Distributed Static Series Compensator (DSSC) for Power Flow Control and Inter-Area Oscillations Damping Studies

M.Khalilian[1], M. Mokhtari, J. Khazaie, D. Nazarpour and M. Farsadi

[1]Department of electrical engineering, Urmia University, Iran
m.khalilyan@yahoo.com, Maghsood.mokhtari@yahoo.com, javad_khazaie@yahoo.com, d.nazarpour@Urmia.ac.ir and *m_farsadi@yahoo.com*

Abstract

This paper proposes a supplementary controller for the Distributed Static Series Compensator (DSSC) to precisely investigate the DSSC's capabilities in Power Oscillation Damping (POD), and transient stability enhancement beside of power flow control. İt is shown that, when the DSSC operates to alter the power flow in the line, low frequency oscillations are apparent in the system. A simple POD controller is designed and granted to DSSC's conventional controller to mitigate such a kind oscillation. Furthermore, it is revealed that, proposed controller is also capable of enhancing the transient stability beside of low frequency oscillation damping. Numerical studies on a multi-machine power system are conducted in the PSACD/EMTDC software and miscellaneous conditions are simulated to validate the proposed model in many aspects. Simulation results reveal that, the designed supplementary controller is efficient enough in damping power oscillations without any adverse interaction in other power system parameters.

1. Introduction

FACTS devices are based on application of power electronics and high voltage high power converters, which are in series or parallel configurations or a combination of both [1]-[5]. These well known devices effectively increase power handling capacity of the line and improve transient stability as well as damping performance of the power system [6]-[10].

Recently a new concept, designated as distributed FACTS (D-FACTS), has been introduced as a possible way to achieve more merits beside those raised by lumped FACTS devices [11]. Distributed Static Series Compensator (DSSC), as a new D-FACTS device, is composed of a low-power single-phase inverter which attaches directly to the transmission line conductor [11]. It should be emphasized that in order to preserve the transmission system symmetry; all three phases of the line in question are identically equipped. Distributed nature of these devices enables a fine granularity in the system rating which, in turn, makes possible to boost the transmission system along with the demand growing. This opportunity grants a salient benefit in the system planning since the increasing requirement in power transfer capabilities would gradually be satisfied by installing new DSSC modules in the most effective line(s). In the sequel, the investment would also be distrusted over the planning time span and it does not necessitate investing all the capital at the project start [11]. The rate of the return on capital employed (ROCG), which is financial metric for most organizations, would be very high and it consequently makes DSSCs more economically justifiable. In the distributed fashion, a single failure brings just one DSSC module out of service while remain modules keep operating. The power system reliability would, therefore, be improved. Lower cost, not very complex design and build cycles, easy repair, and decreased mean time to repair (MTTR) are other attractive features making DSSCs more desirable [11]. DSSCs are capable of dynamically control impedance of transmission lines and a flexible power flow would be realized in the sequence. For those lines with restrictive stability limits, DSSCs could work such as series capacitors and elevate line capacities. These devices profit a prompt and effective control to enhance transient stability as well as power oscillation damping [12], [13].

To the authors' best knowledge, although few efforts have been devoted to the DSSC modeling in power flow calculations [13], [14], a quantitative evaluation of DSSC capability in power oscillation damping and transient stability improvement has not been addressed so far. This paper develops a circuit simulation model of DSSC to investigate these functionalities. The model is designed in PSACD/EMTDC software environment. A simple POD controller is proposed in the main control loop of the DSSC which effectively enhances low frequency oscillation damping and transient stability tolerance. The performance of the proposed model is examined in a multi-machine power system where the power flow control aspect is also taken into consideration. Detailed discussions are raised over the numerical results obtained.

The organization of the paper is as follows. Section 2 briefly describes the DSSC concept and its capabilities and features. Characterization of electromechanical oscillations and transient oscillations are introduced in Section 3. Simulation results including various functionalities associated with DSSC are assessed in section 4 with supporting numerical evidences. Concluding remarks drawn by the paper are finally discussed in Section 5.

2. Distributed Static Series Compensator (DSSC)

2.a DSSC Structure

DSSC is in fact a single-phase model of a SSSC, but in a smaller size, that lies on transmission lines in a distributed manner mainly for power flow control. Each DSSC device is a single-phase but they are deployed on all three phases of a transmission line to preserve symmetry of the power flow. Each module is suspended from the line conductor or is configured as a replacement for the conductor support clamp on an insulator. So, there is no need for phase-ground insulation [11]. The low-power intrinsic of DSSC necessitates installation of hundreds or thousands DSSC modules in a single transmission line.

Fig.1 illustrates DSSC module components in a circuit schematic representation [15]. It mainly consists of a current transformer (CT) to provide the feedback signal required, a processing unit serving as the controller, a small-rated (1-20 kVA) single-phase inverter to generate the compensating sinusoidal voltage, a single-turn transformer (STT) to insert the voltage in the transmission line, a power supply feeding the processor, and a built-in communication hardware to send/receive signals to/from other modules or a centralized controller [16]. DC capacitor holds the voltage level at the DC bus of inverter and power losses of the inverter are compensated through the active power absorbed from the line. Harmonic content of the generated voltage are cleansing by an LC filter connected to output of the inverter. The module is bypassed during the sleep mode of DSSC or in the event of any failure. The required system commands for responding to gradual changes are received from a central control center via a wireless link or power line communication (PLC) technique [17]. An autonomous operating mode could also be considered in which each module works based on a predetermined set points. The STT utilizes the transmission line conductor as the secondary winding and is designed with a high turn ratio (100:1). Hence, the current which is handled by the inverter is reduced and commercial IGBTs can readily be employed for low cost implementations [15]. As depicted in Fig. 1, the transformer core consists of two parts that are clamped around the line conductor in order to form a complete magnetic circuit [18].

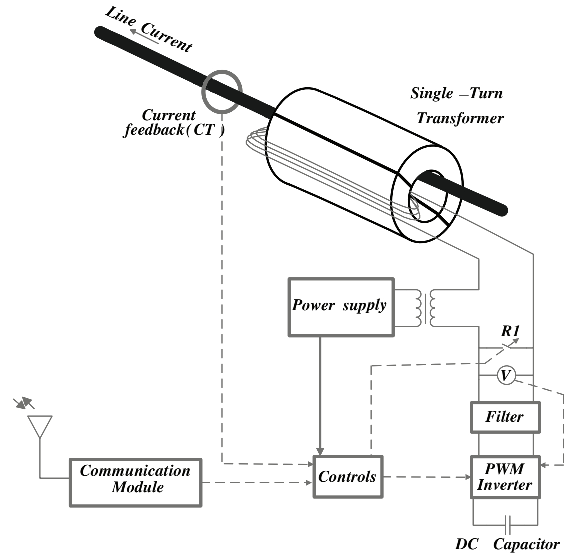

Fig. 1. Circuit schematic of a DSSC module.

2.b Operational Perspective of DSSC beside its Economic Benefits

Useful operation characteristics provided by realization of DSSC deployments comprise:

- Ability to increase or decrease steady state line current under system controller command or autonomously;
- Ability to monitor actual conductor temperature and manually or automatically limit currents as a function of conductor temperature;
- High system reliability due to massive redundancy (single unit failure has negligible impact on the system performance);
- Zero footprint solution;
- Robust and rugged operation under faulted conditions;
- •Applicability with both conventional and advanced conductors;
- Mass production feature, reparability in the factory, and lack of requirement to skilled staff on site;
- Easy and rapid installation (may be possible on hot lines).

The aforementioned operational characteristics would result in some significant economical benefits among them are:

- Increasing respective market revenues with simple scalability and promoting available transfer capability (ATC);
- Postponing construction of new transmission lines restricted with environmental concerns and right-of-way limitations;
- Declining operating cost via minimization of loop flows and wheeling losses;
- Reducing trapped capital in assets sized for future projected growth;
- Enabling bulk energy trading with more flexible transmission system [11].

2.c Effect of DSSC on the Line Power Flow

The DSSC which is connected in series with the transmission line generates a synchronous fundamental voltage that is in quadrature with the line current, i.e., it acts as a pure reactance. Hence, the transmitted power would be a parametric function of the injected voltage. The associated expression is derived as follows [15]:

$$P_{AB} \frac{V_A V_B}{X_L} sin\delta \frac{V_A V_q}{X_L} \cos\left(\frac{\delta}{2}\right)\left\{\frac{\sin\left(\frac{\delta}{2}\right)}{\sqrt{\left(\frac{V_A+V_B}{2V_A}\right)^2-\frac{V_A}{V_B}cos^2\left(\frac{\delta}{2}\right)}}\right\} \qquad (1)$$

Where:

V_A and V_B : The bus voltage magnitudes of the buses which DSSCs are linked between.
δ : The voltage phase difference between two bus voltage
X_L : The impedance of the line, assumed to be purely inductive
V_q : Voltage injected by DSSCs

Consequently, DSSC can increase or decrees the transmitted power depending on its injected voltage polarity [19].

2.d Control System

The main task of the DSSC is to control the power flow in a transmission line. This objective can be achieved either by direct control in which both the angular position and the magnitude of the output voltage are controlled, or by indirect control in which only the angular position of the output voltage is controlled and the magnitude remains proportional to the dc terminal voltage [20].

The inverters which are controlled in a direct mode encounter with more difficulty and higher cost to implement in comparison with indirectly controlled inverters. Also in a direct control mode the inverter function is usually associated with some drawbacks in terms of increased losses, greater circuit complexity and increased harmonic content in the output, hence the control structure used for the DSSC in this model is based on indirect control.

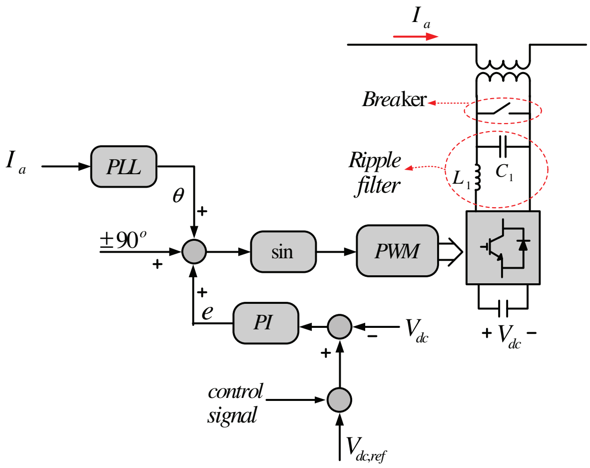

Fig.2 indirect control of DSSC

Here, the controller is used to retain the charge on the dc bus capacitor and to inject a synchronous voltage that is orthogonal to the line current. In order to control the dc capacitor voltage a small displacement 'e' beyond the required 90 degree between the injected voltage and the line current is required. The phase-locked-loop (PLL) is used to provide the basic synchronization signal 'θ', which is the phase angle of the line current. The error signal that is obtained by comparing Vdc with Vdc_{ref} is passed through a PI controller and the resultant will be the required phase angle displacement 'e' [15]. The control signal is the output of POD controller in order to damp low frequency oscillations which will be precisely clarified in the following sections.

3. Electromechanical Oscillations

In this part, electromechanical oscillations are described. Electromechanical oscillations are due to the dynamic of inter-area power transfer in a large inter connected power network that can seriously limits the operation of system and in some condition induces stress in the mechanical shaft of synchronous generators. These oscillations are the main aspects of small signal stability. Small signal stability is the ability of power system in maintaining synchronism after small disturbance. The oscillations which the system is endangered to during small disturbances are usually named to electromechanical oscillations. Usually the electromechanical oscillations divide in two types [21]:

- Local mode, the local mode oscillations are due to swing of one synchronous generator against another generator in same area, they usually have frequencies from 1 to 3 Hz.
- The inter-area mode: the inter-area oscillation involves oscillations of a group of generators in one area against a group of generators in another area. They are in range of less than 1Hz

Transient stability is another part of evaluating stability in power systems. Transient stability is the ability of the power system in maintaining synchronism when subjected to severe transient disturbances. The resulting system response includes large excursions of generator rotor angles and is affected by the non-linear relationship. In this situation, stability depends on both the initial operation state of the system and severity of the disturbance [21]. As cited above, it is great of interest to damp these oscillations and improve the system stability, in this study this goal is achieved by supplementary controller which is granted to DSSC modules in power systems. As illustrated in following sections, proposed POD controller not only improves the small signal stability including local and inter-area oscillations damping, but also enhances the transient stability.

4. Simulation Results

a. Power flow control

This section discusses the ability of DSSC in power flow control. A four-machine two-area system which is a special design for fundamental study of inter-area oscillations is employed in the simulation studies. The multi-machine data is given in [21]. This system is presented in Fig.3 which is composed of four generators and two areas that have been connected together by two 220 km transmission lines namely, L1 and L2. The active power through each line is about 201.7 MW without any DSSC modules ($p_{L1} = p_{L2} = 201.7$ (MW)). To examine the ability of DSSC in power flow control, a number of DSSCs are set in both lines L1 and L2. For each DSSC the dc bus voltage reference ($V_{dc\ ref}$) is adjusted at 1 kV. Therefore with respect to the turn ratio of the STT (1:100), the injected quadrature voltage (V_q) is 10 volt peak to peak.

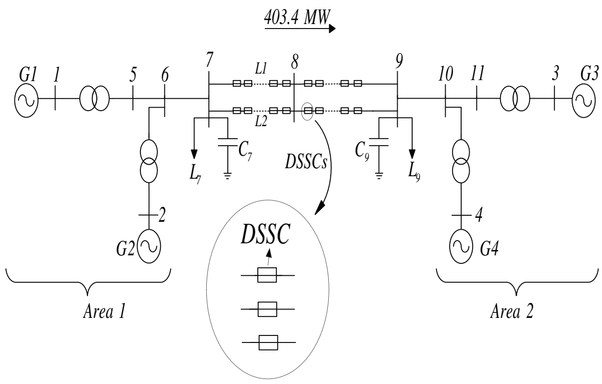

Fig.3 Multi-machine system with DSSC modules in each phase of lines L1 and L2

In the first step, 245 DSSC modules are entered only to each phase of line-1 (L1) in t=5sec in the capacitive form (Control= -1. T_{on} = 5 sec). Control means the mode of DSSC operation, it is set to 1 when inductive mode is favorable, and is set to -1 when operates as capacitive mode. T_{on} means the time in which DSSC begins to operate at power system [15]. With entering the

DSSCs to L1, the active powers change to PL1= 204.5 MW and PL2= 198.9 MW as depicted in Fig. 4. In the second step beside the modules in L1, 245 new modules are entered to each phase of L2 in the inductive form (Control= 1, T_{on} = 40 sec). In the following 245 new modules are added to the existing modules of line-1 again in capacitive form in $T_{on} = 75$ sec. Also in $T_{on} = 110$ sec, 245 new modules are added to the existing modules of line-2 again in inductive form. The variation of active power in each line for the mentioned steps has been shown in Fig.4. The detailed numeric information of each step is gathered in Table.1. As depicted earlier, DSSCs act like a pure reactance. X_{inj} is the injected series reactance with DSSC that is presented in Table 1 ($X_{inj} = \frac{V_{inj}}{I_{Line}}$). V_{inj} is the total voltage injected by DSSCs, and I_{Line} is the line current.

Table 1. Four steps of DSSC operation

State	Number of DSSCs in each phase of L1	Number of DSSCs in each phase of L2	P_{L1} (MW)	P_{L2} (MW)	X_{inj} (ohm) L1	X_{inj} (ohm) L2
Initial state	0	0	201.7	201.7	0	0
Step 1	245	0	204.5	198.9	-j3.3	0
Step 2	245	245	207.5	196	-j3.3	j3.43
Step 3	490	245	210.2	193.1	-j6.54	j3.43
Step 4	490	490	213.2	190.3	-j6.54	j7

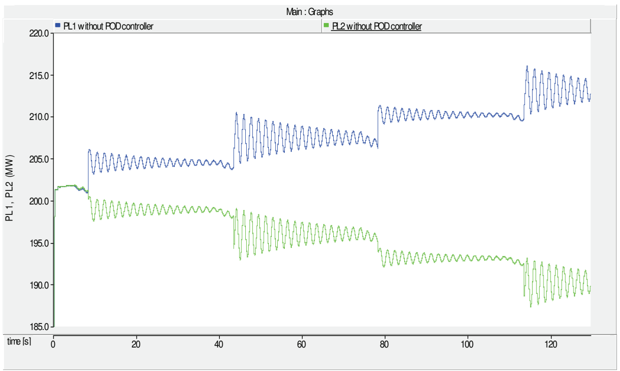

Fig.4 Variation of PL1 and PL2 when the DSSCs are entered to lines without POD controller

The DSSCs entrance in each step to a line will result disturbances in the system. As Fig. 5 shows, these disturbances lead to power oscillations in the system with poor damping.

b. Low Frequency Oscillation Damping and Transient Stability Enhancement

As mentioned earlier, the entrance of DSSCs to the system will result in power oscillations with poor damping. Hence, the main focus in this section is to design a controller to damp these oscillations effectively. Such a stabilizer is called power oscillation damping (POD) controller which generates a control signal that will modulate the magnitude of the series injected voltage during electromechanical transients in order to damp the oscillations. As it is depicted in Fig.5, the POD controller consists of three blocks; a washout filter, a phase compensator block and a gain block. The washout filter is used to avoid it from responding to the steady state changes of the input signal. The phase compensator block provides the appropriate lead/lag characteristics in order to generate the damping torque. Also, the amount of the damping is determined by the stabilizer gain G [22].This controller is added in a proper way to the main control loop of DSSCs as earlier illustrated in Fig.2. Here, the input signal is $\Delta p = P_{ref} - P_{Line}$ where P_{ref} is the reference value of line power and P_{Line} is the measured line power corresponds to the line which consists of DSSC modules.

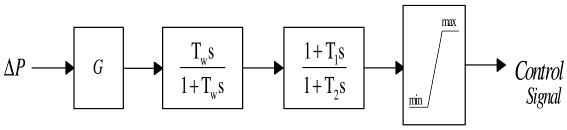

Fig.5. POD controller block diagram

In order to investigate the proposed controller effect in the system, the DSSCs modules are entered to the lines again exactly in the sequence that was explained in section 4.a. Here the POD controller is added to the main control loop. The active powers in each line for the two different cases, namely, without controller and the other with controller, are both illustrated in Fig. 6. It is clearly seen that this controller shows a very good damping in power oscillations. The POD controller parameters are adjusted by hit-trial method. The obtained parameters are as follow:

$G = 0.04,\ T_w = 10,\ T_1 = 0.001,\ T2 = 0.01.$

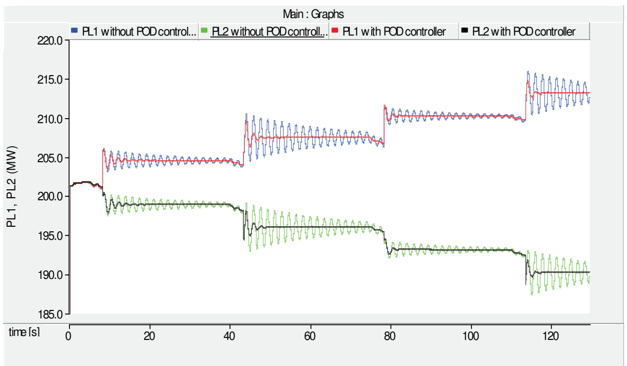

Fig.6 Variation of PL1 and PL2 when the DSSCs are entered to lines with and without POD controller

For analyzing the ability of DSSC in damping the inter-area oscillation modes (speed difference between Gen.1 and Gen.4, Gen.1 and Gen.3, Gen.2 and Gen.3 as well as Gen.2 and Gen.4) and the local modes (speed difference between Gen.1 and Gen.2 and also Gen.3 and Gen.4), a three-phase to ground fault is occurred in bus-10 at t=60 sec for a time duration of 0.15 sec. At this case 490 DSSC modules are placed in each phase of L1 and L2. The DSSCs that are placed in L1 are in the capacitive form and the other ones placed in L2 are adjusted in the inductive form. All of these modules, have been entered to the system at t=5sec (Ton of all modules is 5sec). Figs. 7 and 8 present the local and inter-area oscillation modes with and without POD controller respectively. Simulation results confirm that the DSSCs have a significant influence in damping of inter-area and local oscillation modes in the multi-machine power system.

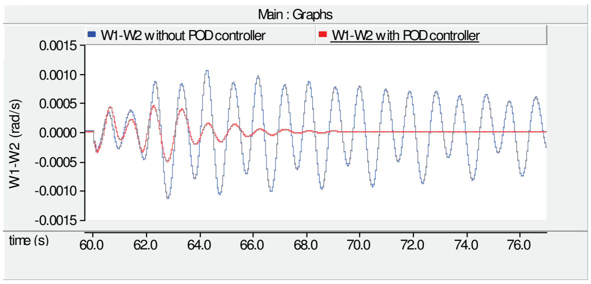

Fig.7 local oscillation mode with and without POD controller

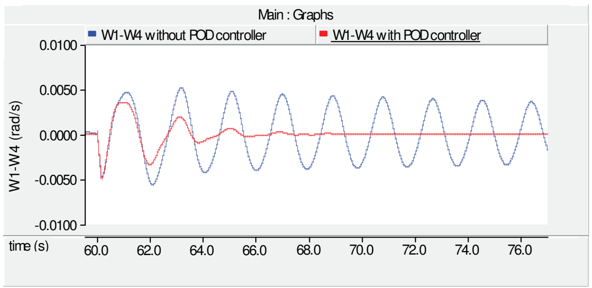

Fig. 8 Inter-area oscillation mode with and without POD controller

In the following, in order to verify the effect of DSSC in transient stability enhancement, a sever fault occurs in bus 10 at t=10 sec for 0.23 sec. With respect to Fig. 9, it can be observed that, when the control loop of DSSCs does not contain POD controller, the system becomes totally unstable due to the long duration of the fault. But as it is illustrated in Fig. 9, by adding the POD controller to the DSSCs control loop, the system oscillations will damp after several cycles and the system will be stable.

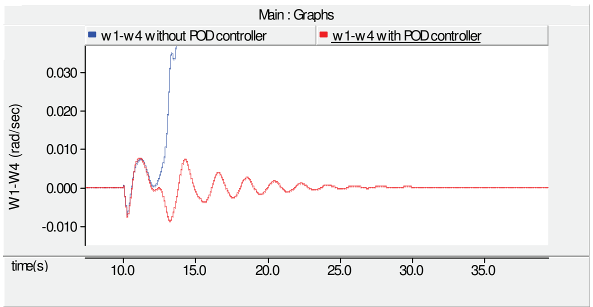

Fig. 9 Inter-area oscillation mode with and without POD controller with severe fault

5. Conclusions

This work shows some performance aspects of the DSSC in power flow control, power oscillation damping and transient stability enhancement through the simulations with PSCAD/EMTDC program. It is shown that the DSSC provides an effective control on the power flow in the system. On the other hand, by the entrance of DSSCs there will be power oscillations in the system. To damp these oscillations, a POD controller has been proposed and tested. Simulation results confirm that the DSSC can be useful in this manner. Also a three-phase to ground fault is occurred in the system which results in the local and inter-area oscillations. It is observed that the proposed POD controller also provides an effective damping in this kind of oscillations. Finally, a sever fault is occurred in the system to examine the controller effect in transient stability enhancement and large fluctuations. It is deduced that in this case the controller retains the system stable. The authors believe that DSSC can be very effective in actual application but there are still more specific studies to confirm this.

6. References

[1] L. Gyugyi, "Dynamic compensation of ac transmission lines by solid-state synchronous voltage sources", IEEE Trans. Power Delivery,19(2),1994, pp.904-911.

[2] K.Sen,"SSSC-Static synchronous series compensator Theory modeling and application.", IEEE Trans. on Power Delivery, 13(1):241-246, January 1998.

[3] P.Rao , M.L. Crow ,Z.Young , " STATCOM control for power system voltage control application", IEEE Trans. Power Delivery ,15,2000, pp.1311- 1317.

[4] H.Wang, F.Li, "Multivariable sampled regulators for the coordinated control of STATCOM ac and dc voltage" , IEE Proc. Gen. Tran. Dist.,147(2) ,2000,pp. 93-98.

[5] A.H.M.A Rahim , M.F.Kandlawala ," Robust STATCOM voltage controller design using loop shaping technique", Electric Power System Research, 68,2004,pp.61-74.

[6] K.Xing, G.Kusic, "Application of thyristor-controlled phase shifters to minimize real power losses and augmentstability of power systems", IEEE T-PWRS, Vo1.3, No.4,Dec., 1988.

[7] E.Z.Zhou, "Application of Static VAr. Compensators to Increases Power System Damping", IEEE T-PWRS,Vo1.8, No.2, May, 1993.

[8] M.Noroozian, L.Angquist, M.Ghandhari, G.Anderson, "Use of UPFC for Optimal Power Flow Control", IEEE Trans. on Power Delivery,Vol.12, No.4, October 1997.

[9] Douglas J. Gotham, G.T.Heydt, " Power Flow Control and Power Flow Studies for Systems with FACTS Devices", IEEE Trans. on Power Systems, Vol.13, No.1, February 1998 .

[10] N.G. Hingorani , L. Gyugyi " Understanding FACTS : Concepts and Technology of Flexible AC Transmission Systems", IEEE Power Engineering Society, IEEE press, Delhi 2001.

[11] Divan, D. et al., 2007. A distributed static series compensator system for realizing active power flow control on existing power lines. IEEE Trans. Power Delivery, 22: 642-649. DOI: 10.1109/TPWRD.2006.887103.

[12] D. Divan "Improving Power Line Utilization and Performance With D-FACTS Devices" IEEE Power Engineering Society General Meeting, 3: 2419-2424. DOI: 10.1109/PES.2005.1489343.

[13] H. Johal, D. Divan, "Design Considerations for Series-Connected Distributed FACTS Converters" Industry Applications, IEEE Transactions on Volume: 43 2007 , Page(s): 1609 - 1618

[14] G. NING, S. HE, Y. WANG, L. YAO, Z. WANG "Design of Distributed FACTS Controller Considerations for Transient Characteristics", Power Electronics and Motion

Control Conference, 2006. IPEMC 2006. CES/IEEE 5th International, 2006, Shanghai.
[15] P.Fajri, D.Nazarpour and S.Afsharnia, “A PSCAD/EMTDC Model for Distributed Static Series Compensator (DSSC),” Electrical Engineering, 2008. ICEE 2008. Second International Conference on Publication Date: 25-26 March 2008.
[16] Deepak Divan, “Distributed Intelligent Power Networks-A New Concept for Improving T&D System Utilization and Performance,”IEEE Transmission and Distribution Conference, 2005, New Orleans, Louisiana
[17] D.J Marihart, “Communications technology guidelines for EMS/SCADA systems,” IEEE Trans. Power Delivery, Vol.16, No..2, Apr 2001, pp.:181-188
[18] Mark Rauls, “Analysis and Design of High Frequency Co-Axial winding Transformers,”MS Thesis, University of Wisconsin Madison.US, 1992.
[19] L. Gyugyi, C.D. Schauder, and K.K. Sen, “Static Synchronous Series Compensator: a Solid-State Approach to the Series Compensation of Transmission Lines,” IEEE Trans. Power Delivery, Vol. 12, No. 1,Jan.1997, pp. 406-417.
[20] N.G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and technology of flexible ac transmission system. IEEE Press, NY, 2000.
[21] P. Kundur. Power system stability and control. Prentice-Hall,N. Y, U. S. A, 1994.
[22] M,S. Castro, H.M. Ayres, V.F. da Costa, L.C.P. da Silva" Impact of the SSSC control modes on small-signal and transient stability of a power system "Electric Power System Research 77(2007) 1-9.