STATCOM Modeling for Voltage and Angle Stability Studies ⋆

Claudio A. Cañizares *

University of Waterloo, Dept. Electrical & Computer Eng., Waterloo, ON, N2L-3G1, Canada

Massimo Pozzi, Sandro Corsi

CESI, Via R. Rubattino 54 , 20134 Milan, Italy

Edvina Uzunovic

New York Power Authority, 123 Main Street, 6th floor, White Plains, NY, 10601, USA

Abstract

This paper proposes and validates models to accurately represent STATic Synchronous Shunt COMpensators (STATCOM) in voltage and angle stability studies of powers systems. The proposed STATCOM stability models are justified based on the basic operational characteristics of this Flexible AC Transmission System (FACTS) controller for both phase and PWM control strategies. These models are first validated by means of EMTP simulations on a test system, and then are implemented into two different programs used to study voltage and angle stability issues in the system. All details of the model implementation, the controls used, and the data for the test system are provided in the paper.

Key words: STATCOM, FACTS, modeling, voltage stability, angle stability, small signal stability, transient stability

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* Corresponding author.

Email addresses: C.Canizares@ece.uwaterloo.ca (Claudio A. Cañizares), Pozzi.Massimo@cesi.it (Massimo Pozzi), Edvina.Uzunovic@nypa.gov (Edvina Uzunovic).

1 Introduction

The development and use of FACTS controllers in power transmission systems has led to many applications of these controllers to improve the stability of power networks [1,2]. Thus, 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 oscillation control [2].

Several distinct models have been proposed to represent FACTS in static and dynamic analyses [3]. The current paper concentrates on describing in detail adequate STATCOM models for these types of studies, based on an energy balance criterion previously used in the modeling and simulation of this Voltage Sourced Converter (VSC)-based controller [4–7]. It is demonstrated here that the proposed models allow to accurately and reliably represent a STATCOM, operating under either phase or PWM control schemes, for voltage and angle stability studies using power flow, steady state and transient stability programs, as the models allow for an appropriate representation of the typical control limits for this controller [5,8,9].

Details of the implementation and use of the STATCOM models proposed here are discussed in regards to two programs used for steady state and transient stability analyses of power systems. These programs are UWPFLOW [10], a program designed for voltage stability analysis of power systems, and EASY5 [11], a program designed for modeling general linear and nonlinear control systems, and used at ENEL and CESI for model validation studies as well as steady state and transient stability analyses of sample power systems. The results of using these programs for the study of the stability of a test system are presented and thoroughly analyzed here, together with all the data required to reproduce these results in any simulation program.

Section 2 describes the proposed STATCOM models, based on the fundamental operation of this controller under both phase and PWM control strategies; improvements of these models with respect to models previously used to represent this controller in power flow and transient stability studies are also discussed in this section. In Section 3, the results of implementing the proposed STATCOM models into two programs used for voltage and angle stability analyses of a sample system are discussed in detail. Finally, Section 4 summarizes the implementation issues associated with the proposed model and discusses its limitations.

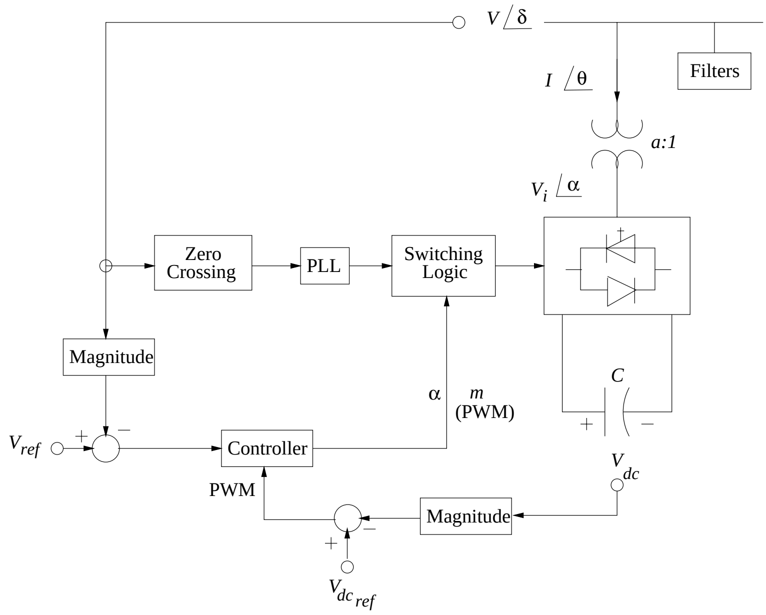

Fig. 1. Block diagram of a STATCOM with PWM voltage control.

2 STATCOM Models

The basic structure of a STATCOM with PWM-based voltage controls is depicted in Fig. 1 [5,8]. Eliminating the dc voltage control loop on this figure would yield the basic block diagram of a controller with a typical phase angle control strategy.

The STATCOM models proposed here is based on the power balance equation

$$P = P_{dc} + P_{loss} \tag{1}$$

which basically represents the balance between the controller's ac power P and dc power P_{dc} under *balanced operation* at *fundamental frequency* (these are the basic assumptions on which steady state and transient stability studies of power systems are based). For the models to be accurate, it is important to represent the losses of the controllers (P_{loss}), as discussed below; previously proposed models in [3] do not consider this issue.

PWM controls are becoming a more practical option for transmission system applications of VSC-based controllers, due to some recent developments on power electronic switches that do not present the high switching losses of GTOs [12], which have typically restricted the use of this type of control technique to relatively low voltage applications. In PWM controls, switching losses associated with the relatively fast switching of the electronic devices and their snubbers play an important role in the simulation, as these have a direct effect on the charging and discharging of the capacitor, and hence should be

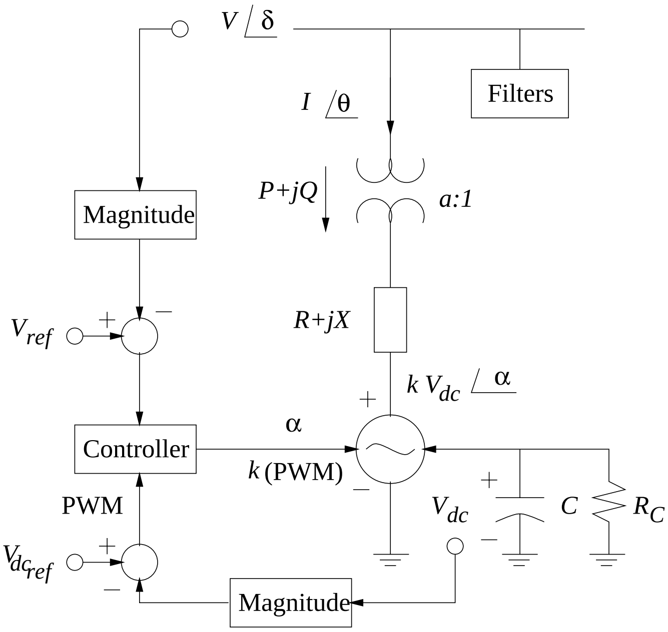

Fig. 2. Transient stability model of a STATCOM with PWM voltage control.

considered in the modeling. The models discussed in this paper assume the use of PWM control techniques, as these allow for developing more general models that can readily be adapted to represent other control techniques (e.g. phase angle control).

2.1 Transient Stability Model

Assuming *balanced*, *fundamental frequency* voltages, the controller can be accurately represented in transient stability studies using the basic model shown in Fig. 2 [5,7]. The p.u. differential-algebraic equations (DAE) corresponding to this model can be readily written as follows:

$$\begin{bmatrix} \dot{x}_c \\ \dot{\alpha} \\ \dot{m} \end{bmatrix} = f_c(x_c, \alpha, m, V, V_{dc}, V_{ref}, V_{dc_{ref}}) \qquad (2)$$

$$\dot{V}_{dc} = \frac{V\ I}{C\ V_{dc}} \cos(\delta - \theta) - \frac{G_C}{C}\ V_{dc} - \frac{R}{C}\ \frac{I^2}{V_{dc}}$$

$$0 = \begin{bmatrix} P - V\ I\ \cos(\delta - \theta) \\ \\ Q - V\ I\ \sin(\delta - \theta) \\ \\ P - V^2\ G + k\ V_{dc}\ V\ G\ \cos(\delta - \alpha) \\ +k\ V_{dc}\ V\ B\ \sin(\delta - \alpha) \\ \\ Q + V^2\ B - k\ V_{dc}\ V\ B\ \cos(\delta - \alpha) \\ +k\ V_{dc}\ V\ G\ \sin(\delta - \alpha) \end{bmatrix}$$

where most of the variables are explained on Fig. 2. The admittance $G+jB = (R+jX)^{-1}$ is used to represent the transformer impedance and any ac series filters (e.g. smoothing reactors), whereas G_C is used to model the "switching inertia" of the converter due to the electronic switches and their associated snubber circuits, which have a direct effect on the capacitor voltage dynamics. The constant $k = \sqrt{3/8}\ m$ is directly proportional to the modulation index m.

The variables x_c and functions $f_c(\cdot)$ in (2) stand for the internal control system variables and equations, respectively, and hence vary depending on whether a PWM or phase control technique is used in the controller. For example, in the simple PWM voltage controller shown in Fig. 3 [13], the variables and differential equations associated with the various control blocks directly define x_c and $f_c(\cdot)$. Observe that in this PWM controller, the ac bus voltage magnitude is controlled through the modulation index m, as this has a direct effect on the VSC voltage magnitude, whereas the phase angle α, which basically determines the active power P flowing into the controller and hence the charging and discharging on the capacitor, is used to directly control the dc voltage magnitude. Note also that the controllers have a bias, which corresponds to the steady state value of the modulation index m_o for the voltage magnitude controller, and to the phase angle δ of the output voltage of the STATCOM for the dc voltage controller (this value changes as the system variables change during the simulation). Although the latter complicates the simulation, it is needed to guarantee a direct control of the charging and discharging of the capacitor, which basically depends on the power flow between the VSC and the ac bus, i.e. it depends on $(\delta - \alpha)$. (This can be simplified by setting the bias of the dc voltage control to the constant value $\alpha_o = \delta_o$, where δ_o stands for the bus voltage phase-shift when the STATCOM is not connected [14].) Typically, the modulation index control would be "faster" than the phase angle control, as there is a significant charging and discharging "inertia" of the

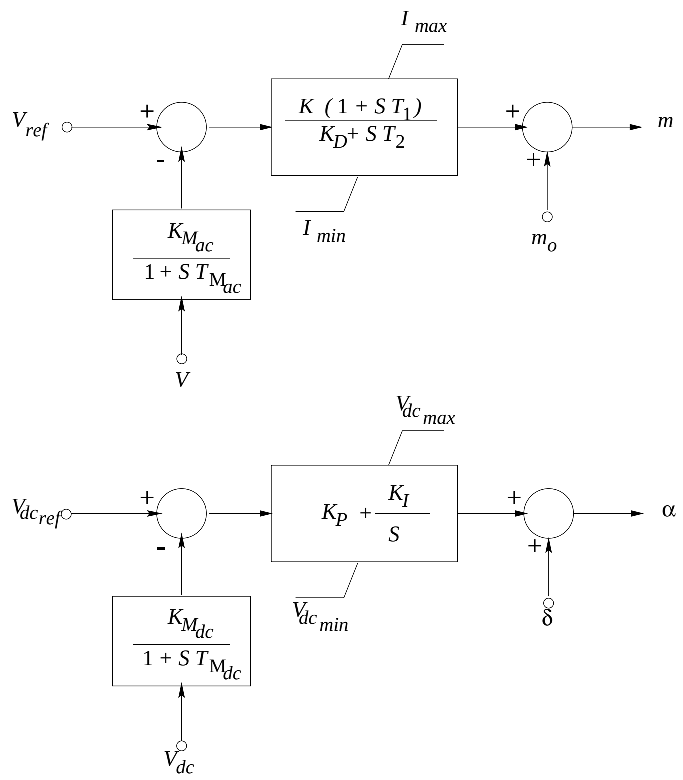

Fig. 3. Basic STATCOM PWM voltage control.

capacitor due to its relative large value, whereas the modulation index has an immediate effect on the output voltage of the controller.

The second equation in (2) is the direct result of applying the power balance equation (1), and allows to represent fairly accurately the dynamics of the dc voltage in the controller model, as demonstrated in Section 3 for a realistic test system. The adequate modeling of the V_{dc} dynamics is important, given the fact that the time constants associated with the dc voltage on the capacitor are in the order of the time constants of interest in stability studies. These dc voltage dynamics are basically defined by the G_C parameter in the proposed model, as its value directly affects the capacitor's charging and discharging time constant. The losses and dc voltage dynamics are considered in the models proposed in [5,7], whereas in the STATCOM model proposed in [3], these are not fully considered, since G_C is not represented in the model, thus introducing errors in the controller representation as demonstrated here.

The control limits of the controller are directly defined in terms of both the current limits in the electronic switches, which is the main limiting factor in VSC-based controllers, and the dc voltage, which is a secondary operational limit in this controller. This direct implementation of limits allows to closely duplicate the steady state V-I characteristics of the controller shown in Fig. 4, as well as allowing for an adequate representation of the basic control limits on an actual STATCOM [2]. In time domain simulations, the integrator blocks, such as those shown in Fig. 3, are "stopped" whenever the converter current I or dc voltage V_{dc} reach a limit. An alternative way of handling these limits for both PWM and phase control techniques to allow temporary controller overload is discussed in Section 3. (Another way to simulate these limits is to determine 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, as discussed in [14].)

2.2 Steady State Model

The steady state or "power flow" model can be readily obtained from (2) by replacing the corresponding differential equations with the steady state equations of the dc voltage and the voltage control characteristics of the STATCOM (see Fig. 4 [2]). Thus, the steady state equations for the PWM controller are

$$0 = \begin{bmatrix} V - V_{ref} \pm X_{SL} I \\ V_{dc} - V_{dc_{ref}} \\ P - G_C\, V_{dc}^2 - R\, I^2 \\ P - V\ I\ \cos(\delta - \theta) \\ Q - V\ I\ \sin(\delta - \theta) \\ P - V^2\, G + k\, V_{dc}\, V\, G\ \cos(\delta - \alpha) \\ +k\, V_{dc}\, V\, B\ \sin(\delta - \alpha) \\ Q + V^2\, B - k\, V_{dc}\, V\, B\ \cos(\delta - \alpha) \\ +k\, V_{dc}\, V\, G\ \sin(\delta - \alpha) \end{bmatrix} \qquad (3)$$

where on the first equation, the positive sign is used when the device is operating on the capacitive mode ($Q < 0$) and negative for the inductive mode ($Q > 0$), since $I \geq 0$.

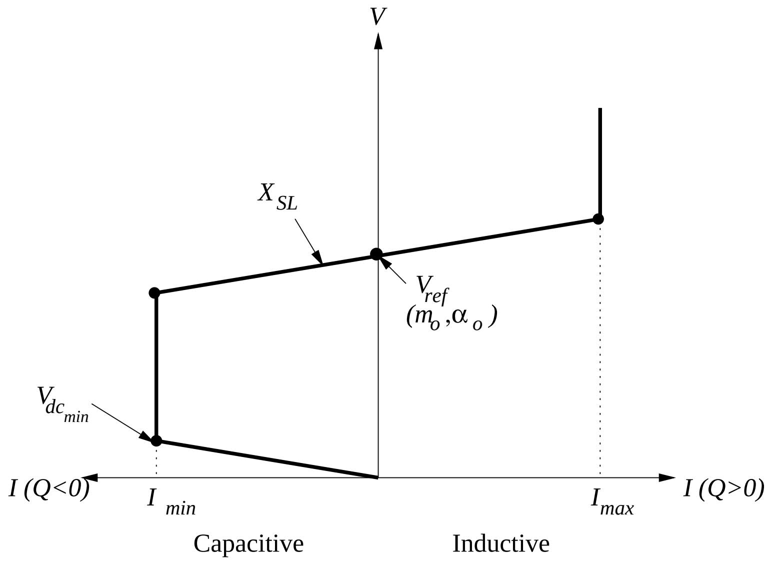

Fig. 4. Typical steady state V-I characteristics of a STATCOM.

Observe that the controller droop X_{SL} is directly represented on the V-I characteristic curve, with the controller limits being basically defined by its ac current limits I_{max} and I_{min}. Usually, $I_{max} > I_{min}$ as the electronic switches self commutate on the inductive region. Furthermore, $V_{dc_{max}}$ and $V_{dc_{min}}$ are typically not an issue on steady state models, given their corresponding relatively high and low values with respect to the typical range of application of these models.

A phase control technique can be readily modeled by simply replacing the dc voltage control equation in (3) with an equation for k, i.e. for a 12-pulse VSC, replace $0 = V_{dc} - V_{dc_{ref}}$ with $0 = k - 0.9$. In this case, the dc voltage changes as α changes, thus charging and discharging the capacitor to control the converter voltage magnitude.

These equations can be directly used to compute the control steady state values and biases as well as its limits. For example, the modulation index bias and steady state is determined by setting $I = 0$, yielding

$$m_o = \sqrt{\frac{8}{3}} \underbrace{\frac{V_{ref}}{V_{dc_{ref}}}}_{k_o}$$

Modulation index and phase-shift control limits corresponding to the controller ac current and dc voltage limits can be readily determined by solving equations (3) [14].

The limits on the current I, as well as any other limits on the steady state model variables, such as the modulation ratio represented by k or the voltage

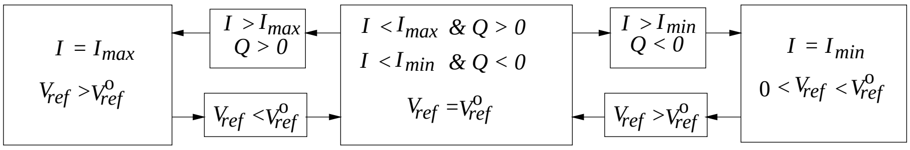

Fig. 5. Handling of limits in the STATCOM steady state model.

phase angle α, can be directly introduced in this model. It is important to properly represent the control mode switching when these limits are reached, as this is needed to properly model FACTS controllers in voltage stability studies [15]. The switching logic depicted in Fig. 5 is proposed here to represent the steady state control mode switching for the STATCOM, which is mainly associate with the controller ac current, as previously discussed. When either maximum or minimum current limits are reached, depending on whether the controller is operating in the inductive or capacitive region, respectively, voltage control is lost; the controller is allowed to recover from its limits when the voltage is again within the control voltage range as defined by the controller voltage droop.

The model presented here allows for a more adequate representation in steady state analysis of the STATCOM than the typical power flow models based on reactive power source representations of the controller (e.g. [7]). In these types of models, limits are usually represented through limits in reactive power, i.e. the STATCOM is basically modeled as a synchronous condenser using a standard PV bus model. This would somewhat represent the controller current limits if its terminal voltage is known; however, this is not always the case, as this voltage depends on control droops, the system conditions, the STATCOM controlled bus, and other controller limits. Hence, the PV bus model presents the following limitations:

- The controller droop cannot be readily modeled.
- Certain controller limits, such as limits on the dc voltage, phase angle and/or modulation ratio cannot be properly represented,
- If the STATCOM controls the voltage at a "remote" bus, the limits in the reactive power will not adequately model the controller current limits.

The proper representation of control droops and controller limits is of particular importance in voltage stability studies [16], as controller limits may lead a power system to voltage collapse problems. These limitations are clearly illustrated through simulations on a realistic test system in the next section.

3 Implementation and Results

The STATCOM model described here was implemented into two software packages that may be used for the stability analysis of power systems, namely, UWPFLOW [10] and EASY5 [11]. The results obtained with these programs were compared with results extracted from [5], where the Electromagnetic Transient Program (EMTP) is used to validate the proposed model. The details of the STATCOM model implementation in these programs and the results obtained from the stability analysis of a realistic test system are discussed in this section.

3.1 Test System

The test system depicted in Fig. 6 is used here to validate the implementation of the STATCOM model into the programs UWPFLOW and EASY5 based on detailed EMTP simulation results.

The EMTP is used in [5] to simulate a detailed switching model of the STATCOM operating under phase control, and to compare the results obtained from this model against those obtained for the controller model described in Section 2. The results of this comparison are depicted on Fig. 7. A load rejection fault is simulated by connecting a large load at Bus 6 at 4.5s, and then opening breaker 3-5 at 4.65 s. Observe how close the results are for the "external" variables, i.e. voltage magnitudes and angles, for the detailed and the reduced models. The "internal" STATCOM variables V_{dc} and $\Delta\alpha$ do not match exactly, although the general trends are similar, as the switching cannot be represented in the stability model. Observe that a value of $G_C = 0$, which basically corresponds to a typical STATCOM stability model [3], yields fairly different results from those obtained for the detailed switching studies.

All the data and controls required for typical stability studies of the given test system were extracted from the detailed 3-phase EMTP data of the system, and are depicted in Figs. 8 and 9, and Tables 1, 2 and 3. It is important to highlight the fact that the value of G_C was carefully chosen to match the system losses and dc voltage dynamics obtained from the EMTP detailed switching studies.

3.2 Voltage Stability Results

The program UWPFLOW, as described in [10], is a tool that can be used to determine the steady state operating conditions of power systems as cer-

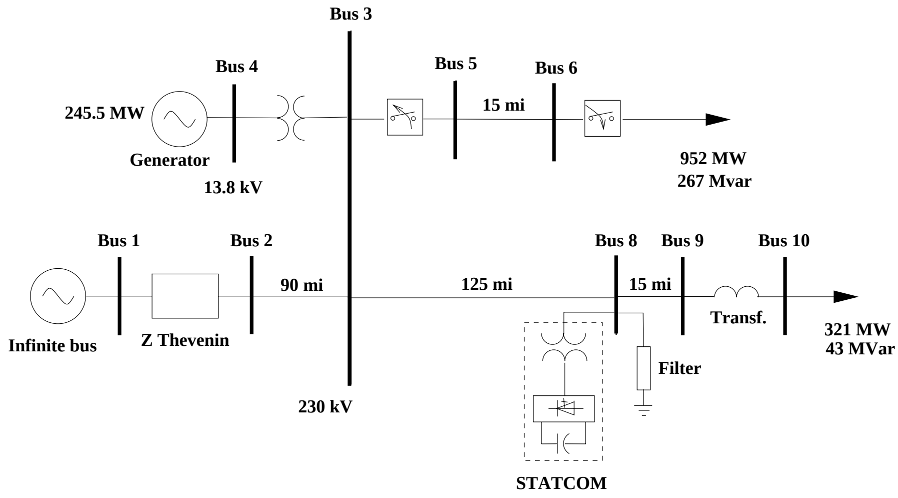

Fig. 6. Test system.

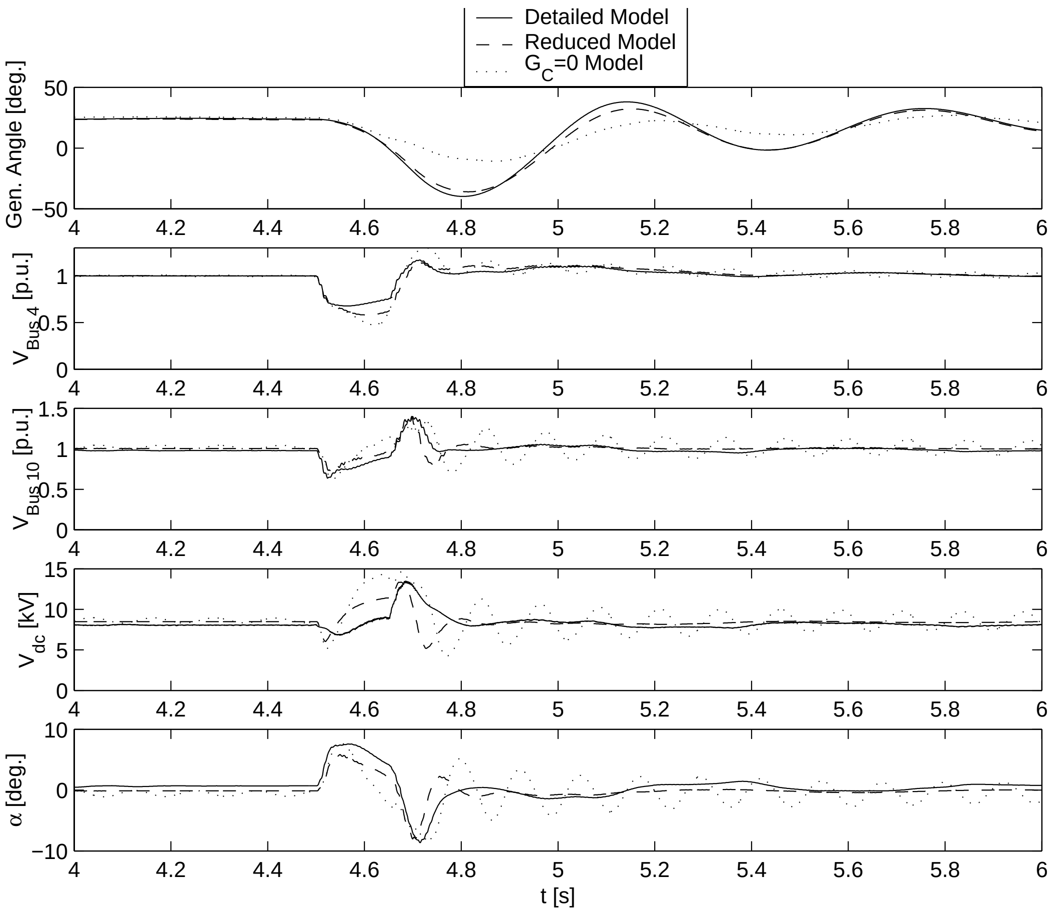

Fig. 7. EMTP results for the test system with different models for a phase-controlled STATCOM.

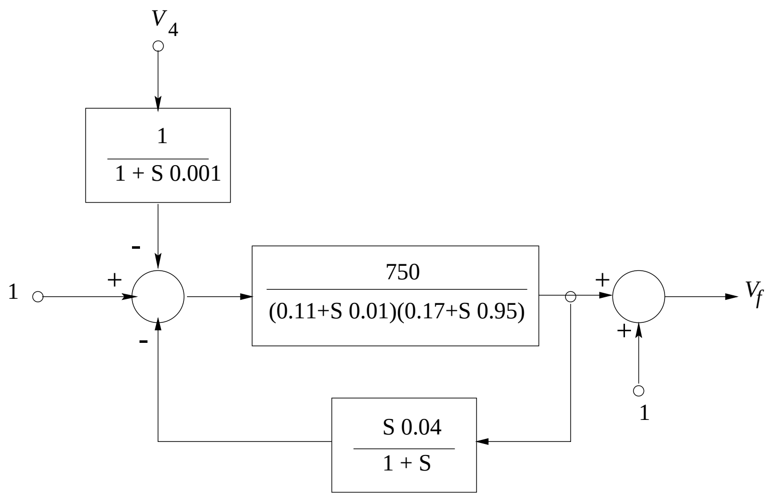

Fig. 8. EMTP generator AVR model for the test system.

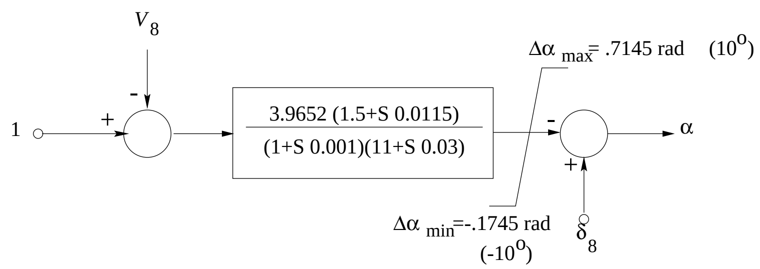

Fig. 9. EMTP phase control for the STATCOM in the test system.

Table 1
Generator data in p.u. with respect to a 200 MVA and 13.8 kV base.

Variable	Value [p.u./s]	Variable	Value [p.u./s]
Poles	2	H	2.7113
R_a	0.001096	D	0
X_l	0.15	T'_{d_o}	6.19488
X_d	1.7	T'_{q_o}	0
X_q	1.64	T''_{d_o}	0.028716
X'_d	0.238324	T''_{q_o}	0.07496
X''_d	0.18469	X''_q	0.185151

tain system parameters change. It can be used to partially study the steady state stability of these systems, especially the issue of voltage stability with respect to a variety of system changes (e.g. load changes). UWPFLOW is basically a continuation power flow program with fairly detailed steady state models of generators and HVDC links, including some of their control systems and corresponding limits. It also contains SVC and TCSC controller models to represent these popular Thyristor Control Reactor (TCR)-based FACTS controllers in power flow and voltage stability studies [15].

Table 2
Transmission system data in p.u. with respect to a 240 MVA base.

Element	R	X	$B/2$
1-2	0.0003	0.0684	0
2-3	0.0159	0.2275	0.0754
3-8	0.022	0.316	0.1047
4-3	0	0.08	0
5-6	0.0026	0.0379	0.0126
6-7	0	0.12	0
8-9	0.0026	0.0379	0.0126
9-10	0	0.12	0
Filter	0.0087	-4.3	0

Table 3
STATCOM data in p.u. with respect to a 150 MVA and 12 kV base.

Variable	Value
R	0
X	0.145
G_C	2.16
C	0.0432
k (Phase)	0.9
$V_{dc_{ref}}$ (PWM)	1
I_{max}	1
I_{min}	1

The model corresponding to equations (3) was programmed into UWPFLOW, which was used to obtain the PV curves and maximum loading conditions for this system as shown in Fig. 10. As expected, the loading margin and voltage profiles of the system are significantly improved by the introduction of the STATCOM, especially for the phase control mode, as the dc voltage is free to change while the current is within its limits, whereas in PWM control mode, the dc voltage is kept constant at a value that could be considered low for the test system. In all cases, current limits are reached before the maximum loading point.

For comparison purposes, the STATCOM was also modeled as a PV bus. Note that modeling the STATCOM as a PV bus with fixed reactive power limits ($Q_{max} = -Q_{min} = 1$ p.u. for $I_{max} = I_{min} = 1$ p.u.) does not properly

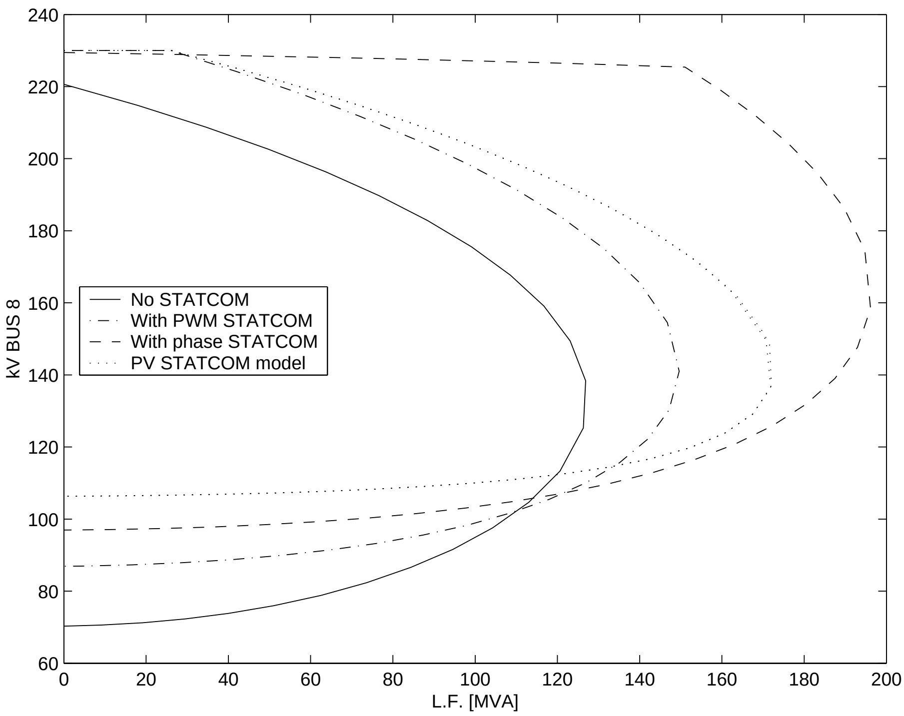

Fig. 10. PV curves obtained with UWPFLOW for the test system with and without STATCOM.

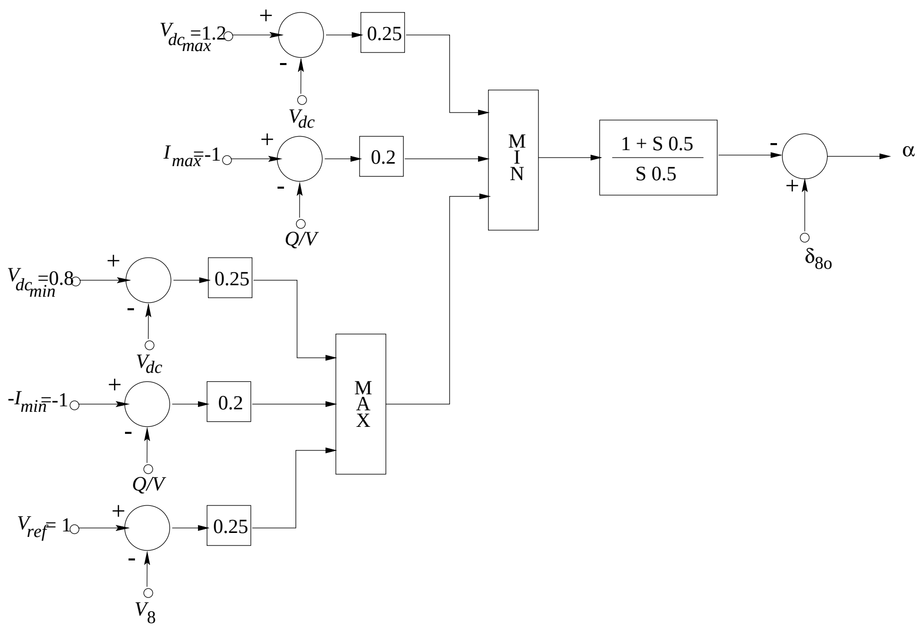

Fig. 11. STATCOM phase controller in EASY5.

represent the controller for these types of studies, as previously discussed.

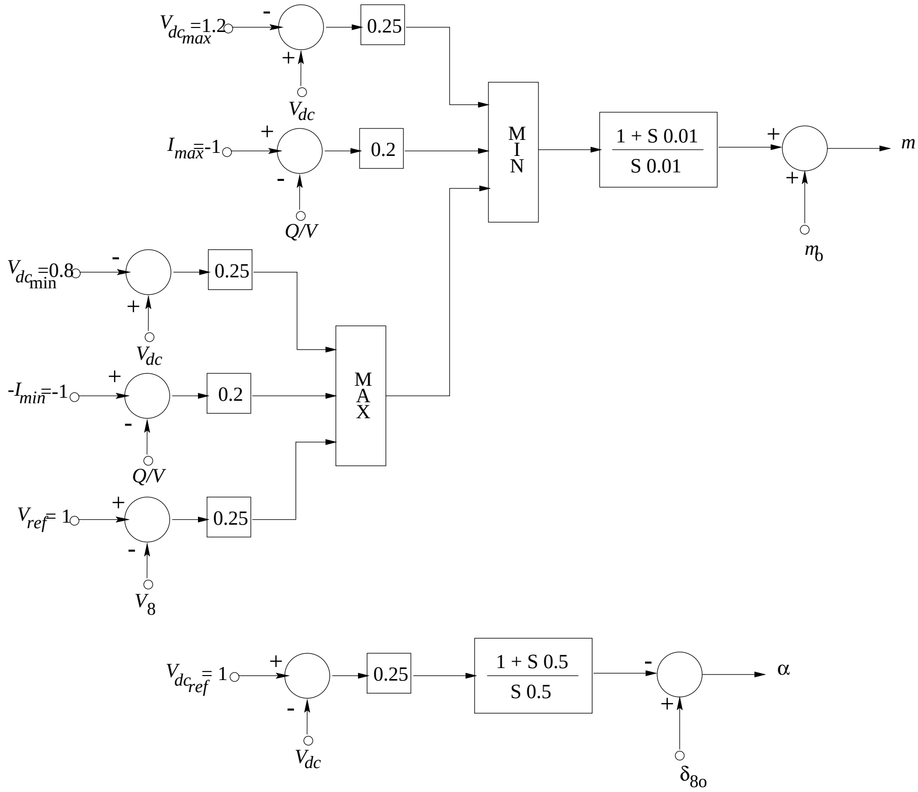

Fig. 12. STATCOM PWM controller in EASY5.

3.3 Transient Stability Results

EASY5 is a program by BOEING used for the simulation of linear and nonlinear control systems [11]. This program allows to graphically represent any linear and nonlinear control system through the definition of its equations and associated graphical icons. Linear matrix analysis tools and nonlinear integration tools allow for the analysis of the steady state as well as the transient stability of any control system defined by the user. Libraries can be readily developed, so that new systems and elements can be easily defined and integrated into other simulations. The different element models and the connections between these elements in a given system must be defined together with the numerical analysis techniques required for its analysis. Thus, as with SIMULINK-MATLAB, the program can be used to graphically model power systems. This program has been successfully used at ENEL and CESI to model and test a variety of power system controllers [17].

The model corresponding to equations (2) for a phase and PWM controllers were implemented in EASY5. The STATCOM phase and PWM controllers are depicted in Figs. 11 and 12, respectively. The generator AVR and STATCOM phase controllers implemented in this program for the test system are not exactly the same as the ones used in the EMTP, particularly for the STAT-

COM phase and PWM controls, which are significantly different from the ones discussed in Section 2 in the way the limits are implemented. The reason for these modeling differences, particularly in the implementation of the STATCOM limits, is to improve the dynamic voltage control characteristics of the system controllers, as transient overload of the STATCOM is allowed to improve its dynamic response; this does not affect the steady state behavior of the controller.

The results of using this program and the corresponding voltage controls to model the test system fault depicted in Fig. 6 are illustrated in Figs. 13 and 14. As in the EMTP example, a load rejection problem is simulated by suddenly applying a large load on Bus 6 at 4.5s, and then disconnecting it at 4.65s by opening the breaker 3-5. Observe that the results are somewhat similar to those obtained with the EMTP; however, one cannot expect an exact match, as the STATCOM controls are basically different and the generator loading conditions are not exactly the same (there is an approximate 2° difference between the EMTP and ESAY5 simulations in the internal generator angle at the initial steady state conditions). It is interesting to notice that under PWM control, the STACOM internal variables, i.e. V_{dc} and α, show less variations than under phase control; however, the controlled load voltage basically presents the same transient response in both cases.

4 Conclusions

The STATCOM transient stability and power flow models proposed in this paper are basically improved versions of models previously proposed in the literature. Thus, the current paper concentrates in discussing and justifying the improvements to these models so that proper voltage and angle stability studies can be performed on networks that contain this kind of FACTS controller. The implementation of the STATCOM model into a couple of stability analysis tools, and the results presented and discussed for a simple test system show how these models can be readily and reliably used for stability studies of power systems.

The models discussed here are all based on the assumption that voltages and currents are sinusoidal, balanced, and operate near fundamental frequency, which are the typical assumptions in transient stability and power flow studies. Hence, these models have several limitations, especially when studying large system changes occurring close to FACTS controllers:

(1) These models cannot be reliably used to represent unbalanced system conditions, as they are all based on balanced voltage and current conditions.

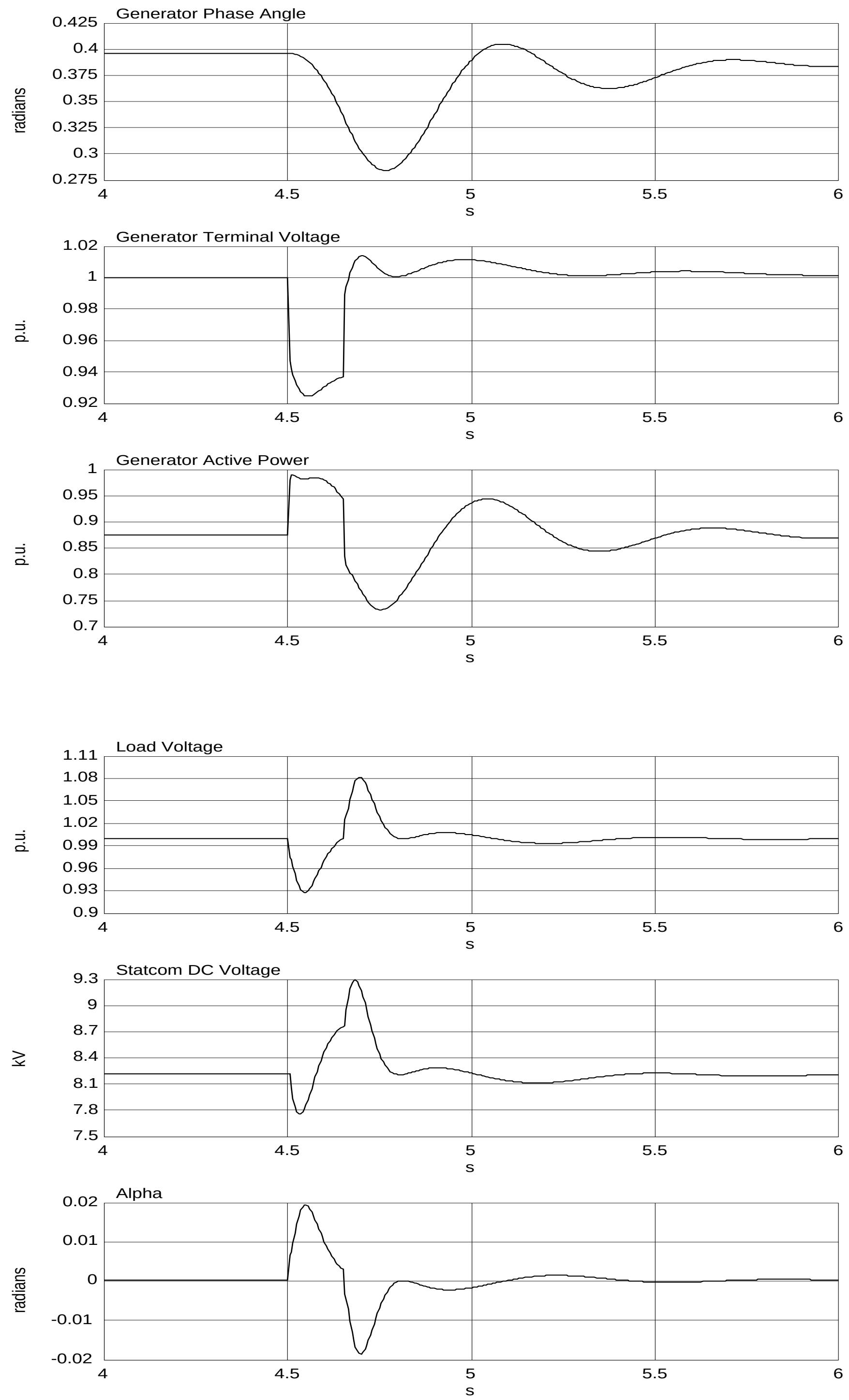

Fig. 13. Fault simulation results obtained with EASY5 for the STATCOM operating under phase control.

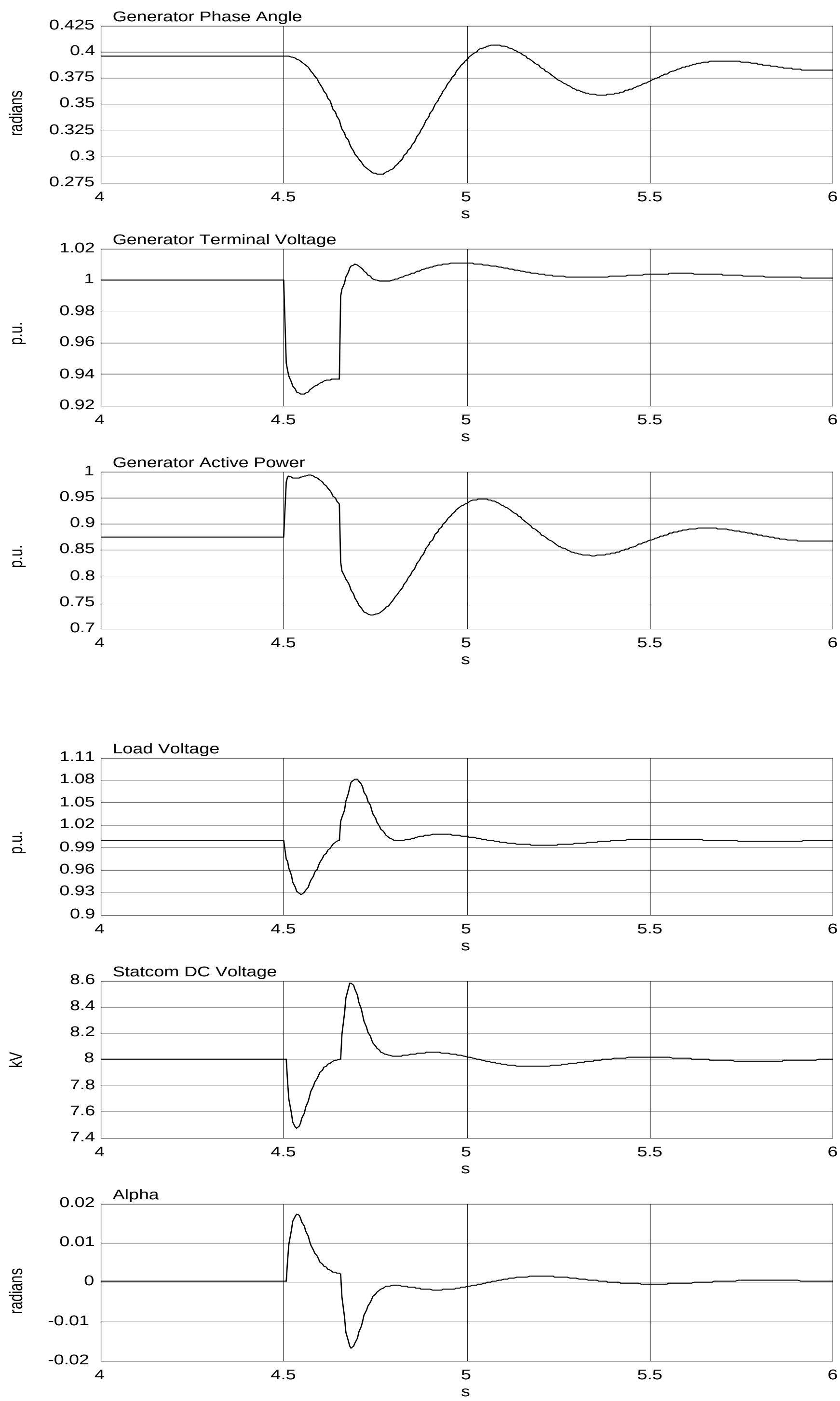

Fig. 14. Fault simulation results obtained with EASY5 for the STATCOM operating under PWM control.

(2) Large disturbances that yield voltage and/or currents with high harmonic content, which is usually the case when large faults occur near power electronics-based controllers, cannot be accurately studied with these models, as they are all based on the assumptions of having sinusoidal signals.
(3) The above also applies for cases where voltage and current signals undergo large frequency deviations.
(4) Internal faults as well as some of the internal variables of the controller cannot be reliably represented with these models.

For all of these cases, detailed EMTP types of studies are required to obtain reliable results. It is important to highlight the fact that these limitations also apply to most models typically used to represent a variety of devices and controllers in transient stability and power flow studies.

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