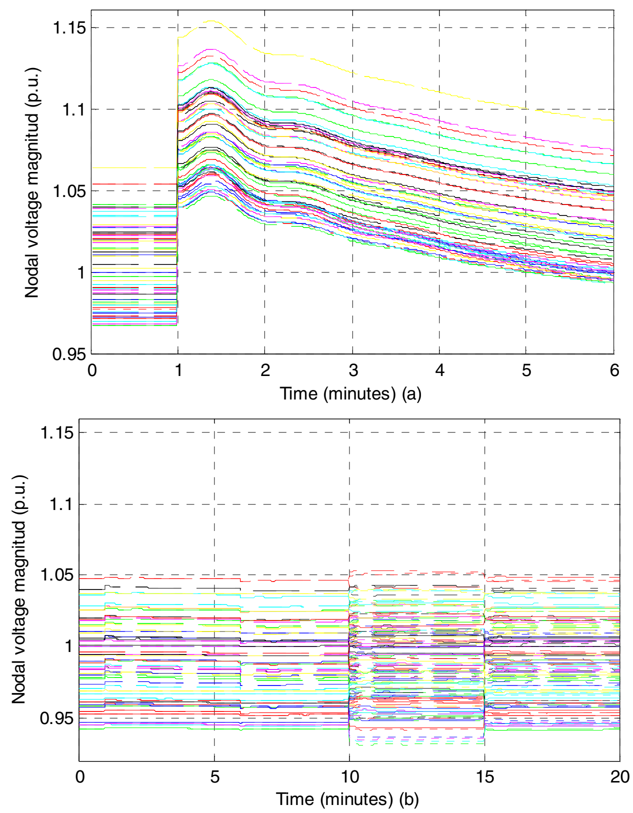


**Fig. 16** Three nodal voltages profile for both cases: a) the base case and b) the modified case, when three STATCOM are incorporated in the network

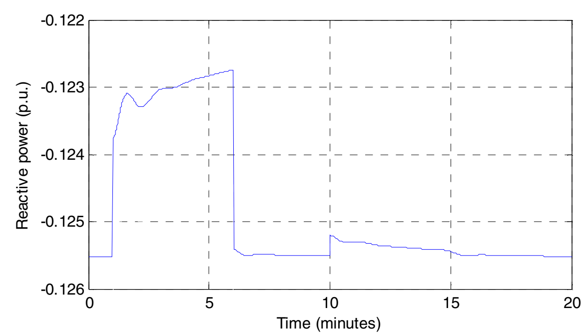


**Fig. 17** Reactive power response.

From Fig. 17 it can be seen that the initial reactive power for the target voltage is lower than the one required for the target during the two disturbances, the three-phase load trip and the one phase transmission line trip.

## VI. CONCLUSIONS

The STATCOM which utilize voltage source converter represent the main research concern in this paper. The goal has been to develop a dynamic model of the STATCOM VSC-based controller and to study its interaction with the electrical power network using its natural frame of reference termed the phase domain. A flexible mathematical model has been derived in the frame of reference of the phases and interfaced with the common elements found in conventional electric power systems. The algorithm solves the non-linear power flow equations by iteration to a specified tight tolerance. In rectangular co-ordinates the real and the imaginary parts of nodal voltages and injected STATCOM voltages are the ones used as the state variables. The results show that the Newton-Raphson power flow method retains its convergence characteristics. The objected oriented programming philosophy used to implement the power flow algorithms should facilitate the inclusion of any new power systems component or FACTS controllers that may become available in future.

The three-phase dynamic power flow algorithm for analysis of large-scale systems with STATCOM controllers has been tested using the five bus test system and the IEEE 7-generators, 57-buses test system. The software has good flexibility enabling any number of events to be analyzed. Moreover, the software has been tested with larger power systems. Simulation result shows that, as expected, the STATCOM controller can effectively enhance dynamic stability of power system by controlling the voltage magnitude at the bus connected.

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## VIII. Bibliographies


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**César Angeles-Camacho** was born in México. He obtained the BSc and the MSc degree from the Instituto Tecnológico de Morelia, in Mexico, in 1992 and 2000, respectively. In 2005, he obtained his PhD degree from the University of Glasgow, Glasgow, Scotland. He joined the institute of engineering of the *Universidad Nacional Autónoma de México* in 2005 as a lecturer and researcher. His research interests include modelling and simulations of FACTS and custom power controllers.

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