Enhancement of a Power System Transient Stability Using Static Synchronous Compensator STATCOM

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ABSTRACT

In modern power system utilities, increased power demand often lead to the situation where the system no longer remains in secure operating region. Flexible AC Transmission Systems (FACTS) controllers can play an important roll in power system security enhancement. The goal of FACTS devices study is to measure their impact on the state of the electrical networks into which they are introduced. Their principal function is to improve the static and dynamic properties of the electrical networks and that by increasing the margins of static and dynamic stability. In this paper the modeling of Static Synchronous Compensator (STATCOM) within Newton-Raphson power flow equations has been presented, discussed, implemented and the transient stability of a power system was tested when three phase fault is applied at a certain branch of the power system. Case studies are carried out on a 5-bus and a 30-bus test systems to demonstrate the effectiveness of the proposed model.

Keywords: Load flow analysis, Newton-Raphson, STATCOM.

تعزيز الاستقرارية العابرة لنظام القدرة بأستخدام المعوض التزامني الثابت

الخلاصة

زيادة الطلب على الطاقة الكهربائية في منشات الطاقة الحديثة يؤدي الى عدم بقاء النظام الكهربائي في المنطقة الامنة. تستطيع اجهزة نقل التيار التبادلي المرنة لعب دور مهم في تعزيز امن منظومة الطاقة. ان الهدف من دراسة هذه الاجهزة هو قياس وقع هذه الاجهزة على حالة الشبكات الكهربائية. ان مبدأ عمل هذه الاجهزة هو تطوير الخواص الثابتة والحركية للشبكة الكهربائية بواسطة زيادة الحد المسموح للاستقرارية الثابتة والحركية. في هذا البحث تم تقديم ومناقشة وتطبيق موديل لهذه الاجهزة بأستخدام معادلات نيوتن رابسون لسريان القدرة, كما وتم فحص الاستقرارية العابرة عند حدوث خطأ ثلاثي في احد فروع النظام الكهربائي. الدراسة المطروحة هي لنظام ذو خمسة عقد واخر ذو ثلاثين عقدة لتوضيح تأثير النظام المقترح.

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INTRODUCTION

The equilibrium point of generator operation changes depending on the generator loading so as to maintain the equilibrium between the mechanical power *Pm* and the electrical power *Pe*. The point of equilibrium will also move during transient instability phenomenon, resulting from large disturbance that occurs in the system, either due to large loss of load or generation. If the difference between *Pm* and *Pe* is significant, the machine operating point may oscillate such that its oscillation may lead to loss of synchronism due to the large excursion of generator rotor angle [1-4]. The system is in a state of transient instability if one or more generators fall out of step with respect to the rest of the system [5]. Power system stability analysis is very important to power system planning, design, operation and control [1-6]. In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor [7].

Recent blackouts in different countries have illustrated the very importance and vital need of more frequent and thorough power system stability. The size of the system makes control an extremely difficult task and open-access legislation and deregulation have added uncertainty to the provision of sufficient transmission capacity for new generating sources [8].

Flexible AC transmission systems (FACTS) have gained a great interest during the last few years, due to recent advances in power electronics. FACTS devices have been mainly used for solving various power system steady state control problems such as voltage regulation, power flow control, transfer capability enhancement, and enhancing power system stability. In the late 1980s, the Electric Power Research Institute (EPRI) formulated the vision of the Flexible AC Transmission Systems (FACTS) in which various power-electronics based controllers regulate power flow and transmission voltage and mitigate dynamic disturbances. Generally, the main objectives of FACTS are to increase the useable transmission capacity of lines and control power flow over designated transmission routes [9]. The development and use of FACTS controllers for power transmission systems has led to the application of these controllers to improve the stability of power networks [10,11]. 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 for enhancing voltage and angle oscillation control [11].

In [12], the modeling of FACTS devices for power flow studies and the role of that modeling in the study of FACTS devices for power flow control are discussed. Three essential generic models of FACTS devices are presented and the combination of those devices into load flow analysis, studies relating to wheeling, and interchange power flow control is explained. The determination of the voltage magnitude and phase angle of the FACTS bus is provided by solving two simultaneous nonlinear equations. These equations are solved with a separate Newton-Raphson approach within each iteration of the large load flow analysis.

In [13], various control methods for damping undesirable inter-area oscillations by PSSs, SVCs and STATCOMs are discussed. It is observed that the damping introduced by the SVC and STATCOM controllers with only voltage control was lower than that provided by the PSSs and the STATCOM provides better damping than the SVC as this controller is able to transiently exchange active power with the system.

In [14] the enhancement of transient stability using STATCOM is introduced using Mipower simulation software. A fault was created at a certain bus to show the effect of connecting the STATCOM on the stability margin, then the STATCOM was connected to a different bus in the same power system and the stability margin was tested.

GENERAL DESCRIPTION OF STATCOM

The STATCOM is a power electronics based synchronous voltage generator that generates a three-phase voltage from a DC capacitor. By controlling the magnitude of the STATCOM voltage the reactive power exchanges between the STATCOM and the transmission line and hence the amount of shunt compensation in the power system can be controlled [15-17]. The most advanced solution to compensate reactive power is the use of a Voltage Source Converter (VSC) incorporated as a variable source of reactive power. These systems offer several advantages compared to standard reactive power compensation solutions. Reactive power generated by generators or capacitor banks alone normally is too slow for sudden load changes and demanding applications, such as wind farms or arc furnaces. Compared to other solutions a voltage source converter is able to provide continuous control, very dynamic behavior due to fast response times and with single phase control also compensation of unbalanced loads.

REPRESENTATION OF STATCOM

The operating principle is like a synchronous condenser [15]. It is a three phase inverter that is driven from the voltage across a DC capacitor, figure (1) shows the operation of STATCOM. VSC is coupled to circuit through a transformer, which provides the safe operating voltage and small reactance, figure (2) shows a diagram of the STATCOM.

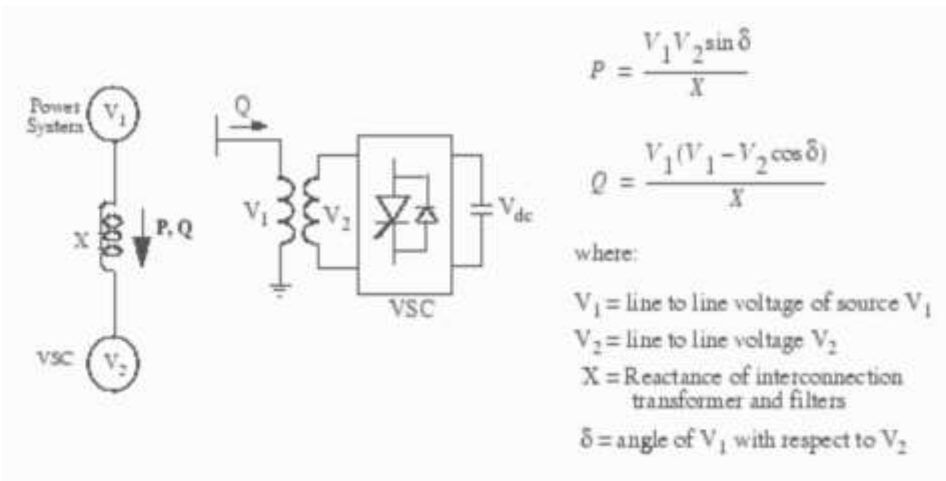

Figure (1) Operation of STATCOM.

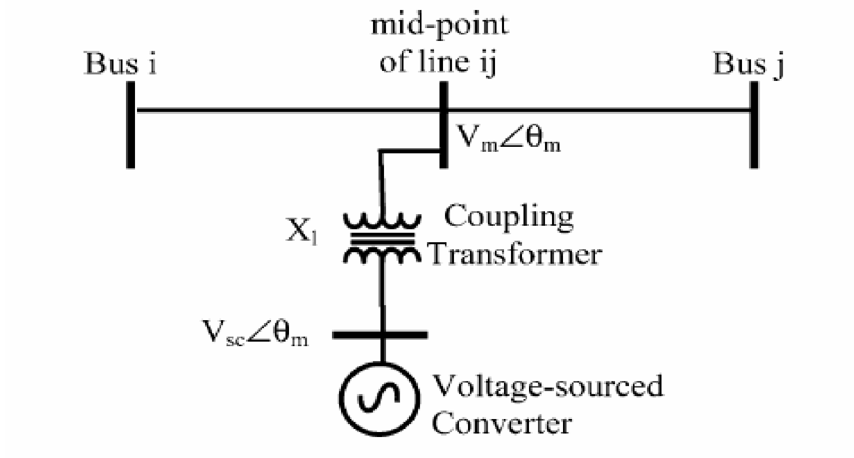

Figure (2) Diagram of STATCOM.

An inverter generates three phase voltages in phase with the AC system voltages. The current lags the voltage drop across the reactor if the inverter voltage is less than the system voltage and leads if the inverter voltage is greater than the system voltage. The reactive power delivered by STATCOM is function of voltage and current [17]. This device can deliver reactive power under reduced voltage condition and has a better performance than a static VAR compensator (SVC)[1,17].

For the purpose of positive sequence power flow analysis the STATCOM will be well represented by a synchronous voltage source with maximum and minimum voltage magnitude limits. The synchronous voltage source represents the fundamental Fourier series component of the switched voltage waveform at the AC converter terminal of the STATCOM [18]. Unlike SVC, the STATCOM is represented as a voltage source for the full range of operation, enabling a more robust voltage support mechanism. The STATCOM equivalent circuit shown in Figure (3) is used to derive the mathematical model of the controller for inclusion in power flow algorithms [19].

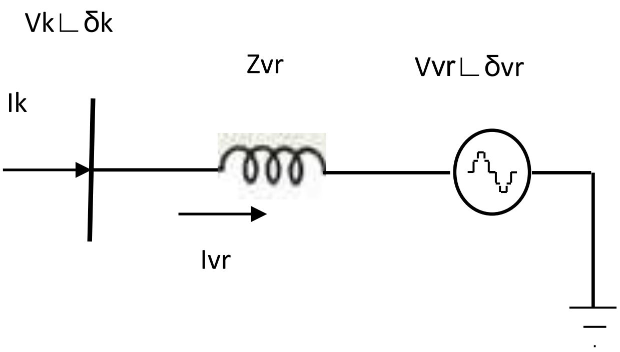

Figure (3) Power Flow Model.

The power flow equations for the STATCOM are derived below from first principles and assuming the following voltage source representation:

$$Evr = Vvr \llcorner \delta vr = Vvr(cos\delta vr + jsin\delta vr) \qquad \ldots (1)$$

Where Evr is the vector voltage of the shunt converter (STATCOM?)
Based on the shunt connection of the STATCOM to a certain bus of the power system as shown in figure (3), the apparent power of the STATCOM may be written as:

$$Svr = Pvr + jQvr = Vvr\ Ivr * \quad \text{... (2)}$$

After performing some complex operations, the following active and reactive power equations are obtained for the converter and bus k, respectively [19]

$$Pk = Vk^2Gvr + VkVvr[Gvrcos(\delta k - \delta vr) + Bvrsin(\delta k - \delta vr)] \quad \text{... (3)}$$

$$Qk = -Vk^2Bvr + VkVvr[Gvrsin(\delta k - \delta vr) - Bvrcos(\delta k - \delta vr)] \quad \text{... (4)}$$

$$Pvr = Vvr^2Gvr + VvrVk[Gvrcos(\delta vr - \delta k) + Bvrsin(\delta vr - \delta k)] \quad \text{... (5)}$$

$$Qvr = -Vvr^2Bvr + VvrVk[Gvrsin(\delta vr - \delta k) - Bvrcos(\delta vr - \delta k)] \quad \text{...(6)}$$

Where $Bvr = 1/Xvr$ is the susceptance of the STATCOM
Using these power equations, the linearized STATCOM model is given below, where the voltage magnitude Vvr and phase angle δvr of the STATCOM are taken to be the state variables [19].

$$\begin{vmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vr} \\ \Delta Q_{vr} \end{vmatrix} = \begin{vmatrix} \partial P_k/\partial\delta_k & \partial P_k/\partial V_k & \partial P_k/\partial\delta_{vr} & \partial P_k/\partial V_{vr} \\ \partial Q_k/\partial\delta_k & \partial Q_k/\partial V_k & \partial Q_k/\partial\delta_{vr} & \partial Q_k/\partial V_{vr} \\ \partial P_{vr}/\partial\delta_k & \partial P_{vr}/\partial V_k & \partial P_{vr}/\partial\delta_{vr} & \partial P_{vr}/\partial V_{vr} \\ \partial Q_{vr}/\partial\delta_k & \partial Q_{vr}/\partial V_k & \partial Q_{vr}/\partial\delta_{vr} & \partial Q_{vr}/\partial V_{vr} \end{vmatrix} \begin{vmatrix} \Delta\delta_k \\ \Delta V_k \\ \Delta\delta_{vr} \\ \Delta V_{vr} \end{vmatrix} \quad \text{- (7)}$$

RESULTS AND DISCUSSION

First the IEEE 5-bus test system is shown in Figure (4), the data of which can be found in [19], is used for the validation of power flow and transient stability. Where the STATCOM is connected to bus3 in order to control its voltage.

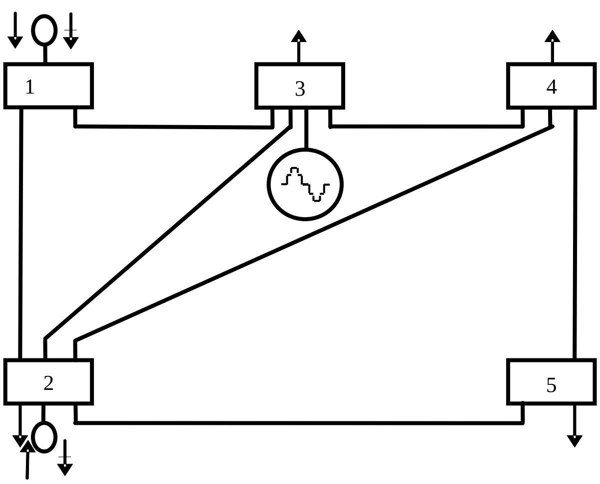

Figure (4) IEEE 5-bus test system with STATCOM.

The Newton-Raphson load flow results without STATCOM is shown table (1)

Table (1) Newton-Raphson load flow results of the 5-bus system without Statcom.

Power Flow Solution by Newton-Raphson Method					
Maximum Power Mismatch = 2.84495e-015					
No. of Iterations = 5					
Bus Voltage Angle	------Load------		---Generation---		
No. Mag. Degree	P(MW)	Q(Mvar)	P(MW)	Q(Mvar)
1 1.060 0.000	0.000	0.000	131.122	90.816
2 1.000 -2.061	20.000	10.000	40.000	-61.593
3 0.987 -4.637	**45.000**	**15.000**	**0.000**	**0.000**
4 0.984 -4.957	40.000	5.000	0.000	0.000
5 0.972 -5.765	60.000	10.000	0.000	0.000
Total	165.000	40.000	171.122	29.223

While load flow results with the STATCOM connected to bus3 in order to control its voltage to 1pu is shown Table (2).

Table (2) Newton-Raphson load flow results of the 5-bus system with Statcom.

Power Flow Solution by Newton-Raphson Method				
Maximum Power Mismatch = 6.05072e-015				
No. of Iterations = 5				
Bus Voltage Angle	------Load------		---Generation---	
No. Mag. Degree	P(MW)	Q(Mvar)	P(MW)	Q(Mvar)
1 1.060 0.000	0.000	0.000	131.056	85.343
2 1.000 -2.053	20.000	10.000	40.000	-77.067
3 1.000 -4.838	**45.000**	**15.000**	**0.000**	**0.000**
4 0.994 -5.107	40.000	5.000	0.000	0.000
5 0.975 -5.797	60.000	10.000	0.000	0.000
Total	165.00	40.000	171.056	8.276

The new system maintains voltage of bus3 to 1pu with a final STATCOM voltage magnitude Vvr=1.0470pu and phase angle δvr=-4.8379.

A three phase fault is created at transmission line (1-3) near bus1, and then cleared by the removal of this faulty line after a critical clearing time (CCT) equal to 0.379sec. A plot of the angle difference between the two generators at bus1 (slack bus) and bus2 (voltage controlled bus) which means (δ2-δ1) is shown in figure (5). The swing curve shows that the power angle returns after a maximum swing indicating that with inclusion of system damping, the oscillations will subside and a new operating angle is attained. Hence, the system is found to be stable for this fault clearing time.

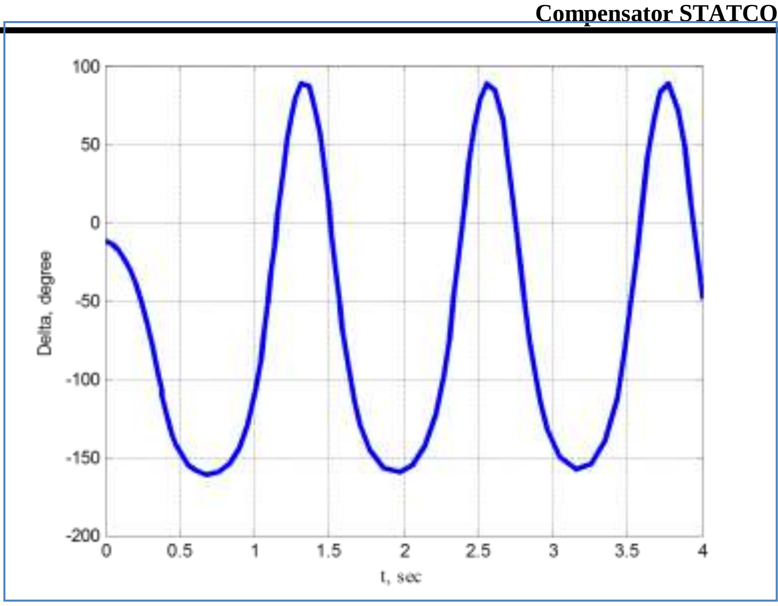

Figure (5) Swing curve without STATCOM and CCT=0.379sec.

When the CCT is increased to 0.380sec, system response shown in Figure (6) shows that the angle difference is increasing towards infinity meaning that the system has lost stability.

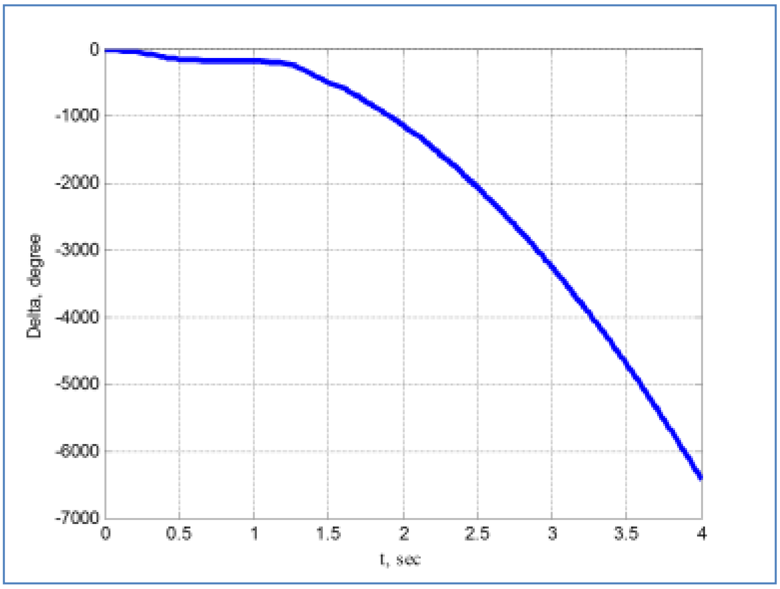

Figure (6) Swing curve without STATCOM and CCT=0.380sec.

However, when the STATCOM was connected at bus3, and the same fault was created at the same location and cleared by the removal of the same transmission line after an even more increased value of CCT=0.383sec, the new system regains its stability as shown in figure (7).

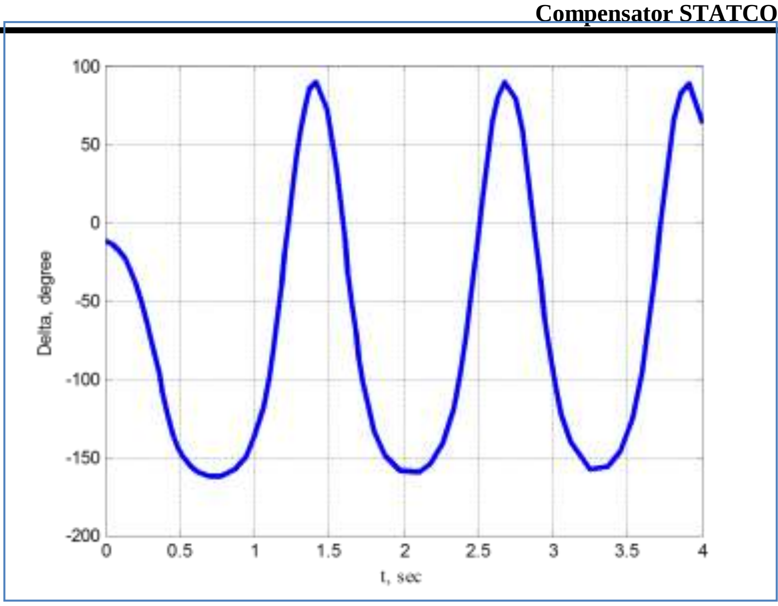

Figure (7) Swing curve with STATCOM and CCT=0.383sec.

The second system is the IEEE-30 bus test system, the single line diagram is shown in figure (8) and the data of which is found in [20].

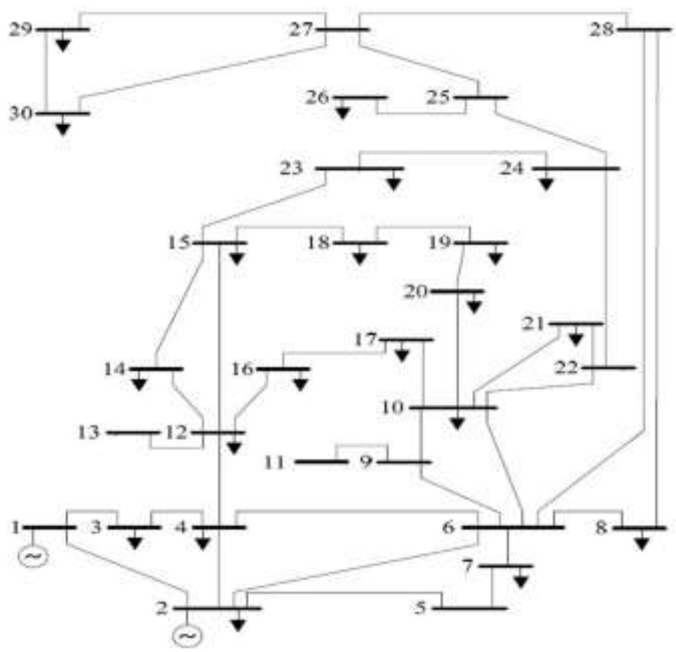

Figure (8) IEEE 30-bus test system.

The STATCOM is connected to bus3 in order to regulate its voltage to a value of 1pu, the new system manages to regulate the voltage of bus3 to the specified value with a final value of Vvr=0.9224pu and phase angle δvr=-7.8051. A fault is created near bus1 at transmission line (1-3) and cleared by the removal this transmission line after CCT=0.190sec . the swing curve figure (9) shows that the system is stable.

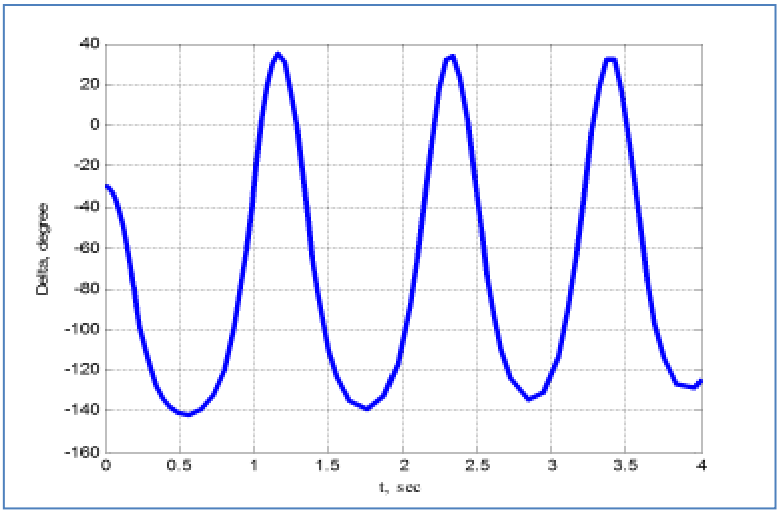

Figure (9) Swing curve without STATCOM and CCT=0.190sec.

When the CCT is increased to a value of 0.191sec, the system losses stability as shown in Figure (10).

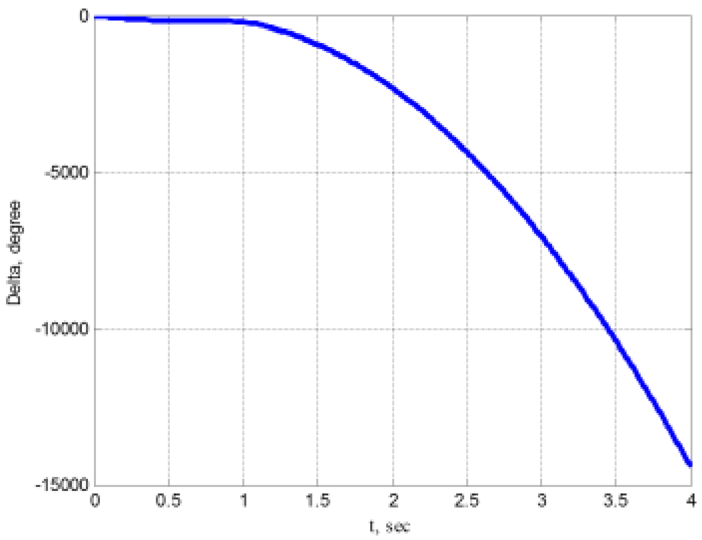

Figure (10) Swing curve without STATCOM and CCT=0.191sec.

However, when the STATCOM is connected at bus3 and the same procedure of creating the same fault is accomplished and clearing the fault by the removal of transmission line (1-3) after an even more increased value of CCT=0.195sec, the system is found to be stable again as shown in figure (11).

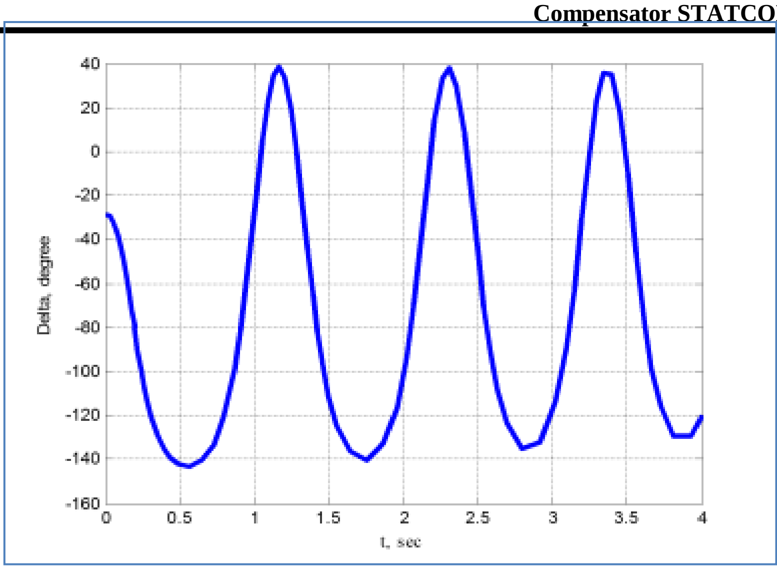

Figure (11) Swing curve with STATCOM and CCT=0.195sec.

CONCLUSIONS

In this paper the model of the STATCOM for the power flow solution was developed. The effectiveness of the proposed model was incorporated through the development of Newton-Raphson load flow method for the desired bus voltage. The proposed model was tested with a five bus system and a thirty bus system. The results show that bus voltage to which the STATCOM was connected was held at the desired value and that the transient stability was indeed enhanced.

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