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Enhancement of a Power System Transient Stability Using Static Synchronous Series Compensator SSSC

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Abstract

Static Synchronous Series Compensator (SSSC) is a well known device for effectively regulating the active power flow in a power system. In this paper, the SSSC linearized power flow equations are incorporated into Newton-Raphson algorithm in a MATLAB written program to investigate the control of active poweer flow and the transient stability of a five bus and a thirty bus IEEE test systems, during abnormal conduction (three phase fault near buses). A comparison of the results obtained for the base case without SSSC and with it to investigate the effectiveness of the device on both of the active power flow and the transient stability.

Keywords: *Load flow analysis, Newton-Raphson, SSSC.*

1. Introduction

Rapid development of power systems especially with the increased use of transmission facilities has necessitated new ways of maximizing power transfer in existing transmission facilities while maintaining the same level of stability [1].

Monitoring the stability status of a power system in real time has been recognized as a task of primary importance in preventing blackouts. In case of a disturbance leading to transient instability, fast recognition of the potentially dangerous conditions is very crucial for allowing sufficient time to take emergency control actions. Several attempts to develop an effective real-time transient stability indicator have been reported in the literature [2–4].

The transient stability of power systems is associated with the ability of the generators to remain in synchronism after a severe disturbance [5]. It depends upon the severity of the contingency and the initial operating state of the power systems. Here the term contingency, also called disturbance or fault, indicates an event like the three-phase short circuit in the grid that will cause large changes in power system [6].

The operating power system will first encounter the hurdle of transient stability before apparatuses thermal limits [7]. When a contingency occures in the electrical network, the power system is likely to lose stability, or may be even worse to trigger large scale blackouts [8].

In order to avoid catastrophic outages, power utilities resort to various planning, protection and control schemes. Preventive control is summoned up when the power system is still in normal status. It encompasses many types of control actions, including generation rescheduling, load curtailment and network switching reactive compensation [9,10]. Those preventive control actions reallocate power system operating state so that it can guarantee satisfactory behavior after a contingency occurred in the grid.

The real time Transient Stability Assessment (TSA) is important to the power system security and efficient operation. Otherwise essential control actions could be delayed, which in turn could trigger a large scale blackout. Further, real time TSA will avoid any unnecessary control commands to ensure the minimum impact on the grid.

The conventional transient stability measure of a system's robustness to withstand a large disturbance is its corresponding Critical Clearing Time (CCT) which is the maximum time duration for which the disturbance may act without the system losing its capability to recover a steady-state (i.e., stable) operation [11].

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. Fast development of power electronic technology has made FACTS promising solution of the future power system. FACTS controllers such as Static Synchronous Compensator (STATCOM), Static VAR Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) are able to change the network parameters in a fast and effective way in order to achieve better system performance [12-14].

These controllers are used for enhancing dynamic performance of power systems in terms of voltage/angle stability while improving the power transfer capability and voltage profile in steady-state conditions [15-17].

In [18], 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 [19], various control methods for damping undesirable inter-area oscillations by Power System Stabilizers (PSS), 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 [20], the main characteristics of controllable reactive series elements (CRSE), which sometimes called controllable series compensation (CSC) and a static synchronous series compensator for power system analysis and control are shown. Modeling of CRSE, containing a simple representation of the transmission system, have been developed. According to theses concepts, the CRSE effect on a longitudinal transmission system was analyzed. The theory of physics and the basic difference shown by a CSC and an SSSC related load flow control are explained. Due to conceptual principles, by the of ability of load flow control, SSSC is considered as more promising than CSC at low power angles. Therefore, SSSC is more suitable in cases where power flow requires to be controlled in short lines or under light-load conditions.

2. Static Synchronous Series Compensator (SSSC)

The SSSC is a member of FACTS family which is connected in series with a power system. It consists of a solid state voltage source converter which generates a controllable alternating voltage at the fundamental frequency. When the injected voltage is kept in quadrature with the line current, it can emulate as inductive or capacitive reactance so as to influence the power flow through the transmission line [21]. While the primary purpose of a SSSC is to control power flow in steady state, it can also improve transient stability of a power system [22].

3. Modeling of SSSC

The SSSC is one of the most recent FACTS devices for power transmission series compensation. It can be considered as a synchronous voltage source as it can inject an almost sinusoidal voltage of variable and controllable amplitude and phase angle, in series with a transmission line. The injected voltage is almost in quadrature with the line current. A small part of the injected voltage that is in phase with the line current provides the losses in the inverter. Most of the injected voltage, which is in quadrature with the line current, provides the effect of inserting an inductive or capacitive reactance in series with the transmission line. The variable reactance influences the electric power flow in the transmission line. The basic configuration of an SSSC is shown in Figure (1).

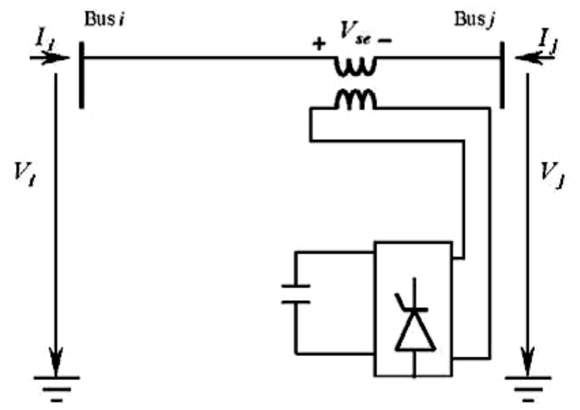

Fig. 1.The Operating Principles of SSSC.

For the purpose of steady-state operation, the SSSC injects voltage in quadrature with one of the line end voltages in order to regulate active power flow. However, the SSSC is a far more versatile controller as it does not draw reactive power from the AC system, it has its own reactive power provisions in the form of a DC capacitor. This characteristic makes the SSSC capable of regulating not only active but also reactive power flow or nodal voltage magnitude [23]. A schematic representation of the equivalent circuit of an SSSC is shown in Figure (2).

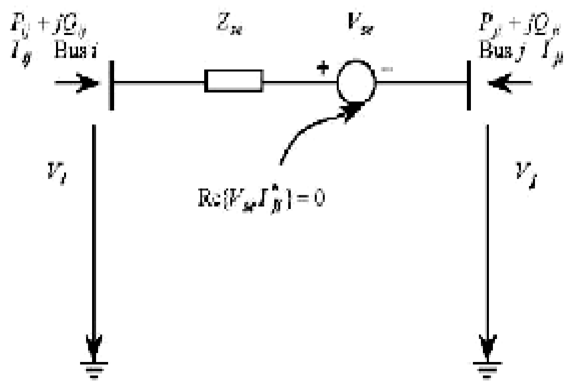

Fig. 2. Simplified Diagram of a SSSC.

The series voltage source of the SSSC may be represented by:

$$E_{se} = V_{se}(cos\delta_{se} + j.sin\delta_{se}) \quad ...(1)$$

The magnitude and phase angle of the SSSC model are adjusted by using any suitable iterative algorithm to satisfy a specified active and reactive power flow across the SSSC. Maximum and minimum limits will exist for the voltage magnitude V_{se}, which is a function of the SSSC capacitor rating, the voltage phase angle δ_{se} can take any value between 0 and 2 radians.

Based on the equivalent circuit shown in Figure (2), the following transfer admittance equation can be written [23].

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} Y_{se} & -Y_{se} & -Y_{se} \\ -Y_{se} & Y_{se} & Y_{se} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \\ E_{se} \end{bmatrix} \quad ...(2)$$

The power equations at bus *i* are:

$$P_i = V_iV_jB_{ij}\sin(\delta_i - \delta_j) + V_iV_{se}B_{ij}\sin(\delta_i - \delta_{se}) \quad ...(3)$$

$$Q_i = -V_i^2B_{jj} - V_iV_jB_{ij}\cos(\delta_i - \delta_j) - V_iV_{se}B_{ij}\cos(\delta_i - \delta_{se}) \quad ...(4)$$

Where: $B_{ij} = \frac{1}{X_{se}} = -B_{jj}$

For the powers at bus *j*, exchange the subscripts *i* and *j*.

In Newton–Raphson solutions these equations are linearized with respect to the series injected voltage. For the condition shown in Figure (2), where the series injected voltage regulates the amount of active power flowing from bus *i* to bus *j* at a value $P_{specified}$, the set of linearized power flow equations are:

$$\begin{vmatrix} \Delta P_i \\ \Delta P_j \\ \Delta Q_i \\ \Delta Q_j \\ \Delta P_{ij} \\ -P_{se} \end{vmatrix} = \begin{vmatrix} \partial P_i/\partial\delta_i & \partial P_i/\partial\delta_j & \partial P_i/\partial V_i & \partial P_i/\partial V_j & \partial P_i/\partial\delta_{se} & \partial P_i/\partial V_{se} \\ \partial P_j/\partial\delta_i & \partial P_j/\partial\delta_j & \partial P_j/\partial V_i & \partial P_j/\partial V_j & \partial P_j/\partial\delta_{se} & \partial P_j/\partial V_{se} \\ \partial Q_i/\partial\delta_i & \partial Q_i/\partial\delta_j & \partial Q_i/\partial V_i & \partial Q_i/\partial V_j & \partial Q_i/\partial\delta_{se} & \partial Q_i/\partial V_{se} \\ \partial Q_j/\partial\delta_i & \partial Q_j/\partial\delta_j & \partial Q_j/\partial V_i & \partial Q_j/\partial V_j & \partial Q_j/\partial\delta_{se} & \partial Q_j/\partial V_{se} \\ \partial P_{ij}/\partial\delta_i & \partial P_{ij}/\partial\delta_j & \partial P_{ij}/\partial V_i & \partial P_{ij}/\partial V_j & \partial P_{ij}/\partial\delta_{se} & \partial P_{ij}/\partial V_{se} \\ \partial P_{se}/\partial\delta_i & \partial P_{se}/\partial\delta_j & \partial P_{se}/\partial V_i & \partial P_{se}/\partial V_j & \partial P_{se}/\partial\delta_{se} & \partial P_{se}/\partial V_{se} \end{vmatrix} \begin{vmatrix} \Delta\delta_i \\ \Delta\delta_j \\ \Delta V_i \\ \Delta V_j \\ \Delta\delta_{se} \\ \Delta V_{se} \end{vmatrix} \quad ...(5)$$

Where the elements of the added row and column are

$P_{ij} = P_{specified} - P_{calculated}$ …(6)

$P_{calculated} = V_i V_j B_{ij} \sin(\delta_i - \delta_j) + V_j V_{se} B_{jj} \sin(\delta_j - \delta_{se})$ …(7)

$P_{se} = V_{se} V_i B_{ij} \sin(\delta_{se} - \delta_i) + V_{se} V_j B_{jj} \sin(\delta_{se} - \delta_j)$…(8)

Where P_{se} is the power for the series converter (SSSC)

4. Prgram Stracture

After reading the line and bus data for the power system, the MATLAB written program starts by forming the bus admittance, then using Newton Raphson method, it calculates the active and reactive power of the slack bus, the voltages and angles of each load bus. Then the stability program calculates the new bus admittance during fault, and the post fault admittance. The solution of the diferrential power equations is solved using Runge-Kutta method to simulate the variation of power angle with time. Figure (3) shows the flow chart of the program.

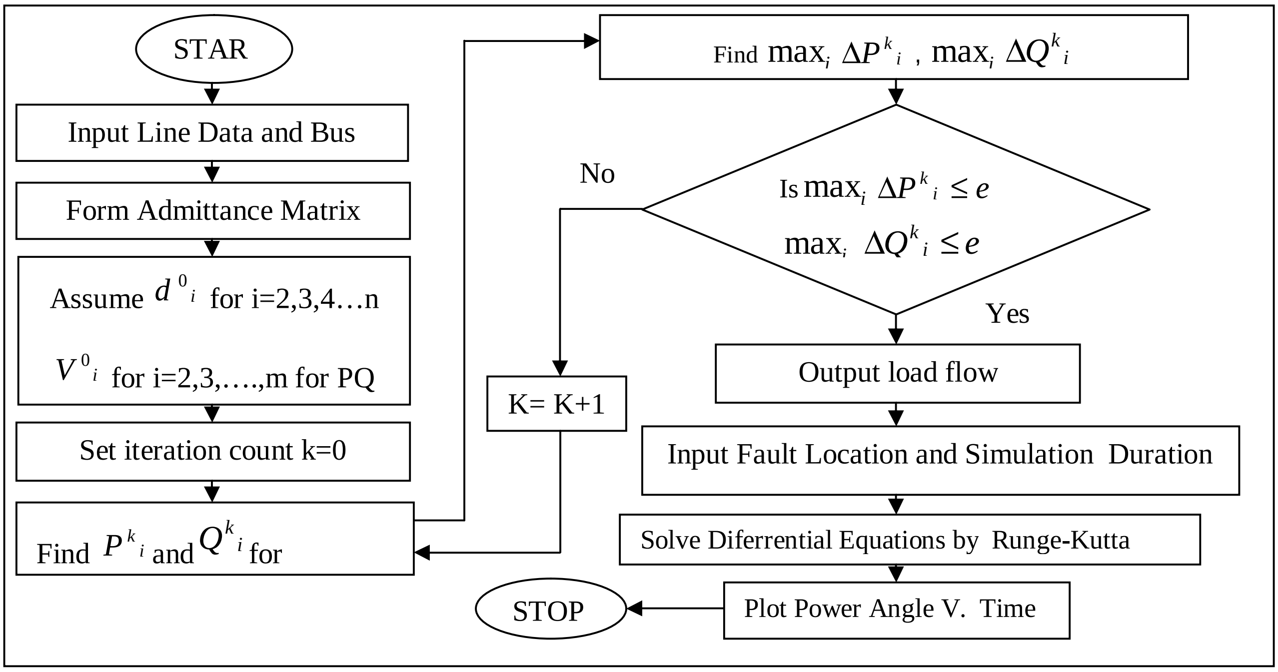

Fig. 3.The Flow Chart of the Transient Stability Program.

5. Simulation and Results

The IEEE 5-bus system, Figure (4), is used to test the effectiveness of connecting the SSSC device between bus3 and bus4, the data of which can be found in [23]. Using Newton-Raphson method, the power flow results of the system without the *SSSC* connected are shown in Table (1).

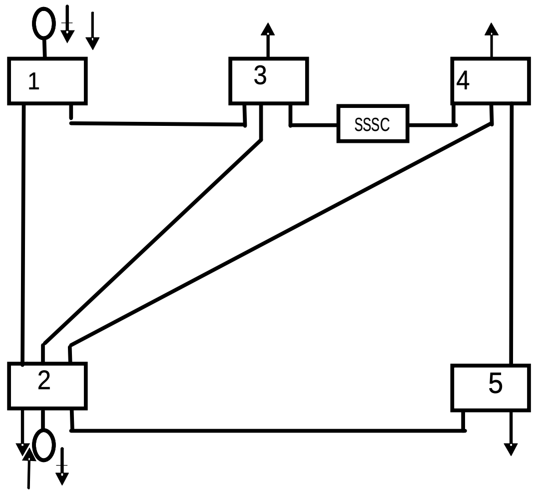

Fig. 4. Single Line Diagram of IEEE-5 Bus Network with SSSC.

Table 1,
Power flow results of 5-bus system without SSSC connected

Line Flow and Losses						
--Line--		**Power at bus & line flow**			**--Line loss--**	
From	**To**	**P (MW)**	**Q (Mvar)**	**S (MVA)**	**P (MW)**	**Q (Mvar)**
1	1	131.122	90.816	159.501		
1	2	89.331	73.995	115.997	2.486	1.087
1	3	41.791	16.820	45.049	1.518	-0.692
2	2	20.000	-71.593	74.334		
2	1	-86.846	-72.908	113.392	2.486	1.087
2	3	24.473	-2.518	24.602	0.360	-2.871
2	4	27.713	-1.724	27.767	0.461	-2.554
2	5	54.660	5.558	54.942	1.215	0.729
3	3	-45.000	-15.000	47.434		
3	1	-40.273	-17.513	43.916	1.518	-0.692
3	2	-24.113	-0.352	24.116	0.360	-2.871
3	4	19.386	2.865	19.597	0.040	-1.823
4	4	-40.000	-5.000	40.311		
4	2	-27.252	-0.831	27.265	0.461	-2.554
4	3	-19.346	-4.688	19.906	0.040	-1.823
4	5	6.598	0.518	6.619	0.043	-4.652
5	5	-60.000	-10.000	60.828		
5	2	-53.445	-4.829	53.663	1.215	0.729
5	4	-6.555	-5.171	8.349	0.043	-4.652
Total loss					6.122	-10.777

It is required to regulate the power flow from bus3 to bus4 to a value of 21MW instead of 19.386MW. This is done by creating a virtual bus between bus3 and bus4 namely bus6, by adding $(v_6 = 1pu, \delta_6 = 0)$ to bus data in the beginning of the iterative process of load flow. Then connecting the SSSC between bus3 and bus6 (setting the value of Xse=0.0216pu in the line data). The new system manages to achieve this task and maintains active power flow at the specified value in six iterations with a final value for the angle δse of -100.888˚, the load flow results and the power flow with the SSSC connected is shown Table (2 and 3) respectively.

Table 2,
Load flow results of 5 bus system with SSSC connected.

Power Flow Solution by Newton-Raphson Method						
Maximum Power Mismatch = 8.48344e-015						
No. of Iterations = 6						
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	131.127	90.937
2	1.000	-2.038	20.000	10.000	40.000	-61.801
3	0.987	-4.727	45.000	15.000	0.000	0.000
4	0.984	-4.811	40.000	5.000	0.000	0.000
5	0.972	-5.701	60.000	10.000	0.000	0.000
6	0.988	-4.461	0.000	0.000	0.000	0.000
Total			165.00	40.000	171.127	29.136

Table 3,
Power flow results of 5-bus system with SSSC connected.

Line Flow and Losses						
--Line--		**Power at bus & line flow**			**--Line loss--**	
From	**To**	**P (MW)**	**Q (Mvar)**	**S (MVA)**	**P (MW)**	**Q (Mvar)**
1	1	131.127	90.937	159.574		
1	2	88.680	74.187	115.619	2.471	1.041
	3	42.447	16.750	45.632	1.555	-0.579
2	2	20.000	-71.801	74.534		
2	1	-86.210	-73.146	113.059	2.471	1.041
2	3	25.497	-2.694	25.639	0.390	-2.777
2	4	26.606	-1.567	26.652	0.425	-2.664
2	5	54.106	5.606	54.396	1.191	0.657
3	3	-45.000	-15.000	47.434		
3	1	-40.892	-17.329	44.412	1.555	-0.579
3	2	-25.107	-0.084	25.107	0.390	-2.777
3	6	20.999	2.412	21.137	0.000	-0.099
4	4	-40.000	-5.000	40.311		
4	2	-26.181	-1.097	26.204	0.425	-2.664
4	6	-20.952	-4.316	21.392	0.046	-1.805
4	5	7.133	0.413	7.145	0.049	-4.638
5	5	-60.000	-10.000	60.828		
5	2	-52.915	-4.949	53.146	1.191	0.657
5	4	-7.085	-5.051	8.701	0.049	-4.638
6	6	0.000	0.000	0.000		
6	3	-20.999	-2.512	21.149	0.000	-0.099
6	4	20.999	2.511	21.148	0.046	-1.805
Total loss					6.127	-10.864

To show that the new system's transient stability has been enhanced, a MATLAB program which uses Runge-Kutta method to solve the diferrential equations of the power system is written A three phase fault is created at the transmission line (1-2) near bus1, and cleared by the removal of T.L. (1-2) for both the base case and the new system. For the base case where no SSSC is connected the power angle curve is shown in Figure (5) for a critical clearing time CCT=0.318sec.

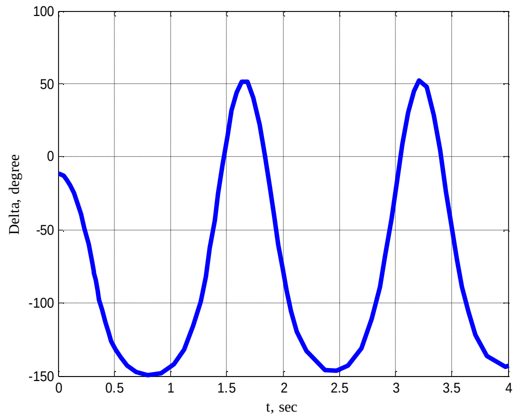

Fig. 5. Fault Cleared at CCT=0.318sec without SSSC.

Figure (5) shown is a plot of the power angle difference between generator at bus2 (south) and the slack at bus1 (north) namely δ21. Since δ21=-2.038° at steady state operation, the increase is in the negative side. As can be seen the generator at south is oscillating with the generator at north, which means that with the inclusion of damping the oscillations would subside, and therefore the system is considered to be stable. The curve shows that the system recovers its stability, however, when the CCT is increased to a value of 0.319 sec. the system looses its stability as shown in Figure (6), where $\delta 21$ decreases to infinity.

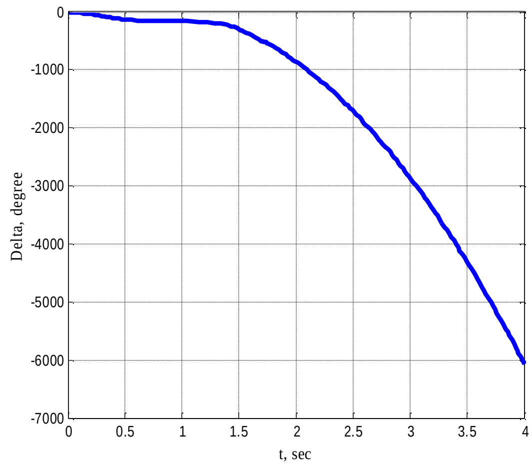

Fig. 6. Fault Cleared at CCT=0.319sec without SSSC.

When the SSSC was included and the system tested for an even more increased critical clearing time CCT=0.320 sec, it retains its stability as shown Figure (7).

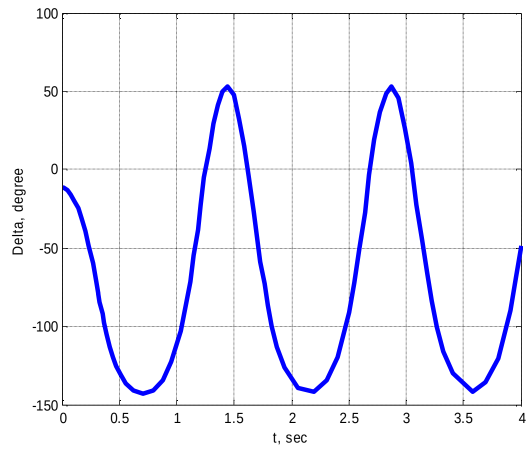

Fig. 7. Fault Cleared at CCT=0.320 sec with SSSC Included.

The other test system is the IEEE 30-bus system, the single line diagram of which is shown in Figure (8) is implemented to evaluate the effectiveness of the SSSC model. The data of which can be found in [24].

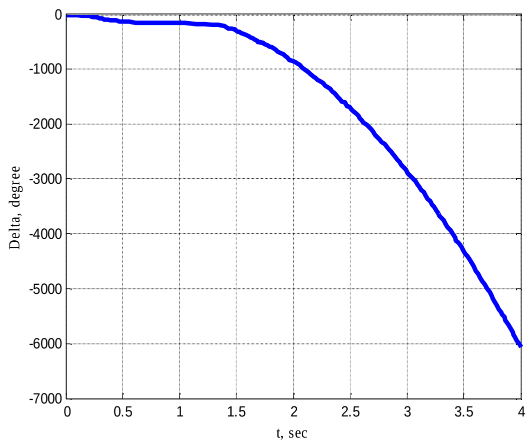

Fig. 6. Fault Cleared at CCT=0.319sec without SSSC.

When the SSSC was included and the system tested for an even more increased critical clearing time CCT=0.320 sec, it retains its stability as shown Figure (7).

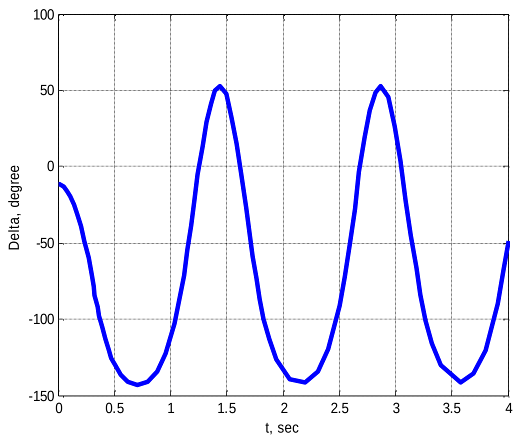

Fig. 7. Fault Cleared at CCT=0.320 sec with SSSC Included.

The other test system is the IEEE 30-bus system, the single line diagram of which is shown in Figure (8) is implemented to evaluate the effectiveness of the SSSC model. The data of which can be found in [24].

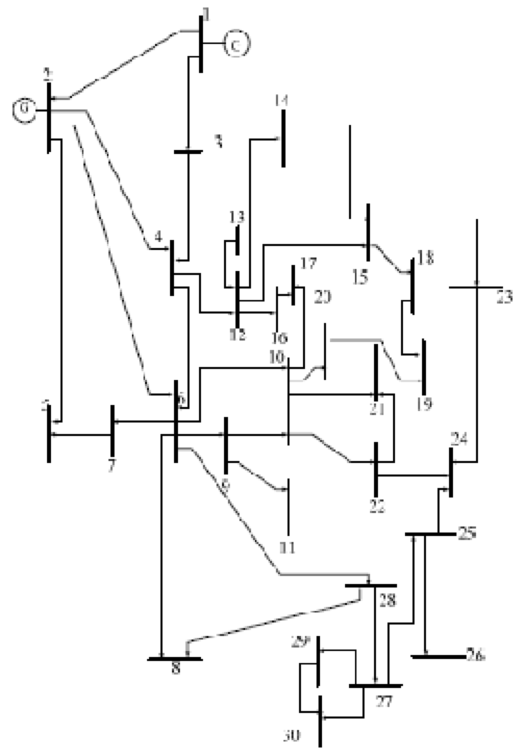

Fig. 8. Single Line Diagram of IEEE-30 Bus System.

Using Newton-Raphson method, the power flow results of the system without the SSSC are shown in Table (4) for bus 3 only.

The SSSC is connected between bus3 and bus4 and is used to regulate the active power flowing from bus3 towards bus4 to a value of 90MW instead of 78.012MW, this is done by creating a new bus31 between bus3 and bus4 to connect the SSSC between bus3 and bus31 (setting the value of Xse=-0.0098pu) so that the active power flowing towards bus4 is the specified regulated power i.e. 90MW as shown in Table (5). The model manages to maintain the specified active power flowing towards bus4 with a final value for Vse=0.001pu and an angle $\delta 21$ =-95.2825°

Table 4,
Power flow results of 30-bus system without SSSC connected.

Line Flow and Losses						
--Line--		**Power at bus & line flow**			**--Line loss--**	
From	**To**	**P (MW)**	**Q (Mvar)**	**S (MVA)**	**P (MW)**	**Q (Mvar)**
3	3	-2.400	-1.200	2.683		
3	1	-80.412	1.958	80.436	2.808	7.085
3	**4**	**78.012**	**-3.158**	**78.076**	**0.771**	**1.344**

Table 5,
Power flow results of 30-bus system with SSSC connected.

Line Flow and Losses						
--Line--		**Power at bus & line flow**			**--Line loss--**	
From	**to**	**P (MW)**	**Q (Mvar)**	**S (MVA)**	**P (MW)**	**Q (Mvar)**
31	31	0.000	0.000	0.000		
31	3	-80.238	2.103	80.266	0.000	-0.601
31	**4**	**90.000**	**-1.847**	**90.019**	**1.017**	**2.047**

To test whether the new system has acquired a new margin of transient stability, a three phase fault is created near bus1 at transmission line (1-3), and removed by removing the faulty transmission line (1-3) for both the base case and the new system with the SSSC. For the model without the SSSC connected, when the faulty line was cleared after a critical clearing time CCT of 0.190 sec, the swing curve shows that the power angle returns after a maximum swing indicating that with the 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, as shown in Figure (9).

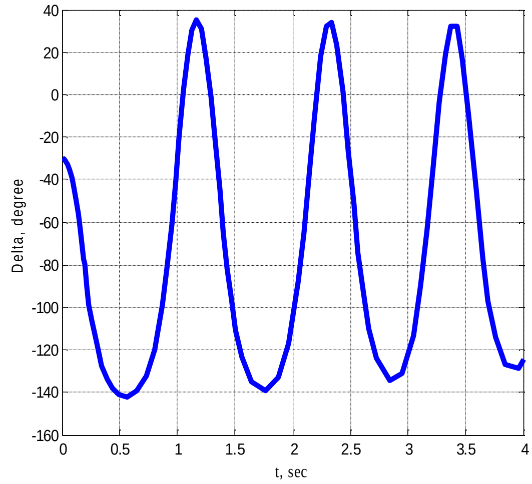

Fig. 9. Fault Cleared at CCT=0.190 sec without SSSC

However, when the CCT was increased to a value of 0.191sec, the difference in rotor angle between machine2 and machine1 is continuously increasing, and therefore the system is considered to be unstable as shown in Figure (10).

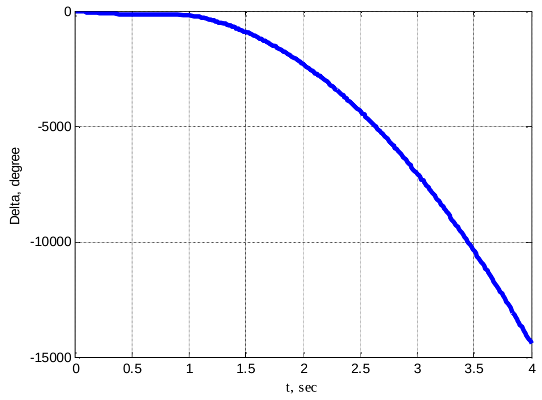

Fig. 10. Fault Cleared at CCT=0.191sec without SSSC.

When the SSSC was included in the model and following the same procedure for the fault at bus1 and removed by the removal of the same transmission line (1-3) after an even more increased CCT of 0.211sec, the system retains its stability as shown in Figure (11).

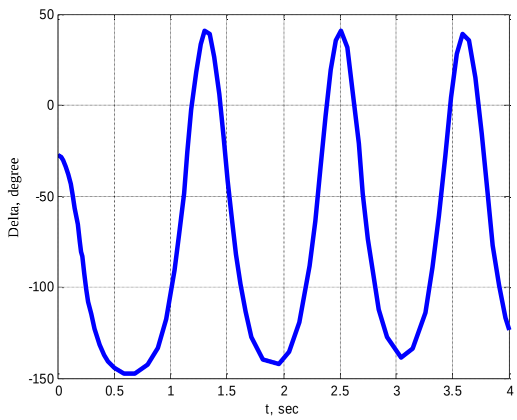

Fig. 11. Fault Cleared at CCT=0.211sec with SSSC Included.

6. Conclusions

In this paper the model for power flow and transient stability for an IEEE five and thirty bus test systems with the SSSC included was developed and the results for specifying the active power flow in a certain branch of the power system were verified, it was found that the active power in branch (3-4) could be increased by nearly 1.6MW for the IEEE-5 bus test system and nearly 12MW for the IEEE-30 bus test system. The transient stability was also tested and the results show that the stability margin was increased by the inclusion of the SSSC device for the IEEE-5 bus by 0.2% and the IEEE-30 bus by 2.1%.

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تعزيز الاستقرارية العابرة لنظام القدرة بأستخدام المعوض التناسقي المتوالي

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الخلاصة

يعرف المعوض التزامني المتوالي كجهاز لتنظيم سريان القدرة الفعالة. في هذا البحث تم استخدام معادلات سريان القدرة بطريقة نيوتن رابسون في برنامج مكتوب بلغة ماتلاب لبحث سريان القدرة الفعالة والاستقرارية العابرة لمنظومة ذات خمسة الواح واخرى ذات ثلاثين لوح عند حدوث خطأ ثلاثي في احد الالواح. تم أجراء مقارنة بين نتائج النظام في حالة وجود المعوض التزامني المتوالي وفي حالة عدم وجوده لدراسة تأثيره على سريان القدرة الفعالة والاستقرارية العابرة.