Effectiveness of power oscillation damping on power system stability

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Abstract:
It was always recognized that ac power transmission over long lines was primarily limited by the series reactive impedance of the transmission line. Series capacitive compensation was introduced many years ago to cancel a portion of the reactive line impedance and thereby increase the transmitted power. Subsequently, within the Flexible AC Transmission System (FACTS) initiative, it has been demonstrated that variable series compensation is highly effective in both controlling power flow in the line and in improving stability. In addition, power oscillation is a common dynamic phenomenon which can influence the power system after a disturbance arises. Power oscillation increases the risk of instability and thus reduces the power transfer capacity, particularly in weak transmission lines. In the meantime , solid-state static series FACTS controllers such as SSSC, because of their fast response dynamics, are employed to improve power oscillations damping. The Static Synchronous Series Compensator (SSSC) can improve Power Oscillation Damping (POD) by intelligent modulating of its series reactive power compensation. Furthermore , an SSSC with its

energy storage can increase the effectiveness of POD by absorbing the real power from or injecting it into the transmission line. In this paper, the effectiveness of power oscillation damping on the power system stability in presence of SSSC is investigated using a simple power system 500 KV network grid equipped with SSSC rated at 100 MVA connected in series with a transmission line in a Matlab Simulnk environment. The simulation results show a great improvement in power system stability when SSSC with POD is introduced.

Key words: SSSC, POD, FACTS, Matlab-Simulink

الملخص

من الأشياء المُسلم بها في الشبكات الكهربائية هو أن انتقال الطاقة عبر الخطوط الطويلة مُقيد بشكل أساسي بالمعاوقة التفاعلية التسلسلية لخط النقل. ولهذا تم تقديم التعويض السعوي المتسلسل منذ عدة سنوات لإلغاء جزء من معاوقة الخط وبالتالي زيادة القدرة المنتقلة. بعد ذلك، تم استخدام نظام نقل التيار المتردد المرن (FACTS) و الd` أثبتت أن تعويض السلاسل المتغيرة فعال للغاية من حيث التحكم في تدفق الطاقة فيا لخط وكذلك تحسين استقرار الشبكة. بالإضافة إلى ذلك، فإن تذبذب الطاقة هو ظاهرة ديناميكية شائعة يمكن أن تؤثر على نظام الطاقة بعد حدوث اضطراب, حيث يزيد تذبذب الطاقة من مخاطر عدم الاستقرار وبالتالي يقلل من قدرة نقل الطاقة، خاصة في خطوط النقل الضعيفة. لهذا يتم إستخدام وحدات التحكم FACTS مثل SSSCوذلك بسبب استجابتها الديناميكية السريعة للتقليل من تذبذبات الطاقة. كما يمكن للمعوضات المُتزامنة الثابتة (SSSC) تحسين تذبذب الطاقة (POD) من خلال التعديل الذكي لسلسلة تعويض الطاقة التفاعلية. علاوةً على ذلك، إن ميزة تخزين الطاقة لـ SSSCتزيد من فعاليةPODعن طريق امتصاص الطاقة من خط النقل أو حقنه فيه.

في هذا البحث، تم التحقق من فعالية التخميد المتذبذب للطاقة في وجود SSSC بإستخدامMatlab Simulink حيث تم إستخدام نظام شبكة طاقة بسيط بـ 500 كيلو فولت مزودة بـSSSC معدلة عند 100 ميجا فولت أمبير و متصلة على التوالي بخط

النقل المراد اختباره. حيث أظهرت نتائج المحاكاة إن هناك تحسنًا كبيرًا في استقرار الطاقة عند توصيل SSSC مع POD.

Introduction

The SSSC controller is a voltage-source converter based compensator and was proposed by Gyugyi in 1989 [1] within the concept of using converter-based technology uniformly for shunt and series compensation, as well as for transmission angle control. It consists of a solid-state Voltage source Converter (VSC) with several Gate Turn Off (GTO) thyristor switches, or any other semiconductor switches with turn-off capability valves, dc capacitor or storage device, a transformer, and a controller. The SSSC is used to generate or absorb reactive power from the line, and hence can be regarded as a transmission line power flow controller. In reality, if the losses of the SSSC are neglected, it generates a quasi-sinusoidal voltage of variable magnitude in quadrature with transmission line current on its output terminal. Therefore, the injected voltage emulate a capacitive or inductive reactance in series with a transmission line, which increases or decreases the total reactance of the transmission line, resulting in a decrease or increase of the power flow in the transmission line. The SSSC can be viewed as analogous to an ideal synchronous voltage source as it produces a set of three-phase as voltage at the desired fundamental frequency of variable and controllable amplitude and phase angle. In addition, SSSC cab is regarded as synchronous generator, because it can generate or absorb reactive power from power system and can, independently from reactive power, generate or absorb real power if an energy storage device is connected instead of the dc capacitor used in the SSSC [2].

The SSSC is typically used to only reactive power exchange with the ac system, neglecting the small amount of real power that used to cover the circuit and switching losses [3].The SSSC can be used to exchange real power with the ac system if the dc capacitor is replaced with an energy storage system. Alternatively, a Static Synchronous Compensator (STATCOM) could send real power to the SSSC through a common dc capacitor link. As a result of this connection of the SSSC and STATCOM is called Unified Power Flow Controller or simply UPFC.

The operation of the SSSC in the four quadrants are shown in Figure1.

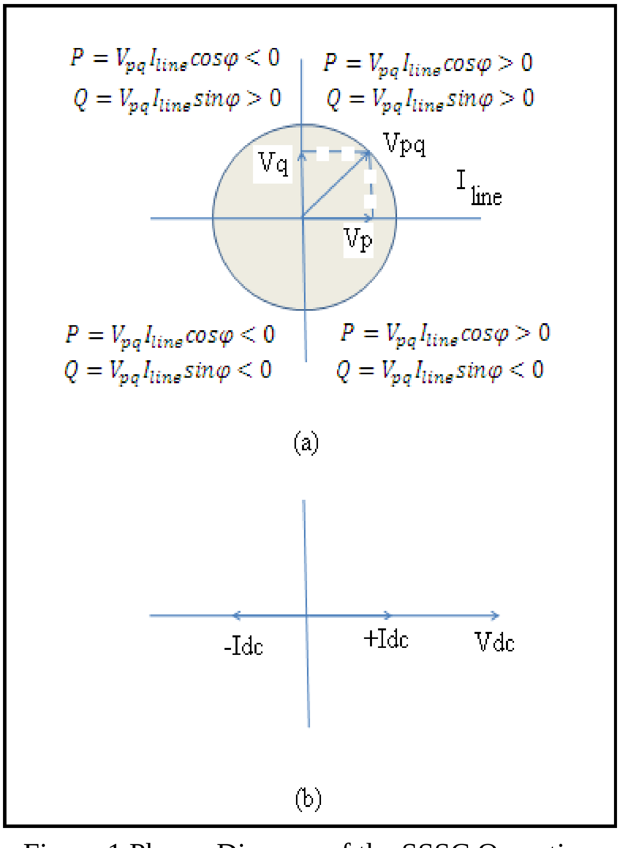

Figure.1 Phasor Diagram of the SSSC Operation

let us assume an energy storage device is connected to the SSSC's input terminals instead of dc capacitor. If the line current phasor

$I_{line}$is taken as reference phasor while the injected voltage SSSC voltage phasor is allowed to rotate around the centre of the circle defined by the maximum injected voltage V_{pq}^{max}. The operation of the SSSC in each of the quadrants is possible theoretically, but there are some limitations to the injected voltage due to operating constrains of practical power system [4]. Theinjected voltage of the SSSC in capacitive mode is made to lag the transmission line current by 90^0; therefore, the SSSC operation is similar to the operation of a series capacitor with variable capacitance KX_ci.e., $V_{pq} = -jkX_cI_{line}$, where K is a variable. As a result of this action, the transmission line totall ractance is reduced while the voltage across the impedance is incrased, which leading to increase the line current and the transmitted power.

If the injected SSSC voltage is reversed by 180^0, i.e., $-V_{pq} = jkX_cI_{line}$. this will cause an increase in the transission line total reactance which result a decrease in the line current and the transmitted power. The equation for V_{pq} shows changes in the phasor magnitude phase angle, it can be somewhat misleading, and also it shows that the series injecte voltage is directly proportional to the magnitude of the line current. But in reality this not true; because, the magnitude of the injected voltage is set by the SSSC control and its independent of the network impedance and, consequently, line current changes. It is assumed that in Figure 1., the losses of the SSSC is neglected, and, therfore, the series injected voltage is perfect with the line current, leadind or lagging.
Figure 2., shows the operating conditions that limit the SSSC operation from the power sysem point of view. By reversing the operation of the SSSC from capacitive to inductive mode, the power flow in the transmission line can be increased or decreased. In inductive mode, the series injected voltage is inphase with the voltage drop developed across the line reactance; thus, the series

compensation has the same effect as inceasing the line reactance. If the series injected voltage magnitude is larger than the voltage drop across the uncompensated line, i.e., $V_{pq} \geq V_{line}$, the power flow will reverse. This fact can limit the SSSC operation to values of $V_{pq} \leq V_{line}$, as in practice, it would be unlikely to use the SSSC controller is high, it is possible to increase or decrease the receiving end voltage above or below the typical operating voltage range of 0.95 p.u.-1.05 p.u., but with possible negative consequences for other system devices [4].

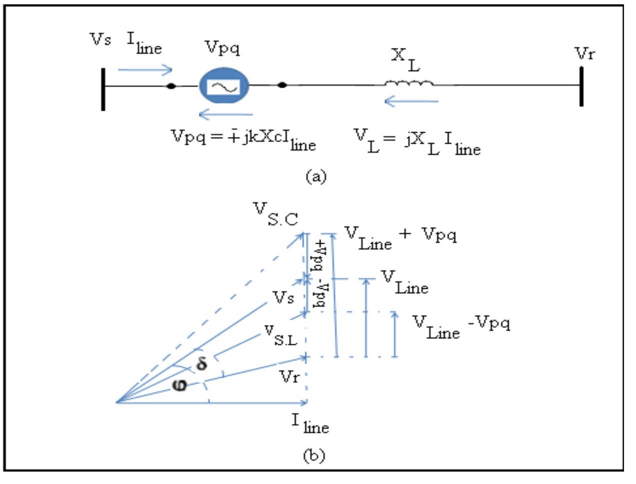

Figure.2 Series Compensation by a SSSC

The output voltage phase angle of the SSSC is correlated to the line current phase angle by ± few degrees to accouunt for changes in the dc voltage. In practice, the injected SSSC voltage V_{pq} is different from the SSSC output voltage V_{SSSC}, due to the voltage drop or rise across the series transformer reactance, i.e. [5].

$$V_{pq} = V_{SSSC} \pm X_{tr} I_{line} \qquad (1)$$

The minus sign corresponds to the capacitive operation, while the negative sign corresponds to the inductive operation of the SSSC and X_{tr} stand for the series transformer reactance. As we can see

from equation 1, the voltage difference between the injected voltage and the output of the SSSC can be small in the case of small transmission line currents, but it can be significant in high loading conditions.
To calculate the active and reactive power exchange between the SSSC and the transmission line ,the following formulas can be used[5] :

$$P_{pq} = V_{pq}.I_{line}cos\emptyset \qquad (2)$$

$$Q_{pq} = V_{pq}.I_{line}sin\emptyset \qquad (3)$$

Where $\emptyset$ is the angle between the injected voltage of the SSSC and the transmission line current.
If the angle between the injected voltage and the transmission line current is approximately 90^0, then we can see from equations (1 and2) that the SSSC real power should be small compared to the reactive power. This should be expected because, the real power going to the SSSC is used only to cover for the losses and charging of the dc capacitor, i.e.,

$$P_{Pq} = P_{dc} + P_{losses} \qquad (4)$$

The losses in the SSSC ciruit are due to the transformer windings and speciallly due to the switching of the GTO (semiconductor switch device) valves.

The Rating of SSSC Equipments

The raing of the SSSC is defined as the amount of the real and ractive power that can be exchanged with the power system. And its determined by the rating of the SSSC components, namely, the series connecting coupling transformer, VSC, and the dc capacitor (energy storage device) [5].
TheVolt Ambier (VA) rating of the SSSC (Solid-state converter and coupling transformer) is simply the product of the maximum line current (at which compensation is still desired) and maximum series compensation voltage is [5]:

$$VA = I_{line\ max.} * V_{SSSC,max.} \quad (5)$$

Note that in practical application for variable impedance type compensators, $I_{max.}$ may be separetly defined for the rated maximum steady-state line current and for a specified short duration overcurrent. According to this, there are two recognizable SSSC rating; Steady-state and short –duration VA ratings [5].

The rating of the GTO converter thyristor valves are characterized by the voltage and current ratings. The GTO thyristor valves for the SSSC are composed of several GTO thyristor connected in series to achieve the required voltage level. Therefore, the valve rating is the sum of the rated voltages of the individual thyristors minus a derating factor; in the usual practice is to place one additional GTO thyristor as a reverse in case of failure of one GTOin the string, under the assumption that the failed GTO goes immediately into short-circuit state [5]. The current rating of the valve include both instantaneous and RMS currents. The RMS current rating translite into restrictions on the converter output currents at the ac side: $I_{line} \leq I_{rating}$ for continous operation and $I_{line} \leq I_{transiant}$ for (1s) transient overload [6].

The dc capacitor or energy storage device limits are characterized by voltage and current rating; the dc bus voltage V_{dc} should not exceed the voltage rating of the dc capacitor or energy storage device. To prevent misfiring of GTO valves, the dc voltage must always be above certain level, and to prevent overvoltages, arresters are connected in parallel with the dc capacitor.

The current rating $I_{dc.min} \leq I_{dc} \leq I_{dc.max}$ and it determines how fast the dc capacitor charged or dischaged [6].

In choosing the right size of the dc capacitor, a special care must be taken in consedering both technical and economical factors. A large dc capacitor would required longer periods for charging and discharging, in this case, large voltage variation on the dc side during a transient on the ac side should be avoided. Reducing dc voltage variations, especially dc voltage increases, should avoid the need for special dimensioning of the semiconductor components, having a positive effect on the overall costs. Some authors suggest that the dc capacitor should be sized to maximum ripple of 10 % in the dc voltage [7]. As presented in [8] a reference value of 2.65 ms for the capacitor time constant corresponds to a 10% ripple in the dc voltage.

Figure 3, shows that the SSSC can provide capacitive and inductive voltage up to its specified maximum current rating.where, as it is assumed in the figure the SSSC can maintain its rated maximum capacitive and inductive voltage even in the sitautions when the line current is equal to zero. But in practice, this is not the case. The practical minimum line current is the one at which the SSSC's dc capacitor voltage can be kept at the desired level while supplying for the controller losses. Note that if the voltage drop/rise across the transformer leakage reactance the V-I characteristic changrs to that depicted with dashed line.

The difference between V-I characteristics is greater at high transmission line currents, and in some cases it can be as high as 40% of the series voltage nominal rating [8].

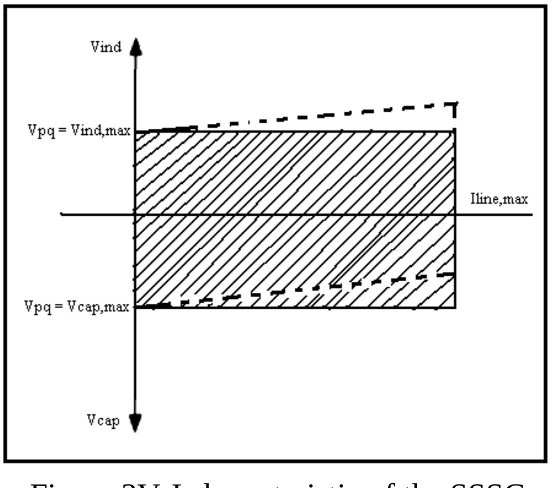

Figure.3V-I characteristic of the SSSC

SSSC Control System

There are two different control techniques. One based on multi-pulse phase control and another based on PWM control. These two control techniques are sometimes characterized as "indirect" and "direct" controls [5]. An indirectly or phase controlled VSC allows control of the output voltage angular position only; the magnitude remains proportional to the dc terminal voltage directly controlled by appropriate valve gating. While for directly or PWM controlled converters both the angular position and the magnitude of the output voltage are controllable. The control objective in both techniques is to achieve a desired current in the compensated line based on a set reference level [5]. The SSSC control scheme has two major functions, one function is to establish the desired capacitive or inductive compensation by an extremely fixed reference, where the reference could be an impedance $Z_{R,}$ and the series injected voltage$V_{SSSC.}$ or simply the current in the compensated lineI_{line}.The second function is to modulate the series reactive compensation so as to improve transient stability and provide power oscillation damping [9].

SSSC implemented to Improve Power Oscillation Damping (POD)

Power oscillation are a common dynamic phenomenon which can influence the power system after a disturbance arises. Power oscillation increase the risk of instability and thus reduce the power transfer capacity particularly in week transmission lines. Nowdays, solid-state static series FACTS controllers such as SSSC, because of their fast response dynamics are employed to improve power oscillations damping. The SSSC can improve POD [10] by intelligent modulating of its series reactive power compensation. In addition, an SSSC with its energy storage can increase the effectiveness of POD by absorbing the real power from or injecting it to the transmission line [5]. To achieve acceptable controllability and damping performances, the output of the SSSC must be adjusted fast and accuretely. In [11] damping function of the SSSC has been presented.

Test System Description

Figure 4, shows a simple power system 500 KV network grid equipped with SSSC rated at 100 MVA connected in series with transmission line L1 designed and simulated in Matlab (Simulink).

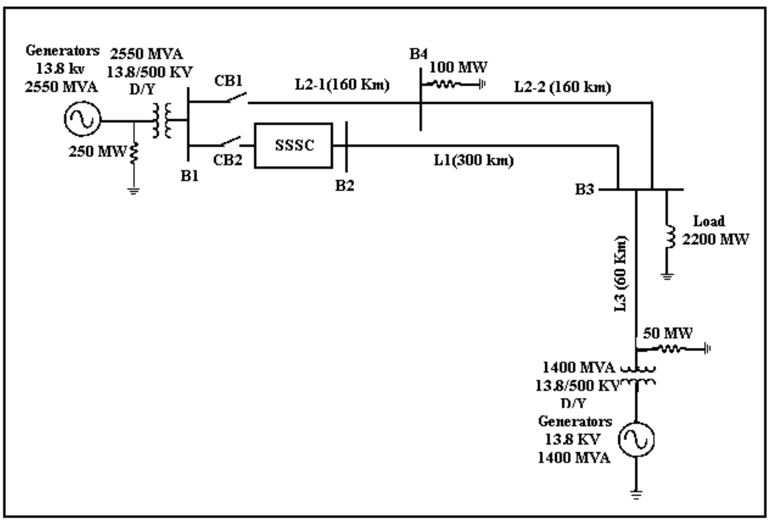

Figure.4, The single line diagram representing a 500 KV power system Equipped with Series SSSC

The power system grid consists of two power generation substation and one major load center at bus B3. The first power station M1 has a rating of 2550 MVA, the othe power station M2 has a rating of 1400 MVA . The load centre is approximately 2200 MVA modeled using three-phase series load. M1 power station is connected to this load by two transmission lines L1 and L2. L1 is 300 km long and L2 is split into equal segment (L2-1 and L2-2) each of 160 km long.

M2 is also connected to the laod centre by 60 km transmission line L3. The SSSC is connected in seeries to L1 through B1 and is capable of injecting up to 10% of the nominal voltageVpq in series with the transmission line where it is connected. As the SSSC does not use any active power source, the injected voltage must stay in quadrature with line current.

The variation of the injected voltage is performed by means of a VSC uses forced-commutated power electronic devices to synthesize a converter voltage V_conv., from a DC voltage source. A capacitor connected on the DC side of the VSC acts as a DC voltage source. A small power is drawn from the line to keep the capacitor charged and provide transformer and VSC losses, so the injected voltage V_{pq} is practically 90^0 out of phase with the line current. Figure 5 shows control system block diagram used in proposed test system.

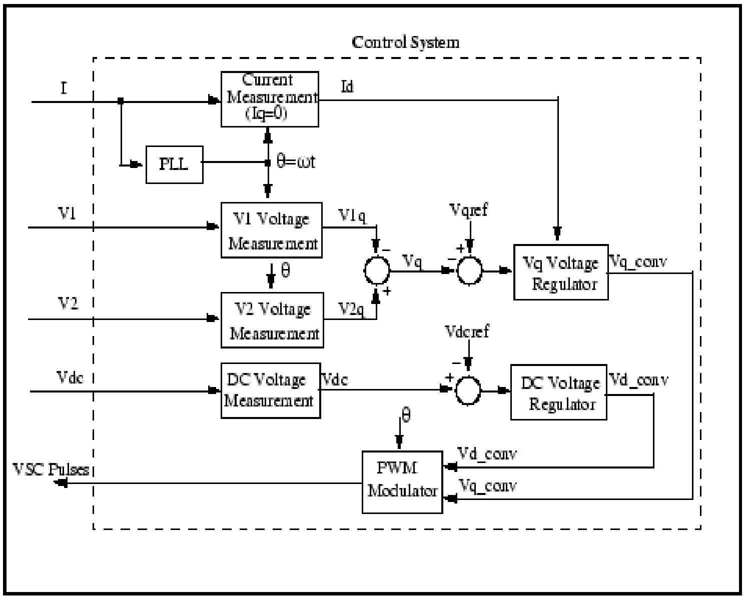

Figure.5, SSSC control system implementation

The control techniqueof [5] is used in this system on the use of PWM to synthesize a sinusoidal waveform from a Dc voltage with a typical chopping frequency of a few KHz. Harmonics are cancelled by connecting filters at the AC sideof the VSC. This type of VSC uses a fixed Dc voltage V_{dc}, by changing the modulation index of the PWM modulator the converter voltage V_con., can be varried.

The SSSC injected voltage reference is normally set by a Power oscillation Damping (POD) controller [12] whose output is connected to the $V_{qref.}$input of the SSSC. The POD controller consists of an active power measurment system, general gain , a low-pass filter, a washout high-pass filter, a lead compensator, and an output limiter. The inputs of the POD controller is the bus voltages and the line current through the line at which the SSSC is connected.

Experementsand Simulation Results

In order to measure the needed values of the system, a number of tests has been carried out:

- Test 1: SSSC is bypass (measure the active power P at bus (2).
- Test 2: SSSC is connected and the injected voltage $V_{inj.}$ is set 0.05 p.u.
- Test 3: Dynamic response of SSSC. The SSSC injected voltage reference is setby POD controller whose output is connected to the $V_{qref.}$ input of the SSSC. $V_{qref.}$is set as follows: Initially $V_{qref.}$ is set 0 p.u, at t = 1 s, $V_{qref.}$ is set to +0.8 p.u. (SSSC is capacitive); at t = 3 s, $V_{qref.}$ is ste 0 p.u.; at t = 7 s $V_{qref.}$ is set to -0.8 p.u. (SSSC is inductive)

- Test 4: Power oscillation damping of SSSC, to compare the test system with and without POD control.
- Test 5: SSSC is subjected to three phase faults at the middle of line 2.

The following figures shows the operation of our test system when the SSSC is connected in series with line at bus B2, with and without POD controller. And the effect of POD on the system subjected to three-phase faults at B4.

Figure 6, shows the test system operated without SSSC, the total active power flow towards the major load is measured at bus 2 (P_B2) flow on line 1 is 740 MW.

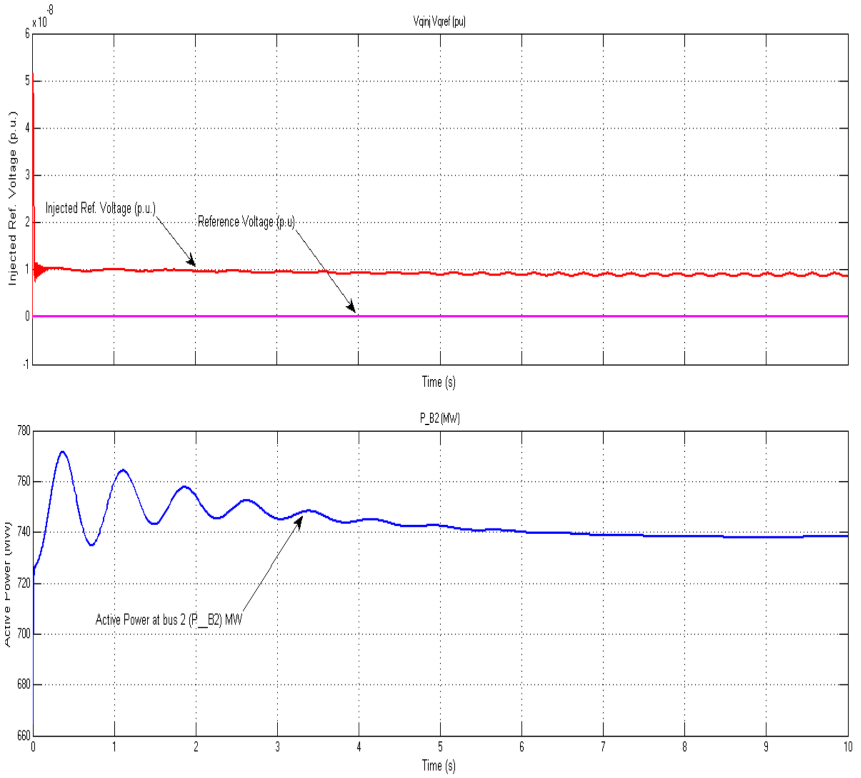

Figure.6 Test System Without SSSC

Figure 7, shows the operation of the test system when SSSC is connected in series with transmission line 1 and its capable of injecting up to 10 % of the normal voltage system, as we can see form the figures, the transmitted power at B2 is varying between 740 MW and 820 MW in accordance to the reference injected voltage of the SSSC.

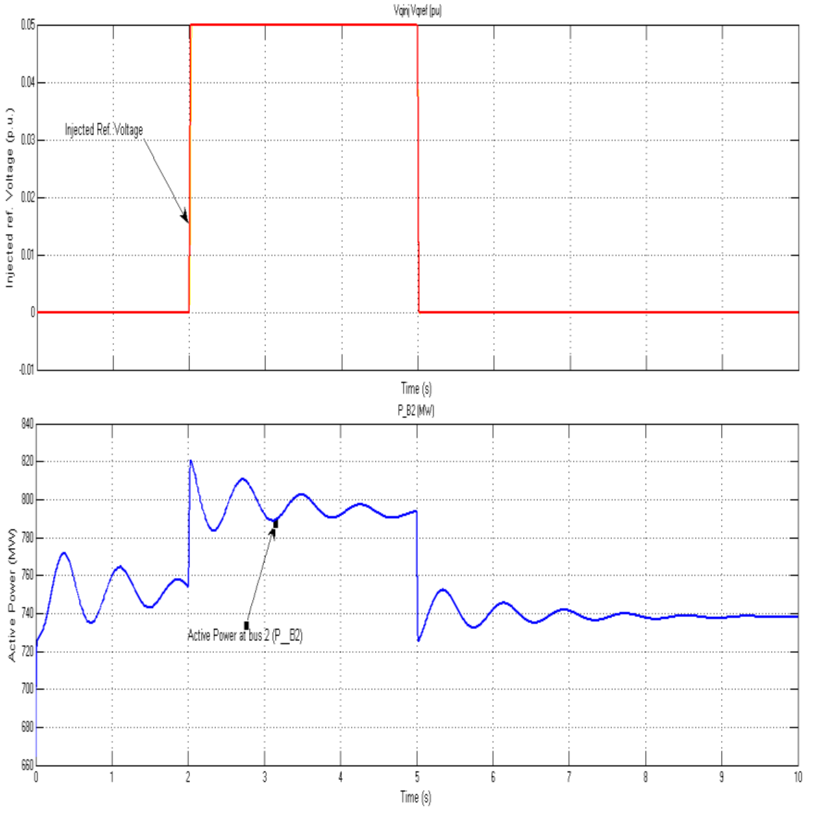

Figure.7 Test System With SSSC

Figure 8, Shows the dynamic response of the test system. In this case the reference voltage is set to vary between inductive and capacitive modes. Note that POD is still disabled. As we can see that the SSSC regulator follows very well the reference signal depending on the injected voltage. The power flow at B2 is varying between 630MW in case of inductive operation and 870 MW in case of capacitive operation.

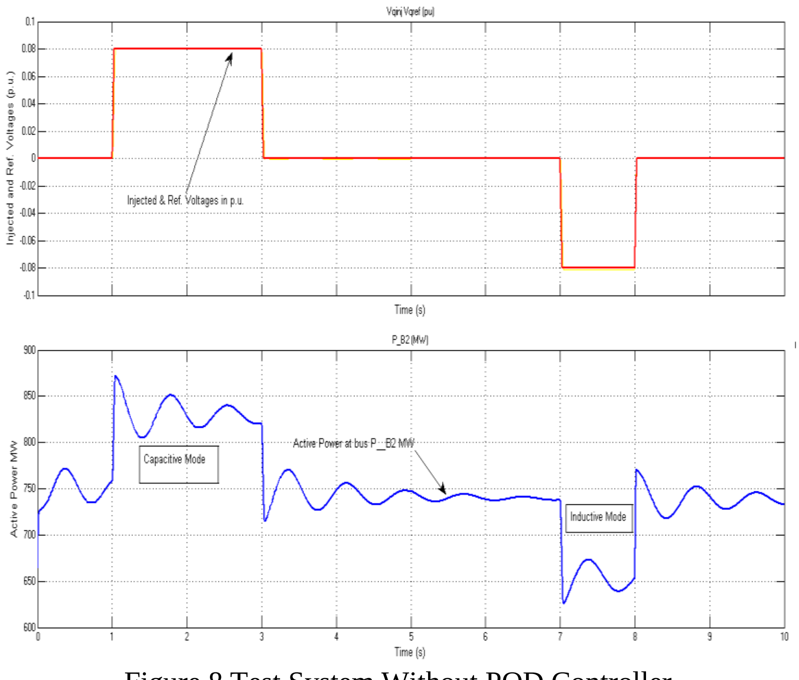

Figure.8 Test System Without POD Controller

The effect of POD on the test system is shown in figure 9. As we can see the SSSC with POD controller is a very effective tool to damp power oscillation because it reduced the signal ripples.

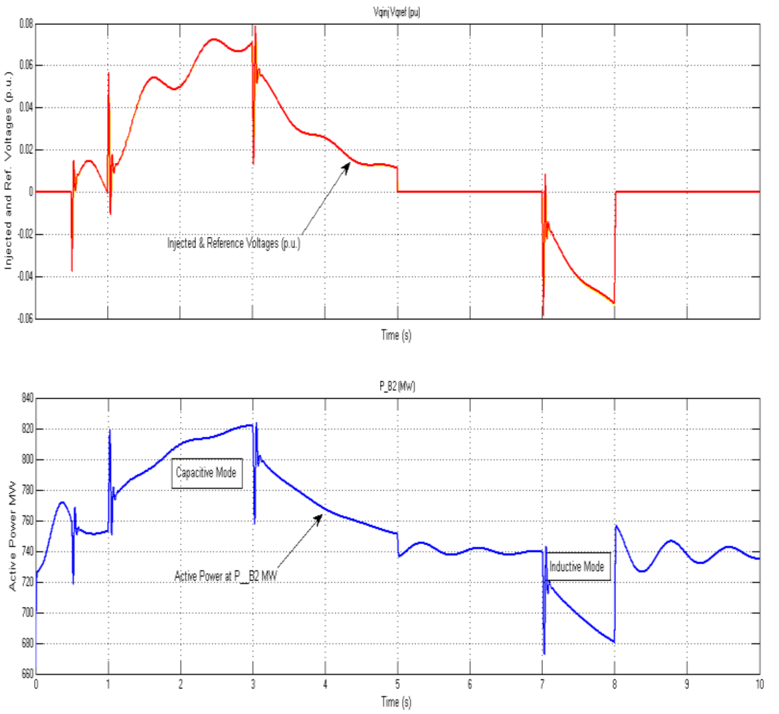

Figure.9 Test SystemWith SSSC and POD

Figure 10, Shows the operation of the test system when the step reference $V_{qinj.}$ is disabled and Initially $V_{qref.}$ is set to 0 p.u, at t = 1 s, then$V_{qref.}$ is set to +0.8 p.u. (SSSC is capacitive); at t = 3 s, and $V_{qref.}$ is set to -0.8 p.u.(SSSC is inductive).

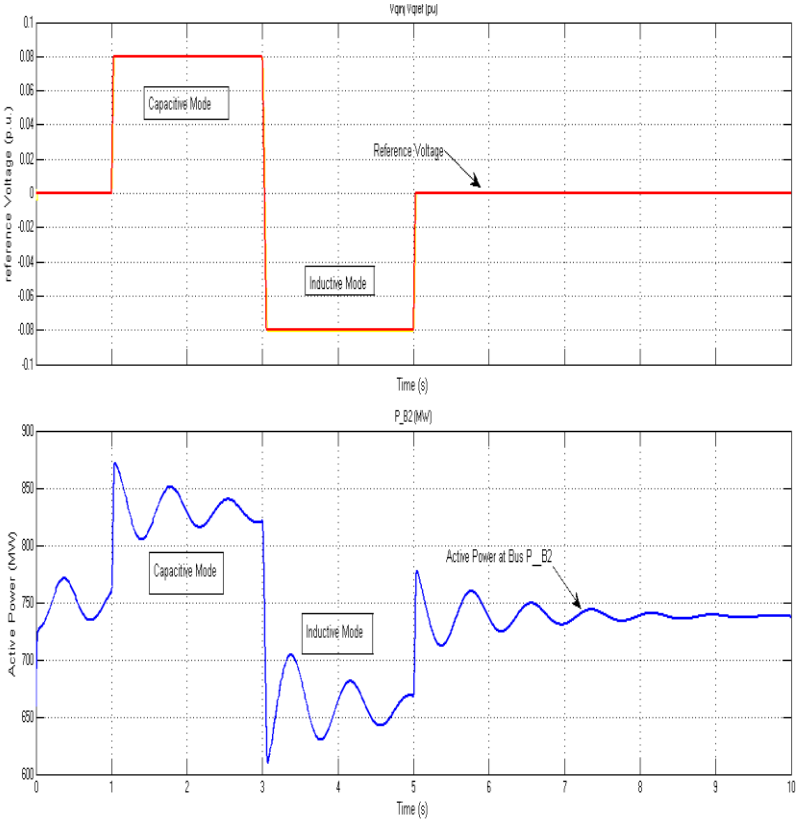

Figure.10 Operation of test system with the reference voltage V_{qref}.

Figure 11, shows the operation of test system when it subjected to three-phase faults at the middle of line 2 without POD

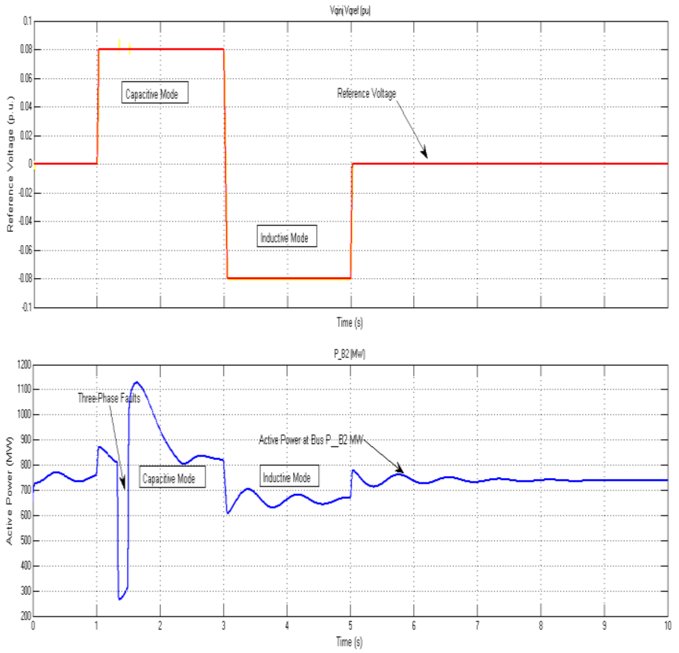

Figure.11 Test system subjected to three-phase faults

Figure 12, Shows the effect of POD controller on test system operation when it subjected to three-phase faults at the middle of line 2. As we can see from the figure, the SSSC with POD controller is a very effective tool to damp power oscillation.

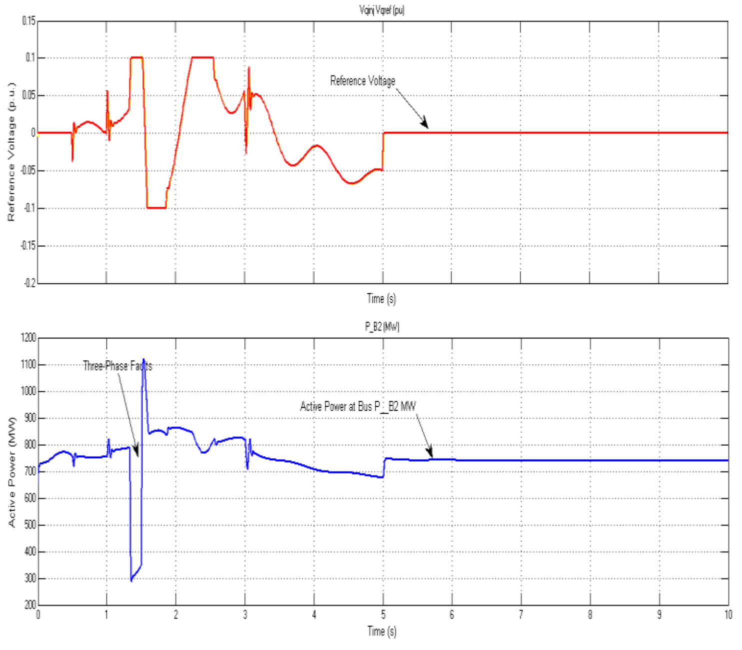

Figure.12 the Effect of POD controller on test system operation

Discussion

The SSSC which is a VSC injects an almost sinusoidal voltage in series with the transmission line. This injected voltage is almost in quadrature with the line current, thereby emulating an inductive reactance or capacitive reactance in series with the transmission line. The power in the transmission line always increases when the injected voltage by SSSC emulates a capacitive reactance in series with the transmission line and the power flow in the transmission line decreases when the injected voltage by the SSSC emulates an inductive reactance in series with the transmission line as illustrated in Figure8. The transition from one mode of operation to the other mode takes place in a sub-cycle time. It is also observed from the variations of system states that the system returns to its normal operating conditions in a time less than 3 second and the overshoot/undershoot of system state response are well within acceptable limits. It is observed in Figure 9 and Figure12 that the POD controller is very effective tool to damp power oscillation and to increase the system stability during normal and fault conditions.

CONCLUSIONS

- static synchronous series compensator operated without an external energy source as reactive power with output voltage is in quadrature with and fully controllable independently of the transmission line current for the purpose of increasing or decreasing the overall reactive voltage drop across the transmission line and thereby controlling the electric power flow.
- The injected voltage is almost in quadrature with the transmission line current; thereby can effective as an inductive or capacitive equivalent reactance in series with the transmission line.
- The dynamic power flow in the transmission line always decreases when the injected voltage by the SSSC in an inductive reactance mode and the power flow increases when the injected voltage by the SSSC in a capacitive.
- The SSSC can improve POD by intelligent modulating of its series reactive power compensation. In addition, an SSSC with its energy storage can increase the effectiveness of POD by absorbing the real power from or injecting it to the transmission line.

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