A Novel Strategy for Controlling a Group of Distributed Static Series Compensators

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Abstract

This paper presents a new control strategy for controlling a group of Distributed Static Series Compensators (DSSCs) that can be clamped onto an existing power line and have the ability to change the series impedance of the line in order to control the flow of power. A harmonic analysis of an electromagnetic model of the DSSC is also presented in PSCAD/EMTDC to investigate the amount of harmonic injection of each model and based on the results different control strategies are applied to a group of DSSCs distributed along a transmission line. The effect of each control strategy on active power flow, THD injection and group response time is compared by simulations carried out in PSCAD/EMTDC and the most suitable control scheme for operating a group of DSSCs distributed along a transmission system is presented both for capacitive and inductive compensating modes.

1. Introduction

Power flow control in electric power networks is becoming one of the crucial factors of electric power system development. This is mostly due to an increase in power consumption and the deregulation of the electrical market. As a result the electrical power sector experiences nowadays a need in new techniques for increasing the capability of the existing transmission systems infrastructure. Growing interest in the field of FACTS [1] in the last few years has led to the development of new devices. One such device referred to as the distributed static series compensator (DSSC) was proposed in [2, 3] which is believed to enhance dynamic control in power systems and to improve system utilization just like other FACTS devices, but at a much lower cost and higher reliability. The DSSC is a small, light weight cylinder that clamps directly onto conductor cables and can control the flow of power. Each DSSC module consists of a small rated (~10kVA) single phase voltage source inverter using IGBTs and a single turn transformer. The transformer and mechanical parts of the module form a complete magnetic circuit only after the module is clamped around the conductor [2]. Also, each module has a control circuit and built in communication capability in order to have a coordinated operation when operated as a group. The operation of the DSSC can be summarized as follows: as the module starts up, the inverter voltage is in phase with the line current and real power is extracted from the line to charge the DC bus capacitor of the inverter. After charging the capacitor to a predetermined voltage, the unit is controlled so that it injects a quadrature voltage or reactive impedance in series with the line, resulting in an increase or decrease of transmitted power along the transmission line [2]. When there is no more need for compensation, the unit is bypassed and turned off, meaning that the DSSC has the ability to be turned on and off as many times as needed during operation. Many modules may be distributed over a power system grid to allow impedance control of the power lines and to steer power through the grid, but in order to benefit from DSSCs an appropriate control is crucial, especially if the number of DSSCs in a grid increase or the distances between them decrease. The operation of each individual module may be controlled and coordinated using an isolated communication link such as a radio receiver incorporated in each module or through use of other commercially available communication systems such as power line communication [4], with a control strategy that benefits the overall system operation.

In this paper a harmonic analysis of an electromagnetic model of the DSSC is presented. Also the effects of different control strategies applied to a group of DSSCs distributed along a transmission line are discussed and based on the results, the best control scheme for operating a group of DSSCs along a transmission line is presented.

2. Harmonic Analysis of DSSC

In order to study the effects of different control strategies on the quality of power being transmitted, a harmonic analysis was carried out to define the amount of harmonic distortion injected by each DSSC. The circuit model used here to analyze the behavior of DSSCs on power quality is the same model that was presented in [5] which consists of a power circuit, sinusoidal PWM generators and internal control system. The power circuit is modeled by a single turn transformer with a 1:75 ratio, a voltage source inverter consisting of 4 IGBT devices and a low pass LC filter. The main purpose of the internal controller is to retain the charge on the DC capacitor and to inject a voltage that is in quadrature with the line current.

To investigate the amount of harmonic distortion injected by each DSSC device, one DSSC model was placed on each phase of a typical 138 kV transmission line with the parameters of the transmission line given in Table 1 [6]. The amount of quadrature voltage injection of each model was set to 14 V resulting in an injection of almost 10 kVAr, considering line currents of 750 A. Figures 1 to 4 show the results obtained from simulations carried out in PSCAD/EMTDC [7] in order to study the effects of DSSCs on injecting harmonics to the line current.

Table 1. Transmission line parameters

Operating Line Voltage	138 kV
Operating Current	750 A
Impedance per Kilometer	0.104+j0.49
Line Length Used for Simulation	10 km

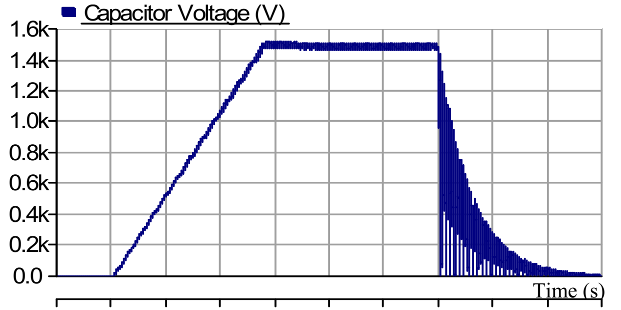

Fig. 1. Capacitor voltage variation of each DSSC

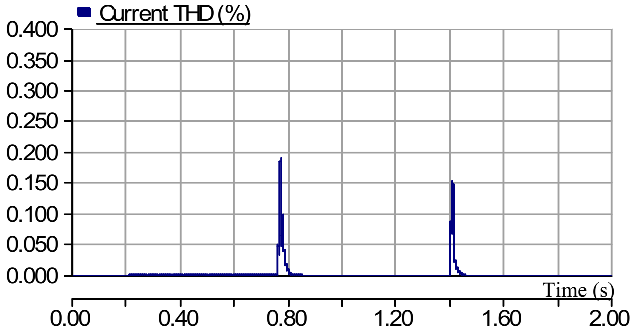

Fig. 2. THD injected to the line current by one DSSC

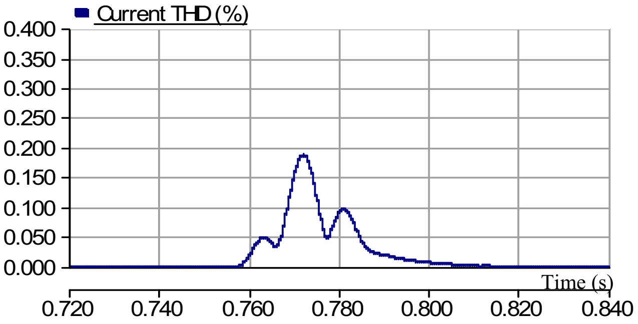

Fig. 3. Amount of THD injected to the line current by one DSSC

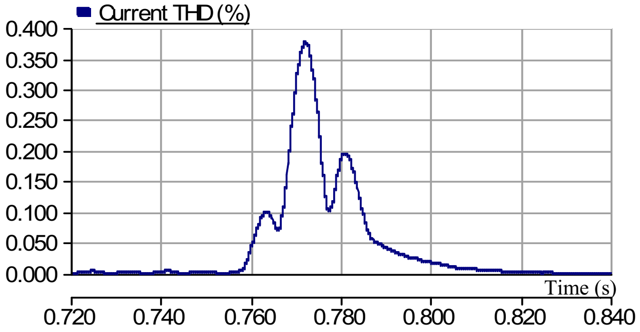

Fig. 4. Amount of THD injected to the line current by two DSSCs

Figure 1 shows the variation of the DC bus capacitor voltage of each DSSC. As the module is turned on at t=0.2s, active power is extracted from the line and the capacitor voltage increases until it reaches 1500 V, from this point on the capacitor voltage is kept constant and the injected voltage is almost in quadrature with the line current, resulting in a purely reactive series compensation of the line. As the module is turned off at t=1.4s, the transformer secondary winding is bypassed and the capacitor is discharged through the snubber circuit. Figure 2 shows the total harmonic distortion (THD) injected to the line current by one DSSC module. It can be noted that the most THD injection occurs at the transition period in which the capacitor is fully charged and the voltage phase is being shifted in order to be in quadrature with the line current. There is also some harmonic injection at the time the module is switched off. Figure 3 shows the amount of THD injected to the line current by one DSSC on each phase in the time of transition and Fig. 4 shows the THD injection with two DSSC modules distributed evenly along each phase of the line and operated at the same time. The results indicate that the THD injected to the line current increases as the number of DSSC devices increase, which implies that for an adequate compensation with many DSSC devices distributed along a transmission line, a particular control algorithm is needed in order to avoid injection of harmonic distortions.

3. Coordinate Control of DSSCs

A controlled transmission line implemented with multiple DSSC modules can be used to increase the capacity of an existing AC transmission system and also control the flow of power. But coordination is needed in order to achieve the fastest response time as a group while minimizing the amount of distortion injected. In this section, different control strategies are discussed for controlling a group of DSSCs distributed along a transmission line while taking into account the effect of the DSSC devices on the rest of the power system. The system used to investigate the impact of different control strategies consists of 9 DSSC models placed equally apart from each other along each phase of a 138 kV transmission line as shown in Fig. 5. The transmission line is modeled by distributed parameters of a real transmission line mentioned in Table 1. The effect of each applied control strategy is evaluated using PSCAD/EMTDC software package.

3.1. Case 1

This case represents the most simple control strategy in which all the DSSCs distributed along the transmission line are switched on at the same time of t=0.2s and after being charged, start to compensate the line all at the same time . The DSSCs are also switched off as a group at the time of t=7.3s. Figures 6 to 9 show the simulation results of this control strategy for two different capacitive and inductive compensation of the line.

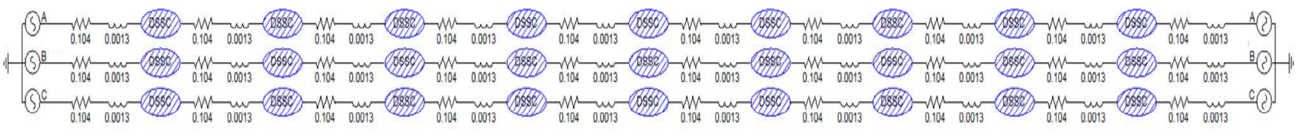

Fig. 5. System used to investigate the impact of different control strategies

The results of THD injection shown in Fig. 7 indicate that because in this control strategy all the DSSCs are switched on and charged at the same time, the maximum THD of the line current for each phase which is estimated to be 1.65%, equals to the sum of maximum THD injections of all the DSSCs distributed in each phase of the line.

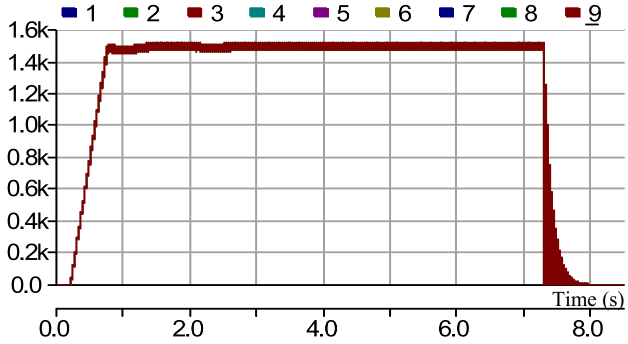

Fig. 6. Capacitor voltage variation of DSSCs on each phase

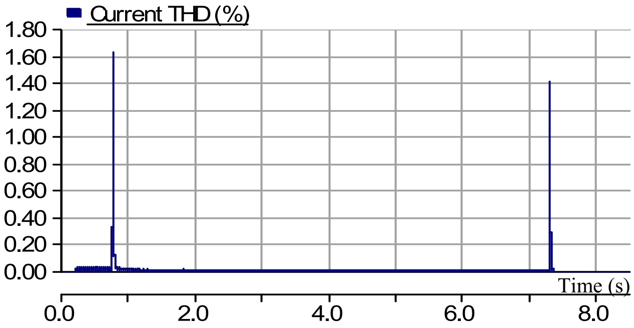

Fig. 7. THD injected by DSSCs to the line current

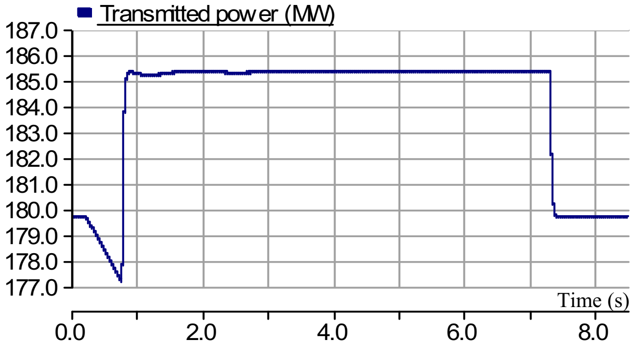

Fig. 8. Active power variation in capacitive mode

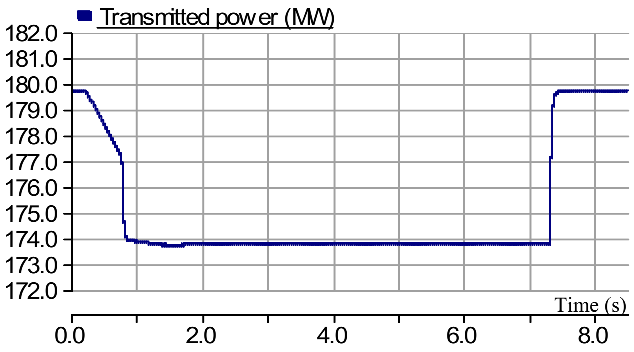

Fig. 9. Active power variation in inductive mode

Also it can be seen from Fig. 8 that in the capacitive compensation mode, in which the aim is to increase the active power being transmitted by compensating the line reactance, the transmitted power decreases by 2.48 MW as the DC bus capacitor of each DSSC module is being charged. This is because in this time period each DSSC acts as an active impedance and extracts active power from the line in order to increase the charge on its DC bus capacitor, hence the active power being transmitted is decreased for a short time. But after the capacitors are charged, the DSSCs begin to compensate the line reactance at t=0.8s, and the power is instantly increased by 8.13 MW which results in a 5.65 MW increase of power with respect to the power being transmitted before compensation. In the inductive compensation mode shown in Fig. 9, which the aim is to decrease the flow of power along the line, this control scheme has a fast and effective influence as it gradually reduces the active power flow by 2.48 MW while the capacitors are being charged and at t=0.8s the transmitted power is instantly reduced by another 3.44 MW as a result of quadrature voltage injection and inductive compensation.

3.2. Case 2

In this case only one DSSC in each phase is switched on at t=0.2s and the other DSSCs in each phase of the line are only switched on when the previous DSSC has been fully charged and started to compensate the line. The DSSCs in each phase are also turned off at t=7.3s with a 40ms time delay from each other in order to prevent THD injection overlap. The simulation results of this control strategy are shown in Fig. 10 to Fig. 13. Results illustrate that the response time which is defined here as the time from the first DSSC being switched on until the last DSSC of the group being fully charged, is very long compared to the previous case.

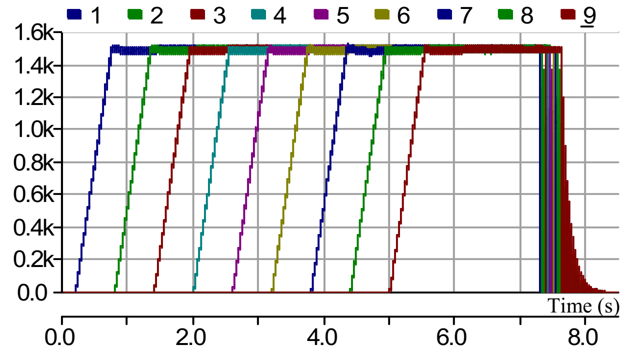

Fig. 10. Capacitor voltage variation of DSSCs on each phase

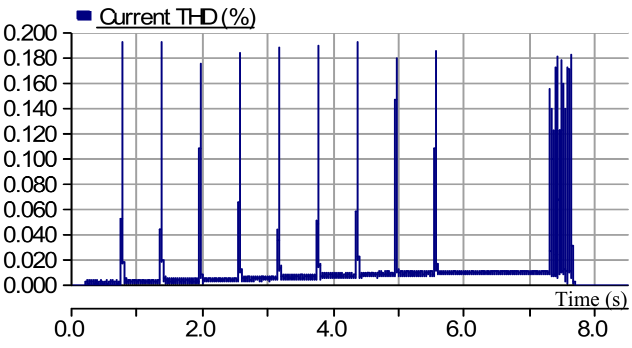

Fig. 11. THD injected by DSSCs to the line current

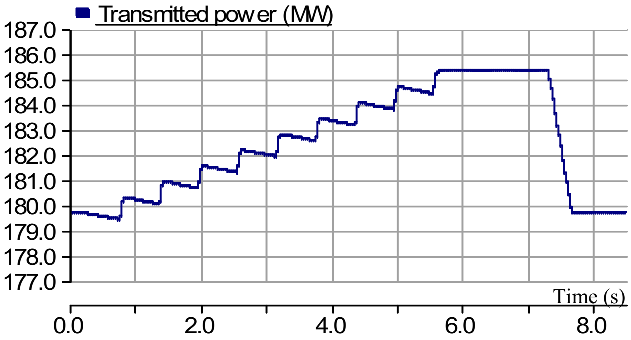

Fig. 12. Active power variation in capacitive mode

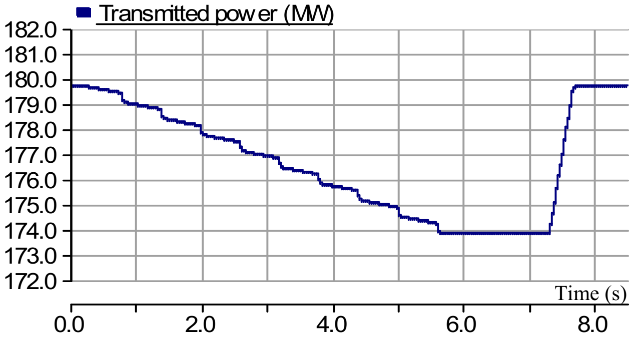

Fig. 13. Active power variation in inductive mode

Also because the DSSCs are switched and charged at different time intervals, the maximum THD injection as shown in Fig. 11 is minimized to a level of only 0.19% which is the same as the effect of one DSSC on each phase. It can be seen from Fig. 12 that the first DSSCs to be switched on in each phase reduce the power by 0.27 MW while being charged, and increase it by about 0.58 MW when compensating in capacitive mode. Therefore by applying this control strategy for capacitive compensation, the initial reduction in power flow is limited to only 0.27 MW.

3.3. Case 3

The results obtained from the two previous strategies indicate that in order to minimize the injection of harmonic distortion of DSSCs as a group, they should be controlled such that no two DSSCs in one phase are switched on at the same time and a time delay of about 40ms is adequate in order to prevent an overlap of maximum THD injection areas of the DSSC modules. It can also be noted that in the capacitive compensation mode neither of the two strategies discussed can simultaneously provide a fast response and minimize power flow tolerance. Therefore a third strategy is presented based on the results obtained from previous cases that when one DSSC on each phase is being charged, the power flow along the transmission line is decreased by 0.27 MW as a result of active power being extracted from the line in order to charge the DC bus capacitor, but on the other hand when the DSSC is fully charged and is operating in a capacitive compensation mode, its influence on increasing the power flow is about 0.58 MW. Hence the reduction effect of two DSSCs being charged can be cancelled out by one DSSC capacitively compensating the line, therefore for this control strategy, the number of DSSCs to be switched on at each time interval for each phase can be calculated by (1), simply by doubling the number of DSSCs already active and compensating the line.

$$M_n = \begin{cases} 1 & n = 1 \\ 2\sum_{x=1}^{n-1} M_x & n = 2,3,4\ldots \end{cases} \qquad (1)$$

Where Mn is the number of DSSCs switched on at each time interval (n). Also for each set of DSSCs switched on at the same time there is a 40ms time delay in order to eliminate the THD injection overlap and ensure a lower harmonic injection. The simulation results of this control strategy applied for capacitive and inductive compensation of the line are shown in Fig. 14 to Fig. 17 in which the number of DSSCs switched on in each phase for 3 time intervals are calculated and given in Table 2. Also the DSSCs are switched off with a 40ms time delay from each other at t=7.3s.

Table 2. DSSCs switch on time for 3 time intervals

Time Interval (n)	Number of DSSCs Switched on (Mn)	Switch on Time
1	1	0.2 sec
2	2	0.8 sec
		0.84 sec
3	6	1.44 sec
		1.48 sec
		1.52 sec
		1.56 sec
		1.60 sec
		1.64 sec

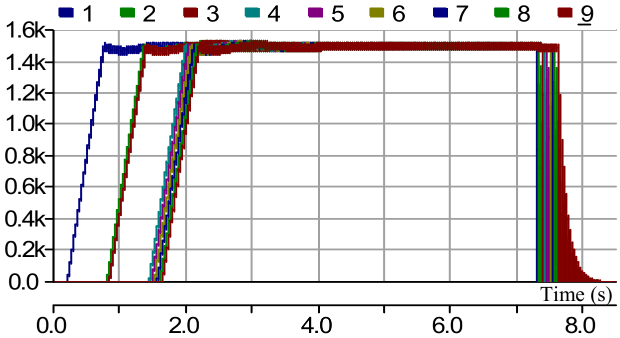

Fig. 14. Capacitor voltage variation of DSSCs on each phase

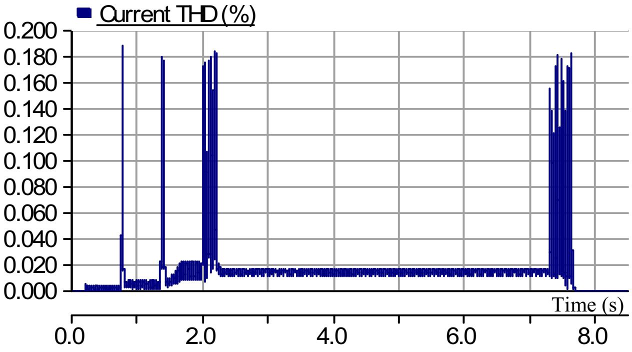

Fig. 15. THD injected by DSSCs to the line current

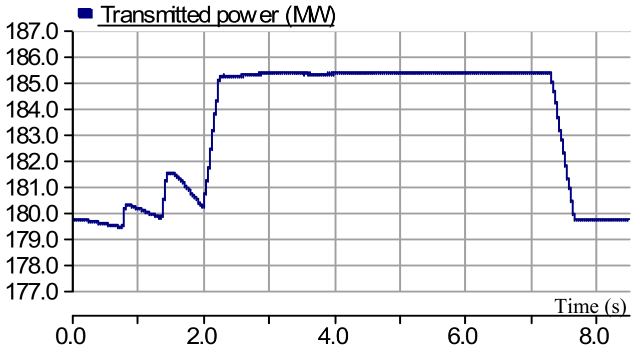

Fig. 16. Active power variation in capacitive mode

Fig. 17. Active power variation in inductive mode

The results indicate that with this control strategy applied, the amount of THD injection to the line current for both the capacitive and inductive compensation is kept well below 0.19%. Also in the capacitive compensation mode the power flow reduction at the beginning is limited to 0.27 MW which was also obtained by the second control strategy, but the advantage of this algorithm is that despite reducing the power flow tolerance it has a faster response time compared to the second control strategy.

4. Discussion

In order to compare the effect of each control strategy on power flow, response time and power quality, results obtained from each strategy are summarized in Table 3.

Table 3. Results of different control strategies

Control Strategies		**Strategy 1**	**Strategy 2**	**Strategy 3**
MAX THD Injection		1.65 %	0.19 %	0.19 %
Group Response Time		0.6 sec	5.4 sec	2.04 sec
Initial Power Flow Reduction in Capacitive Mode		2.48 MW	0.27 MW	0.27 MW
Total Change in Power Flow	Capacitive	+ 5.65 MW	+ 5.65 MW	+ 5.65 MW
	Inductive	- 5.92 MW	- 5.92 MW	- 5.92 MW

It can be seen from Table 3 that all the 3 strategies have the same effect on total power flow change but strategy 2 and 3 have the least power flow reduction in capacitive compensation mode and among these two, strategy 3 has the fastest group response time. Therefore if the aim of controlling a group of DSSCs operating in capacitive mode, is to minimize power flow tolerance and THD injection with an acceptable response time, strategy 3 has an advantage over the other two strategies discussed. As for the inductive compensation mode in which the aim is to decrease the flow of power, strategy one has the fastest response time but injects the most harmonic distortion to the line. However this harmonic injection can be decreased if the DSSCs are switched on with a 40ms time delay from each other and although this time delay will have an effect on the response time, but still strategy 1 would have the fastest response time compared to the other 2 strategies. Therefore in the inductive mode, strategy 1 (with some changes) seems to be the best control strategy applied to a group of DSSCs.

5. Conclusion

In this paper the effect of different strategies for controlling a group of DSSCs distributed along a transmission line have been discussed. Harmonic analysis of an electromagnetic model of a DSSC demonstrated that the harmonic distortion introduced by each DSSC device is maximum at a time when the DC bus capacitor is fully charged and the device is starting to inject a voltage that is almost in quadrature with the line current in order to compensate the line reactance. Simulation results indicate that one way of reducing harmonic injection of DSSC devices as a group is to allow a 40ms time delay between each switch on, in order to eliminate overlap of maximum harmonic injection zones. Also based on the simulation results of 3 different scenarios it is concluded that the best control strategy for controlling a group of DSSCs can be obtained by applying strategy 3 for capacitive compensation mode and strategy 1 (with some changes) for inductive compensation mode of operation.

6. References

[1] N. Hingorani, "Flexible AC Transmission," *IEEE Spectrum*, v. *30*, No. *4*, Apr. 1993, pp *40-45*.

[2] D. Divan, *et al*., "A Distributed Static Series Compensator System for Realizing Active Power Flow Control on Existing Power Lines," *Power System Conference and Exposition*, vol. *2*, pp. *654-661*, October 2004.

[3] D. Divan, "Improving Power Line Utilization and Performance with D-FACTS Devices," *Power Engineering Society General Meeting,* vol. *3*, pp. *2419-2424*, June 2005.

[4] D.J Marihart, "Communications Technology Guidelines for EMS/SCADA Systems," *IEEE Trans. Power Delivery*, Vol. *16*, No. *2*, pp. *181-188*, April 2001

[5] P. Fajri, *et al*., "A PSCAD/EMTDC Model for Distributed Static Series Compensator (DSSC)," *Second International Conference on Electrical Engineering (ICEE),* Lahore, Pakistan, 2008, pp. *1-6*.

[6] *Electrical Transmission and Distribution Reference Book*, Westinghouse Electrical, 1950.

[7] A.M. Gole, O.B. Nayak, T.S. Sidhu, M.S. Sachdev, "A Graphical Electromagnetic Simulation laboratory for Power system Engineering Programs*" IEEE Trans. on Power Systems*, Vol. *11*, No. *2*, pp. *599-606*, May 1996.