Reversing the Power Flow in the Looped Electrical Distribution Network by Using a Cascaded H-bridge D-SSSC

M.Saradarzadeh, S.Farhangi
School of Electrical and Computer Engineering
University of Tehran
Tehran, Iran
saradar@ut.ac.ir
farhangi@ut.ac.ir

J.L.Schanen, P-O.Jeannin, D.Frey
Laboratoire d'Electrotechnique de Grenoble
CNRS UMR 5529 INPG/UJF, Grenoble, France
jean-luc.schanen@grenoble-inp.fr
pierre-olivier.jeannin@g2elab.inpg.fr
frey@g2elab.grenoble-inp.fr

Abstract— **In new configuration of electrical distribution network the distributed generation is connected directly to the medium voltage link. For achieving the total generation of DGs the distribution network radial configuration is changed to the loop or meshed configuration by using a power electronic device in the connection point to control the power flow. *Distribution Static Synchronous Series Compensator* (D-SSSC) is able to control the power flow between two feeders from different substations. Thanks to use the multilevel converter topology, D-SSSC is connected directly to the line, omitting bulky transformer. Cascaded H-bridge is the best option for this kind of realization. Controlling the power flow in new configuration of electrical distribution system is source of advantages. One of the great impacts of D-SSSC is balancing the power flows of connected feeders, avoiding congestion of feeders and cables damages. This system sometimes needs to reverse the power flow in the line despite of the phase angle between the feeders. The conventional SSSC control strategy uses current phase to inject a voltage in phase with the current to maintain the DC bus voltage at its reference value and a quadratic component to control the power flow. This control strategy is fail to operation while the power reference is reversing due to loosing the current phase track at low and zero line current. In this paper the feasibility of a D-SSSC for reversing the power flow is discussed and a new control strategy based on voltage phase track is introduced.**

Cascaded H-bridge, D-SSSC, power flow control, phase locked loop

I. INTRODUCTION

The available electrical network is divided in three parts, generation, transmission and distribution. The customers' energy are produced in large power plants and transmitted via transmission lines near the consumption centers and then it is distributed among the customers by use of the electrical distribution network. But these days, by increasing amount of distributed power generations (DG's) which mainly connected to the distribution network, the new configuration starts to appear. The most important feature of this new system should be achieving the total amount of DG's energy. So the conventional radial distribution network is not able to handle these new demands and needs to change to loop or even meshed distribution network [1].

For avoiding the loop power flow, increasing the use of DGs and achieving the other benefits of looping the radial system, the separated feeders from different substations are connected together via a power electronic device. The FACTS device is the best option for this configuration. The D-SSSC, *Distribution Static Synchronous Series Compensator* is able to inject a voltage in series to the line to control the power flow between two feeders. This power flow controlling is the source of advantages like voltage regulation, losses reduction, avoiding congestion in the feeders, load sharing between feeders, increasing reliability and using the total amount of DG's generation [2]. The D-SSSC injected voltage to the line can be arranged in order to reverse the power flow despite of the phase angle between substations. This feature is so important in sharing the loads between connected feeders and it will be discussed more precisely by using some examples in section IV.

To connect the D-SSSC directly to the medium voltage network, the multilevel converter is used as a main topology omitting the heavy and bulky transformer [3]. Among the multilevel topologies the cascaded H- Bridge due to modularity and less elements is used as a desired topology.

Too many articles discussed the modeling and control of SSSC in the electrical transmission system [4]-[6]. In [7] the authors show the modeling and control ability of the D-SSSC in the electrical distribution system.

The conventional control strategy uses the phase angle of line current by a phase locked loop and injects a voltage in phase to line current to maintain the DC bus voltage and a voltage in quadrature to the line current for control the power flow. But when the power flow is going to reverse the line current PLL is not able to work properly due to the low and zero current at that point. Losing the line current phase track will fail the whole control strategy. In this paper the electrical distribution system modeling for reversing the power flow is discussed and a new control strategy based on tracking the phase of feeder voltage is proposed. The feasibility of this method to reverse the power flow is demonstrated via simulation results. A real part of Tehran electrical distribution network is used for simulation results.

II. SYSTEM MODELING

Fig. 1 shows the electrical distribution system models which two feeders from different substations are connected via a D-SSSC together. The three phase expression of the time domain is defined in (1).

$$
\begin{aligned}
\left[V_{main1\_abc}\right] &= (R_{l1}+L_{l1}p)\left((\sum_{n=1}^{k-1}\left[i_{loadn\_abc}\right]) + \left[i_{linek\_abc}\right]\right) \\
&+(R_{l2}+L_{l2}p)\left((\sum_{n=2}^{k-1}\left[i_{loadn\_abc}\right]) + \left[i_{linek\_abc}\right]\right)+\dots \\
&+(R_{lk}+L_{lk}p)\left[i_{linek\_abc}\right]-\left[V_{S\_abc}\right] \\
&+(R_{l(k+1)}+L_{l(k+1)}p)\left(\left[i_{linek\_abc}\right]-\left[i_{loadk\_abc}\right]\right)+\dots \\
&+(R_{lm}+L_{lm}p)\left(\left[i_{linek\_abc}\right]-\sum_{n=0}^{m-1-k}\left[i_{load(k+n)\_abc}\right]\right) \\
&+(R_{l(m+1)}+L_{l(m+1)}p)\left(\left[i_{linek\_abc}\right]-\sum_{n=0}^{m-k}\left[i_{load(k+n)\_abc}\right]\right) \\
&+\left[V_{main2\_abc}\right]
\end{aligned}
\tag{1}
$$

Where V_{main_abc} is the substation three phase voltages, L_l and R_l are represented for the line reactance and resistance respectively. m is the number of loads which is connected to the feeders and the D-SSSC is placed in the K branch. By arranging (1) according to the loads and the k branch currents, (2) will be obtained. Transferring (2) into the dq rotating frame leads to achieve (3).

$$
\begin{aligned}
\left[V_{main1\_abc}\right] &= \left[V_{main2\_abc}\right]-\left[V_{S\_abc}\right] \\
&+\sum_{j=1}^{k-1}\left((\sum_{n=1}^{j}(R_{\ln}+L_{\ln}p))\left[i_{loadj\_abc}\right]\right) \\
&-\sum_{j=k}^{m}\left((\sum_{n=j+1}^{m+1}(R_{\ln}+L_{\ln}p))\left[i_{loadj\_abc}\right]\right) \\
&+(\sum_{n=1}^{m+1}(R_{\ln}+L_{\ln}p))\left[i_{linek\_abc}\right]
\end{aligned}
\tag{2}
$$

By considering the $i_q = 0$ equation (4) is obtained. Using (4) the active and reactive power flow are shown in (5) and (6). As we see the line current between the feeders is related to the difference voltage between the ends of feeders and the injected voltage.

$$
\begin{aligned}
\left[V_{main1\_dq}\right] &= \left[V_{main2\_dq}\right]-\left[V_{S\_dq}\right] \\
&+\sum_{j=1}^{k-1}\left(\begin{bmatrix} \sum_{n=1}^{j}(R_{\ln}+L_{\ln}p) & -\omega\sum_{n=1}^{j}L_{\ln} \\ +\omega\sum_{n=1}^{j}L_{\ln} & \sum_{n=1}^{j}(R_{\ln}+L_{\ln}p)\end{bmatrix}\left[i_{loadj\_dq}\right]\right) \\
&-\sum_{j=k}^{m}\left(\begin{bmatrix} \sum_{n=j+1}^{m+1}(R_{\ln}+L_{\ln}p) & -\omega\sum_{n=j+1}^{m+1}L_{\ln} \\ +\omega\sum_{n=j+1}^{m+1}L_{\ln} & \sum_{n=j+1}^{m+1}(R_{\ln}+L_{\ln}p)\end{bmatrix}\left[i_{loadj\_dq}\right]\right) \\
&+\begin{bmatrix} \sum_{n=1}^{m+1}(R_{\ln}+L_{\ln}p) & -\omega\sum_{n=1}^{m+1}L_{\ln} \\ +\omega\sum_{n=1}^{m+1}L_{\ln} & \sum_{n=1}^{m+1}(R_{\ln}+L_{\ln}p)\end{bmatrix}\left[i_{linek\_dq}\right]
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
i_{linek\_d} &= \frac{1}{+\omega\sum_{n=1}^{m+1}L_{\ln}}(-V_{S\_q}+ \\
&\left(V_{main1\_q}-\sum_{j=1}^{k-1}\left((\omega\sum_{n=1}^{j}L_{\ln})i_{loadj\_d}+(\sum_{n=1}^{j}(R_{\ln}+L_{\ln}p))i_{loadj\_q}\right)\right)- \\
&\left(V_{main2\_q}-\sum_{j=k}^{m}\left((\omega\sum_{n=j+1}^{m+1}L_{\ln})i_{loadj\_d}+(\sum_{n=j+1}^{m+1}(R_{\ln}+L_{\ln}p))i_{loadj\_q}\right)\right))
\end{aligned}
\tag{4}
$$

$$P_k(s)=\frac{3}{2}V_{k\_d}(s).i_{linek\_d}(s) \tag{5}$$

$$Q_k(s)=-\frac{3}{2}V_{k\_q}(s).i_{linek\_d}(s) \tag{6}$$

As shown in (4), when the injected voltage is more than the difference of this voltage the current sign and so the power flow is reversing.

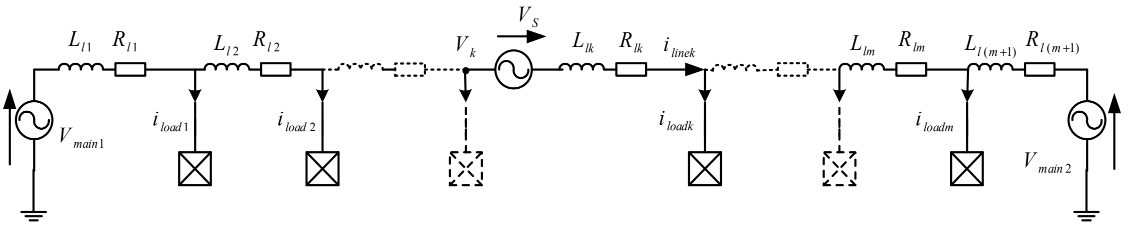

Figure 1. Loop configuration of electrical distribution system

III. CONTROL STRATEGY

The main control strategy which is used for control the power flow in the electrical distribution system is showed in Fig. 2. As a result of not including any auxiliary source power this strategy can control only the active or reactive parts of power flow. This control strategy uses two control loop, one for maintaining the DC bus voltage at its reference value which produces the in phase part of injected voltage with the line current and the second loop, control the amount of power flow in the connected line which makes the quadratic part of injected voltage with current. The reference current, active or reactive power is compared with the actual value and passing through a PI controller generates the quadratic part amplitude. To increase the power flow the D-SSSC acts as a capacitor impedance compensating the line impedance while to decrease the power flow it acts as a inductive impedance which is added to the line impedance. The PI output controller is used to identify the mode of operation. The reference DC bus voltage is compared with actual DC bus voltage and using another PI controller the amplitude of in phase part of injected voltage is produced. This control strategy has good results while the power flow is positive and current phase locked loop works well. But in crossing from the zero current for reversing the power flow the PLL is not able to produce the well results and lose the current phase track which causes the mal function of whole control system. Also because of changing the phase of line current after reversing the power flow another 180° should be added to control loop. Actually the D-SSSC acts as capacitive impedance in two times of operation. Once in the positive power flow controlling which the injected voltage is less than the difference voltages of feeders ends and second in the reversed power flow which the injected voltage is more than the difference voltages of feeders ends. So when the power flow is going to reverse the injected voltage needs to change from inductive mode to capacitive mode. These problems are more challenging when the system is going to implement.

So for solving this problem another control strategy is proposed which uses the phase of feeder voltage instead of current phase. As a result of not having the current phase, it is not possible to maintain the DC bus voltage by controlling the in phase part of injected voltage directly. So the new control strategy which is showed in Fig. 3 uses the variable DC bus voltage. The active power or current is compared to the actual value and passing a PI controller the voltage reference is produced. In this control strategy, the DC bus voltage is not fixed and varies by the changing in power flow while the modulation index is fixed at (0.9). This reference is compared with the actual DC bus voltage value and using another PI controller, a phase displacement γ is obtained. As a result of having one of feeder voltages close to the injected voltage, it is easy to use it as a reference for phase synchronization. Note that the feeder voltage unlike the feeder current has no changes during reversal of power flow and becomes a good choice for synchronization. The same control strategy like Fig. 3 with current PLL is achievable [7] while it is suitable for one direction power flow demanding. In this strategy the DC bus voltage is more than the difference voltages between feeders at connection point when the power flow is reversed. Also using the voltage phase, there is no need to change the control strategy while power flow is reversed.

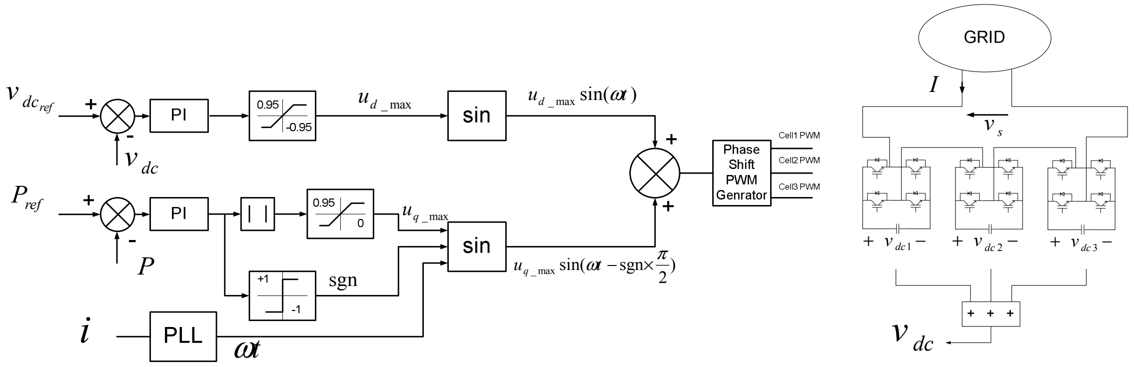

Figure 2. Power flow control with current phase locked loop

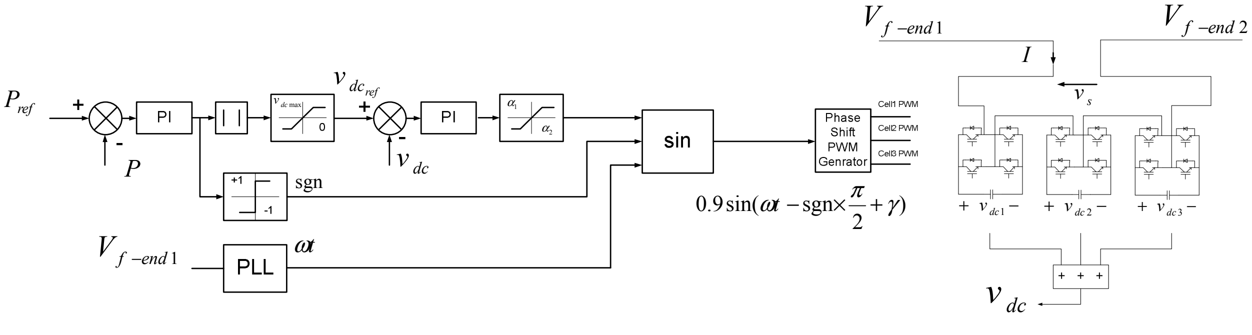

Figure 3. Power flow control with voltage phase locked loop

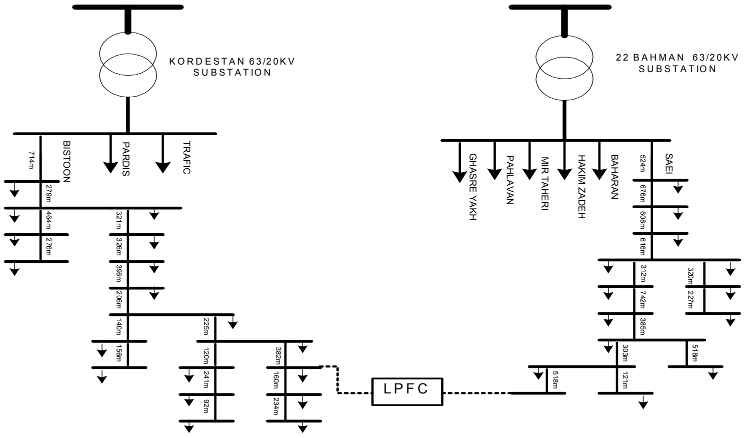

Figure 4. loop connection between “KORDESTAN” and “BAHMAN” substations in Tehran distribution network

IV. SIMULATION RESULTS

Fig. 4 shows a part of Tehran electrical distribution system which SAEI feeder from BAHMAN substation is connected to the BISTOON feeder from KORDESTAN substation via a D-SSSC. Fig. 5 shows the power flow for control strategy in Fig. 2 which uses the current phase. There is a step change from 500KW to -1500KW at the time 3 second which reverses the power flow. The DC bus voltage reference is set to 2500 Volt to fulfill the power flow reversing requirements. Fig. 6 shows the DC bus voltage and line current for this strategy. As it is clear this strategy fails to reverse the power flow.

Fig. 7 shows the power flow between the feeders for the same changes for the proposed control strategy which uses the voltage phase as phase synchronization. The results show the feasibility of this control strategy to reverse the power flow and the power flow follows its reference value properly.

Fig. 8 shows the DC bus voltage and line current for the proposed strategy which shows the DC bus voltage is more than the difference voltage of feeders when the power flow is reversed. Fig. 9 shows the injected voltage and line current for two modes of operation. In Fig. 9 the D-SSSC acts as inductive impedance at 500KW power flow and acts as capacitive impedance at -1500KW. As we mentioned before the D-SSSC acts as capacitive impedance in two mode, one in the direct power flow (injected voltage is less than the difference voltage) and another in the reverse power flow (injected voltage is more than the difference voltage).

For showing the benefits of an electrical distribution system which has an ability to reverse the power flow the following examples are considered.

One of the most suffering issues in the electrical distribution system is the unpredictability of load demands which sometimes follows damages to the cables and too much time network unavailability to fix the problems. Looping two feeders from different substations will help to balance the power between them. Assuming that each feeder is connected to different kinds of loads (residential, commercial, industrial) which do not have the same load demands at each time. Fig. 10 shows the active power of two connected feeders via a D-SSSC when the BISTOON feeder has a large power demands while the SAEI feeder load demands is not a large value. At the time before one second the transmitted power is zero. In this case by controlling the power flow between two feeders in +1000KW the two feeders have the same load demands. In Fig. 11 the SAEI feeder has a very large power demand and the BISTOON feeder has not too much load demands at that time. When the transmitted power flow is zero, the SAEI Feeder demands almost 2700KW and BISTOON feeder demands about 600KW. By controlling the transmitted power on -1100KW the two feeders are loaded almost the same manner.

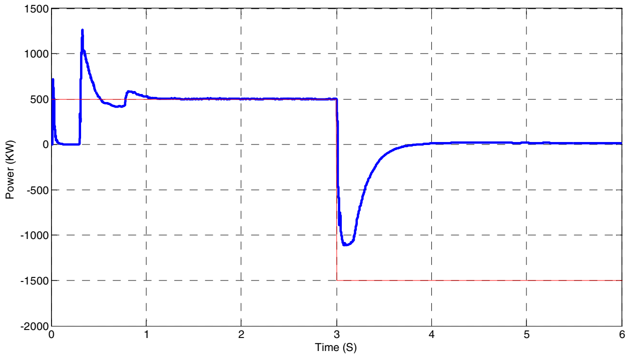

Figure 5. Power flow between two feeders for conventional strategy

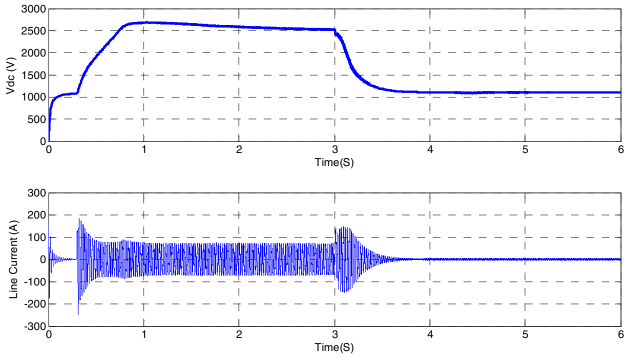

Figure 6. DC bus voltage and line current for conventional strategy

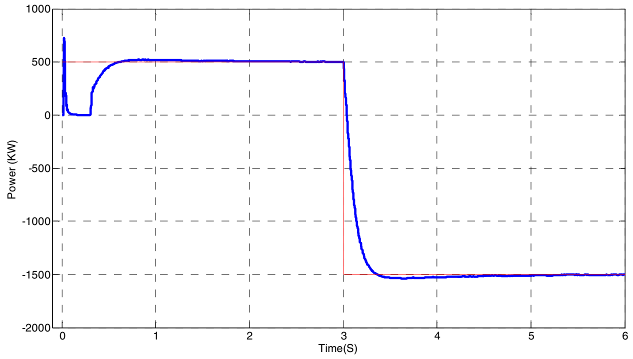

Figure 7. Power flow between two feeders for proposed control strategy

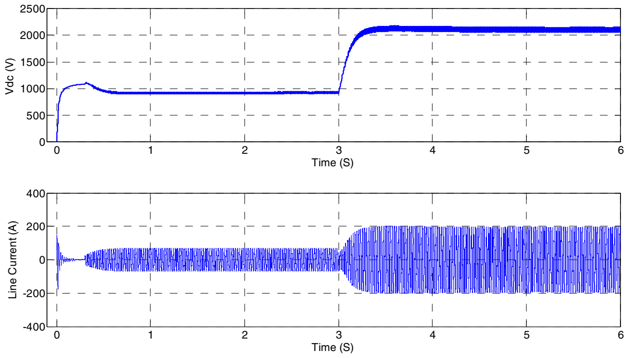

Figure 8. DC bus voltage and line current for proposed control strategy

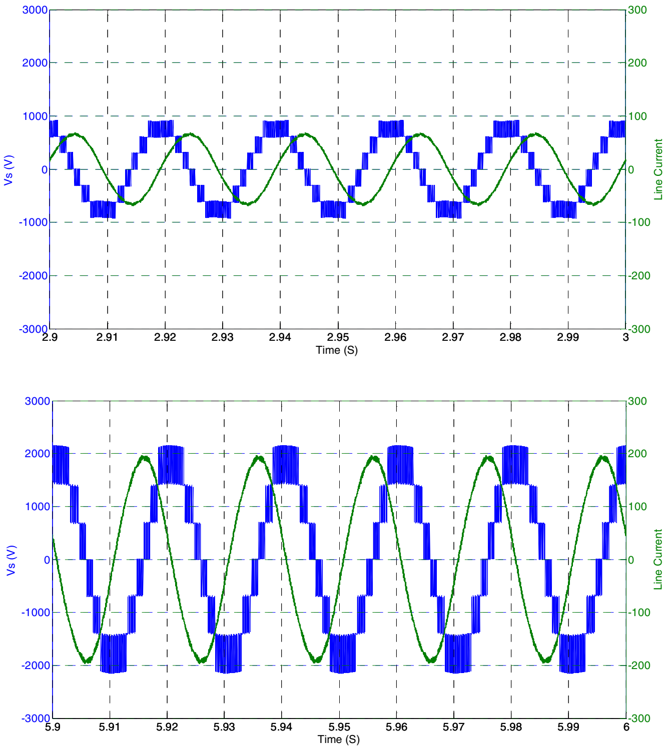

Figure 9. Injected voltage and line current a: Direct power flow b: Reverse power flow

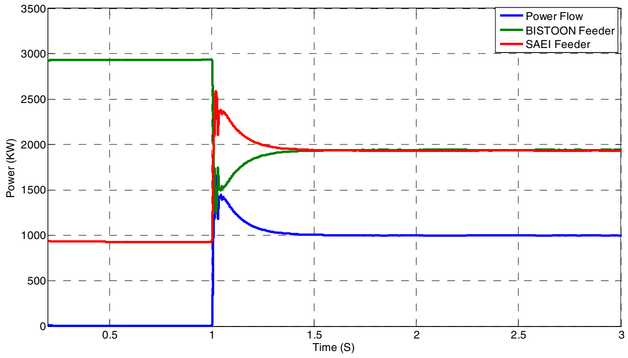

Figure 10. Feeder Power flows and transmitted power when BISTOON feeder is high loaded

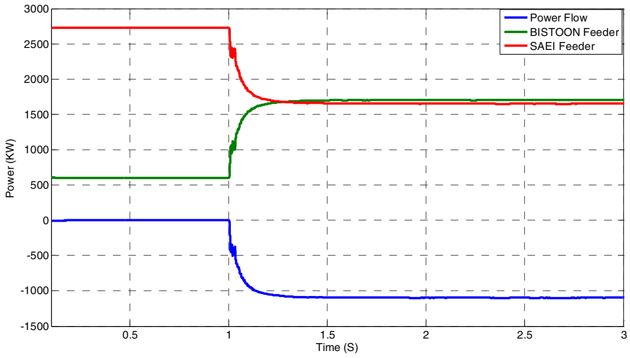

Figure 11. Feeder Power flows and transmitted power when SAEI feeder is high loaded

V. DESIGN TOPOLOGY

For connecting the D-SSSC directly to the medium voltage and omitting the bulky transformer, the multilevel converter is the best choice. The most famous topologies are diode clamp, flying capacitor and cascaded H-bridge converters. Cascaded H-bridge as results of its modularity, simple control and less elements is the best choice for this application while its major drawback is DC bus voltages unbalancing [8]. Fig. 12 shows a seven level cascaded H-bridge which is used as a D-SSSC in series to line. Each phase consists of 3 cells which should be designed for the $V_{DC}/3$ voltage. The maximum DC bus voltage is specified by the maximum amount of reversing power.

Too many modulation strategies can be used for switching modulation like Phase Shift Carrier PWM, Phase Disposition Carrier PWM, Phase Opposition Disposition Carrier PWM and etc. Phase Shift Carrier PWM is able to cancel the entire carrier and their side bands up to $2N$ th carrier group while N is the number of cells [9]. Each cell carrier is shifted by $180^\circ/N$ and compared with the sinusoidal and its 180° phase shifted reference to produced switching commands. Fig. 13 shows the carriers signals and reference voltage for the Phase Shift Carrier PWM.

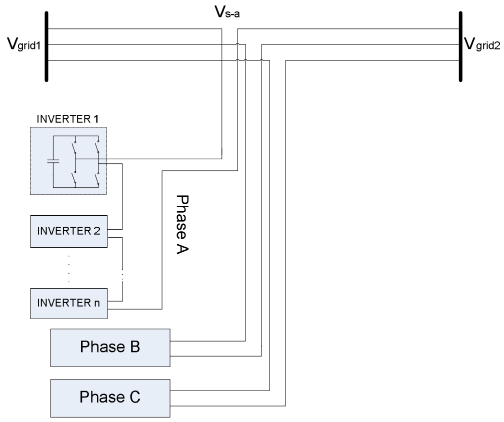

Figure 12. Seven level cascaded H-bridge D-SSSC

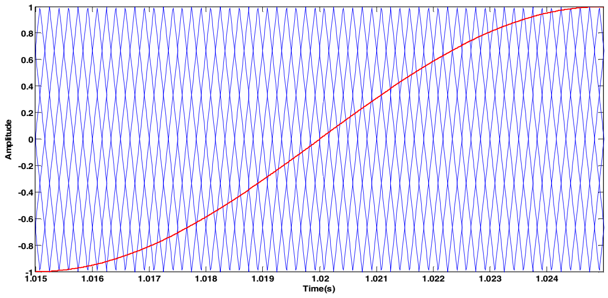

Figure 13. Phase Shift Carrier PWM

VI. CONCLUSION

In this paper modeling and power flow control of a D-SSSC in the electrical distribution system is discussed. The D-SSSC is used to control the power flow between two feeders from different substations. The new control strategy is designed to reverse the power flow properly. This strategy uses one of the feeders' voltages to obtain the synchronization phase by a PLL unlike the strategies which use the line current for phase synchronization. Due to not having the line current phase directly the controller has to have a variable DC bus voltage. A seven level cascaded H-bridge is used as a D-SSSC and the control strategy is simulated in a part of Tehran electrical distribution system which shows proper results especially in the reversal of power flow.

REFERENCES

[1] G. Celli, F. Pilo, G. Pisano, V. Allegranza, R. Cicoria, "Distribution Network Interconnection for Facilitating the Diffusion of Distributed Generation," *in Proc. 2005* International Conference on Electricity Distribution

[2] M.Saradarzadeh, S.Farhangi, J.L.Schanen, P-O.Jeannin, D.Frey, "The benefits of looping a radial distribution system with a power flow controller," in *Proc. IEEE Power and Energy conf.* (PECON 2010), Malaysia, Nov 29-Dec 1, 2010, pp. 723-728.

[3] Rodriguez, J.-S. Lai, and F. Z. Peng, "Multilevel inverters: A survey of topologies, controls, and applications," *IEEE Trans. Ind. Electron.*, vol. 49, no. 4, pp. 724–738, Aug. 2002.

[4] 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 Del.*, vol. 12, no. 1, pp. 406–417, Jan. 1997.

[5] K. K. Sen, "Static synchronous series compensator: Theory modeling and applications," *IEEE Trans. Power Del.*, vol. 13, no. 1, pp. 241–246, Jan. 1998.

[6] J. M. Gonzalez, C. A. Canizares, J. M. Ramirez, "Stability Modeling and Comparative Study of Series Vectorial Compensators," *IEEE Trans. Power Del.*, vol. 25, no. 2, pp. 1093–1103, April 2010.

[7] M.Saradarzadeh, S.Farhangi, J.L.Schanen, P-O.Jeannin, D.Frey, "Using Cascaded H-Bridge D-SSSC to Control Power Flow in the Electrical Distribution System," unpublished.

[8] M.Saradarzadeh, S.Farhangi, J.L.Schanen, P-O.Jeannin, "A Novel Fuzzy Logic DC Bus Voltage Balancing Controller for a D-SSSC Cascaded H-bridge Converter," *in Proc.* Power Electronic & Drive Systems & Technologies Conference (PEDSTC), 2010

[9] B. P. McGrath and D. G. Holmes, "Multicarrier PWM strategies for multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 49, no. 4, pp. 858–867, Aug. 2002.