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A Novel Method to Increase the Power Capacity of Transmission Lines Using Transformerless Static Synchronous Series Compensator

Mohammad Ghorbani*, Ali Zarein, Ali Mosallanejad

Department of Electrical Engineering, Shahid Beheshti University, Tehran, Iran, Mohamad.ghorbani@ymail.com

Abstract

In this paper a transformerless Static Synchronous Series Compensator (SSSC) to increase the power capacity of a 230 kV transmission line is proposed. In order to eliminate the transformer, a 15-level cascade H Bridge (CHB) inverter is employed within the proposed compensator structure to inject reactive power to the transmission line. The theory of instantaneous p-q power using in the compensator is in such a way that allows for the system to be controlled in one phase. However, this method is used with three-phase systems. The proposed control method is also able to balance the voltage of dc-link capacitors at a desirable level. Modulation technique used by the inverter is Phase-Shifted PWM. In order to validate the proposed compensator's application, a three-phase transmission line is tested by MATLAB software. The transmitted active power of this transmission line is equal to 160 MW. The results obtained from a dynamic simulation are presented. Simulation results indicated 39% increase in the transmitted active power of the line.

Keywords: cascade H bridge multilevel inverter, Flexible ac transmission system (FACTS), Instantaneous pq theory, static synchronous series compensator (SSSC), Transformerless
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1. Introduction

In the recent years, taking into consideration the growing increase in the demand for electrical power and the rising costs of installing new transmission lines, idea of increasing the transmission lines capacity particularly by FACTS devices has intrigued researchers. FACTS can be installed either in parallel or in series. The SSSC is a series device, first introduced by Gyugyi in 1989 [1].

In [2] a SSSC coupled with a transformer was compared with Controllable series compensation (CSC). In spite of the fact that SSSC and CSC both are employed to increase transmission capacity of a line, they differ in terms of their exact application. SSSC is indeed a controlled reactive voltage source and CSC, controlled impedance. When compared, SSSC is found to be of much higher compensatory power, in particular when current is small. Therefore, SSSC is more suitable for reactive power control. Series devices are commonly embedded in the line by an isolation transformer.

In [3], a SSSC based hybrid series-capacitive compensation scheme is investigated for damping subsynchronous resonance oscillations. Also, [4] analyzes the subsynchronous resonance (SSR) characteristics of the hybrid series compensated power system and proposes a simple method for the extraction of subsynchronous components of line current using filter. In both of these papers, a coupling series transformer is used in SSSC to inject series voltage into the transmission line, as shown in Fig. 1.

[5] Presents the comparative results on stability improvement of an offshore wind farm fed to a synchronous generator based power system using SSSC and a series vectorial compensator (SVeC**)**. this structure also has a coupling transformer.

Since transformers increase volume and cost of a system, their removals undoubtedly will help to enhance the system proportions and cost effectiveness. With recent advances in technology and manufacture of power electronics devices of considerably high voltage and nominal power, the notion of creating tranfomerless compensators to be used by transmission lines seems feasible.

Most studies carried out so far into tranformerless compensators have their focus placed on parallel devices such as STATCOM [6, 7 & 8]. The only work on tranformerless SSSC was performed in 1998, using a diode clamped voltage source inverter [9]. Owing to its large number of power electronics devices on high voltage levels, this structure appears not to be cost-effective.

In enhancing the transmission capacity, this study proposed a transformerless SSSC based on a 15-level CHB inverter. Multilevel inverters deliver such advantages as symmetrical structure, helping to reduce voltage stress on switches, lower harmonics and less number of devices and these merits make them appropriate for high power levels [10]. Furthermore, this study proposed a control algorithm employing the theory of instantaneous p-q power [11, 12]. The theory tends to be employed by three-phase systems; however, in this paper it is used in each phase separately. In addition, unbalance compensation of the voltage of dc-link capacitors was also taken into account in the control circuit. Moreover, P-S PWM technique is employed to achieve lower THD in the inverter's output voltage.

The proposed transformerless SSSC with nominal values of 19.63 kV and 11.03Mvar together with the foregoing control method were simulated to compensate a 230 kV transmission line. Results of dynamic simulation are presented. Simulation results indicated an increase of transmission line active power.

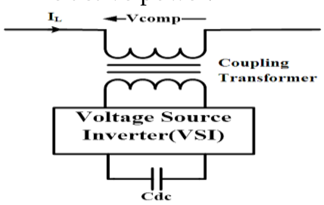

Fig. 1. Structure of SSSC

2. Proposed Structure

The proposed system's single line diagram is presented in Fig. 2. The system is consist of an infinite busbar (busbar 1) with a voltage source Vs1, balanced three-phase load that connected to the busbar 2, series reactance of line 1-2 (XL1), series reactance of line 2-3 (XL2), PV busbar (busbar 3) that fixed the load voltage at reference value with source Vs2 and transformerless SSSC at the middle of the line 1-2.

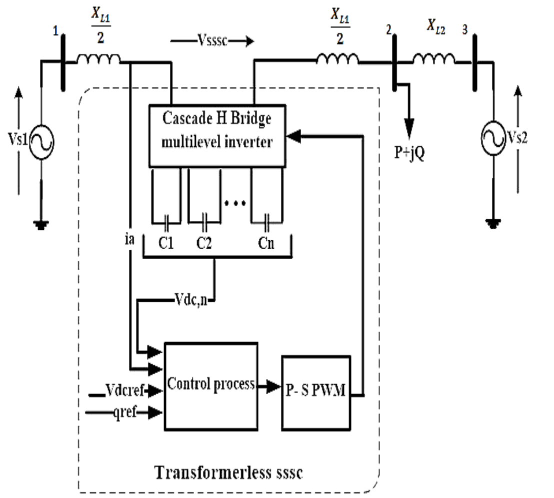

Fig. 2. Single line diagram of the proposed system

A) *SSSC Performance Principles*

Since SSSC is a series reactive power compensator based on voltage source inverter with no power source, a controlled voltage with $\pm 90^{\circ}$ out of phase with regard to the line current is applied to the transmission line. If the line current is assumed the following:

$$i_{line} = I_{line} \sin(\omega t + \theta_i) \quad (1)$$

hence the voltage of the SSSC can be achived by:

$$v_{sssc} = V_{sssc} \sin(\omega t + \theta_i \pm 90^{\circ}) \quad (2)$$

In other words, SSSC can be regarded as either variable capacitor or inductor depending on its generated voltage to be lead/lag .

The transmitted active power through the line is obtained from the below equation:

$$P_t = \frac{V_s V_r \sin(\varphi_s - \varphi_r)}{X_l} \quad (3)$$

Where V1 and V2 represent the voltage of the line's head and end respectively. $\phi_1 - \phi_2$ denotes the phase difference between the foregoing voltages. Considering the inverse relationship of XL1 and transmitted active power, with decrease the XL1 by SSSC, the transmitted active power increases.

B) *Design of SSSC*

In designing a compensator, first stage is to determine the number of H-bridges required by inverter to achieve a desirable voltage level. Before compensation, in the line 1-2 due to its high reactive losses, it can be transmitted only 68% of active power that load required. Therefore SSSC will be designed for compensate 70% of the reactive losses of line 1-2, hence the nominal values of transformerless SSSC is equal to

19.63kV and 11.03Mvar, based on reactive losses in line 1-2. Since GTOs capable of tolerating the maximum voltage 4.5 kV are readily available, the number of H-bridges is 6.17 calculated from (4):

$$H=\frac{V_{linkdc,max}}{V_{GTO}} \quad (4)$$

Therefore the number of H-bridges shall be considered 7, so the level number of CHB inverter can be calculated as follows:

$$m=2H+1 \quad (5)$$

According to (5), the level number of inverter is equal to 15. Fig.3. shows the configuration of CHB multilevel inverter.

Next stage is to calculate the minimum capacity of dc-link capacitors. 3.89 mF is obtained from (6).

$$C_{dc}=\frac{S_N}{f_{cr}V_{dc}^2} \quad (6)$$

3. Control System

Diagram block of control algorithm is shown by Fig. 4. As can be seen, the instantaneous p-q power theory has been defined in one phase and each phase is a application independent of the other phases. So the current obtained from equation 1 for each phase is embedded in the control algorithm as below:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 \\ 1\angle 120^\circ \\ 1\angle 240^\circ \end{bmatrix} i_{line} \quad (7)$$

Considering the instantaneous p-q power method, the matrix of compensator voltage can be expressed as below[12]:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \frac{1}{i_\alpha^2+i_\beta^2} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (8)$$

Where i_α and i_β can be obtained by applying Clarke Transformation in (7). Furthermore, p and q are reference active and reactive power in compensator terminal. Such as (7) for voltages, it can be written that:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 \\ 1\angle 120^\circ \\ 1\angle 240^\circ \end{bmatrix} V_{ref} \quad (9)$$

And then reference voltage of the compensator is obtained:

$$V_{ref}=\sqrt{\frac{2}{3}}\left(\frac{i_\alpha}{i_\alpha^2+i_\beta^2}p-\frac{i_\beta}{i_\alpha^2+i_\beta^2}q\right) \quad (10)$$

Since SSSC mainly is designed only for active power flow, it is concluded that:

$$p=p_{ref}=0 \ , \ q=q_{ref} \quad (11)$$

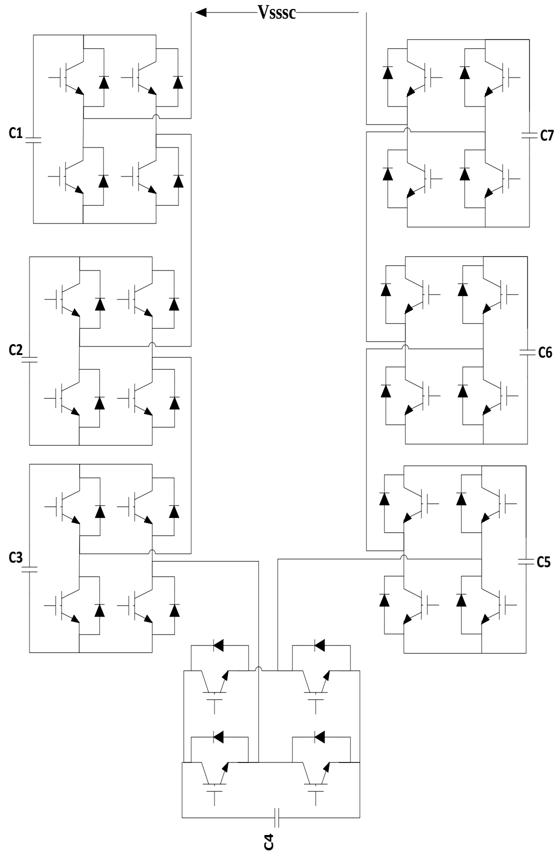

Fig. 3. Configuration of the multilevel inverter

4. Voltage Balancing of the Capacitors

Capacitors used in H-bridge cells are charged by the line's active power. The control signal $p_{loss,n}$ is generated by comparing the calculated voltage of capacitor's terminal with the reference voltage. This signal is sent, after passing through the PI controller, to the control algorithm for dc-link voltage balance to be maintained.

$$p_{loss,n}=V_{dc,ref}-V_{dc,n}\left(K_p+\frac{K_i}{s}\right) \quad (12)$$

Where $p_{loss,n}$, $v_{dc,ref}$ and $v_{dc,n}$ represent the power required to preserve the balance of capacitor voltage, reference voltage and voltage of dc-link capacitors, respectively. By using (10) and (12), therefore, reference voltage can be defined as below:

$$V_{ref,n}=\sqrt{\frac{2}{3}}\left(\frac{i_\alpha}{i_\alpha^2+i_\beta^2}p_{loss,n}-\frac{i_\beta}{i_\alpha^2+i_\beta^2}q_{ref}\right) \quad (13)$$

These voltages are directly sent, as reference, to PWM method in order to produce switching pulses.

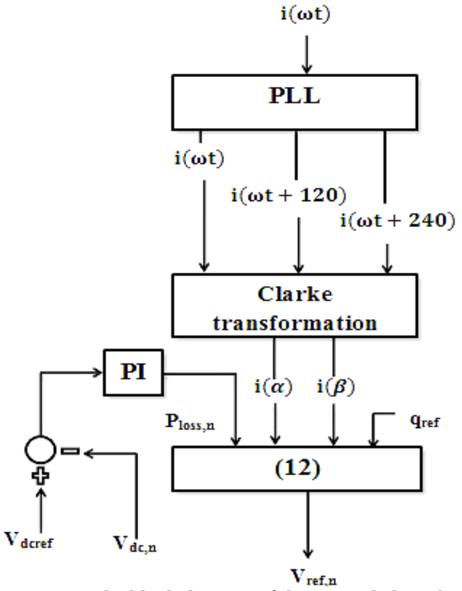

Fig. 4. The block diagram of the Control algorithm

5. Switching Pattern

Order to producing switching pulses of the 15 levels CHB inverter, P-S PWM technique is preferred due to its better output harmonic response. Fig. 5 shows the P-S PWM technique and switching pattern which is employed to each bridge of CHB inverter.

As it is obvious in Fig. 5, to control each H-bridge, two triangular carrier signals with 180°phase shifted but the same frequency and magnitude are required. Therefore, 14 carrier signals are needed to control each phase of the inverter.

Regarding to (14), carrier signals of the adjacent bridges reveal 25.7° phase shifted [13]:

$$\varphi_{cr}=\frac{360^{\circ}}{(m-1)} \qquad (14)$$

Where φ_{cr} represents the angle between the adjacent carriers signals.

6. Simulation Results

To investigate the proposed compensator's application, a transmission line with specifications according to table.1 is simulated by MATLAB.

To achieve the maximum increase in capacity of line 1-2 in the simulation, the compensator's generated reactive power is set to the capacitor maximum mode. So that, the line before 0.2 seconds has no compensator and then the SSSC is introduced to the circuit to inject the 11.03 MVar reactive powers to the line.

The compensator's instantaneous active and reactive powers are presented by Fig. 6& 7, respectively.

As Fig. 6 illustrates, the active power consumed to charge dc-link capacitors can be overlooked in comparison to the reactive power generated by the SSSC.

As depicted in Fig. 6& 7, the power generated by the transformerless SSSC compares favourably in terms of power quality and response speed with series compensators which are connected to the grid by transformer [14].

Fig. 8 presents the transmitted active power of line 1-2. Apparently, introducing the compensator at the moment of 0.2 S makes the transmitted active power increase from 53.24 to 74.09 MW. This value is equal to 39% of active power increasing in the line. Fig. 9 also presents the transformerless SSSC's waveform of three-phase output voltage in the capacitor maximum mode.Fig.10 provides an FFT analysis of the waveform of the phase a voltage. It is clear that this voltage having an acceptable THD of 3.99% possesses a more appropriate harmonic spectrum than those of other modulation methods.Fig. 11 shows proper application of the control system in balancing charge voltage of the capacitors. Since the speed of circuit stability depends on its capacitor's charging duration, therefore the voltage of capacitors reach to their ultimate value in a short time period of 0.1 S with an acceptable ripple of 6%.

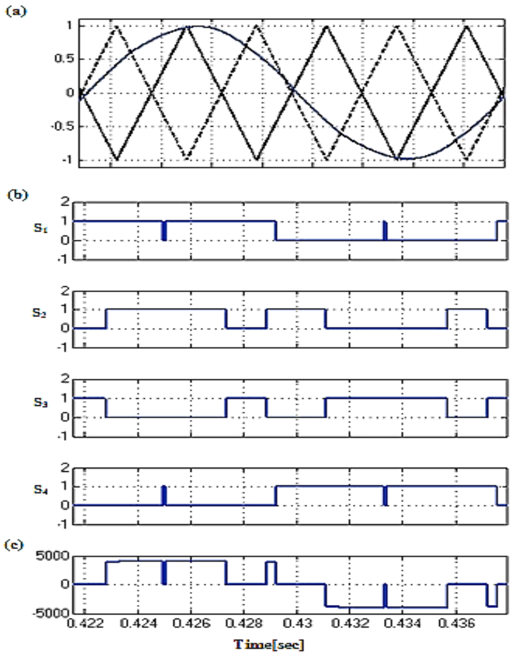

Fig. 5. P-S PWM technique to create switching signals for each bridge of CHB inverter: (a) carrier signals, (b) switching pattern, (c) equivalent modulated Signal

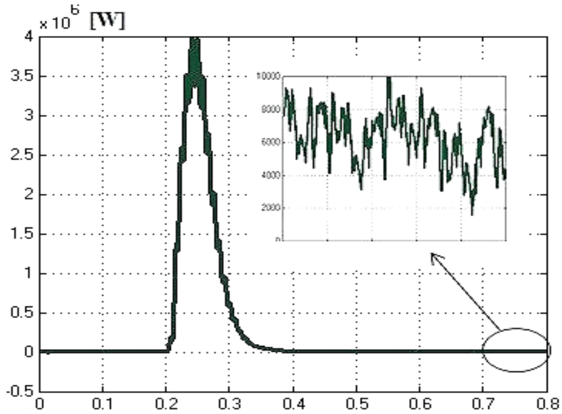

Fig. 6. Instantaneous active power of the Trasformerless SSSC

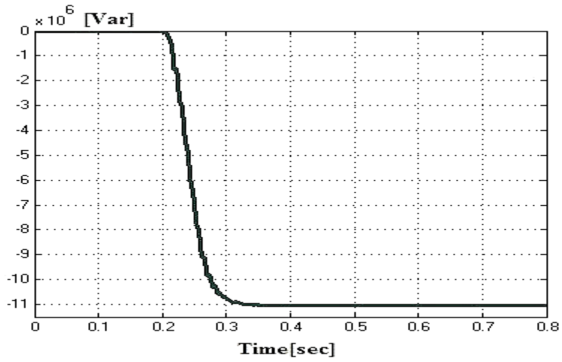

Fig. 7. Instantaneous reactive power of the Trasformerless SSSC

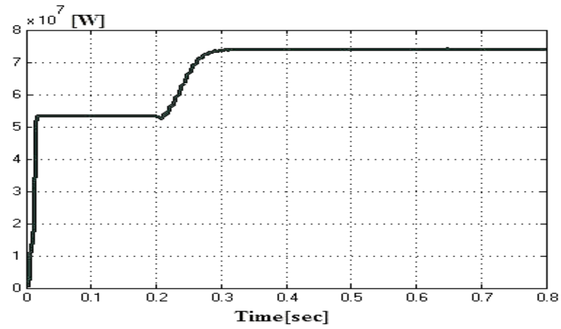

Fig. 8. Transmitted active power of the 1-2 line

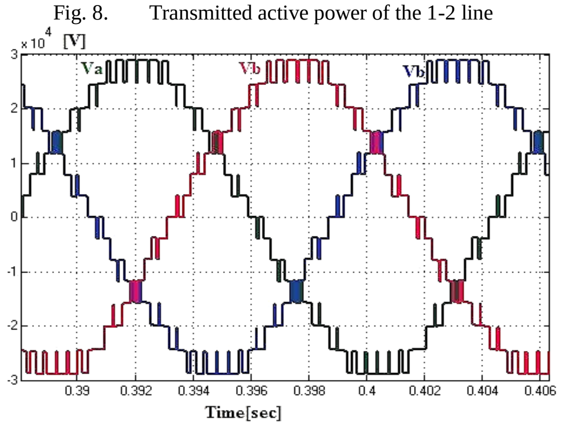

Fig. 9. Three-phase output voltage waveforms of the Trasformerless SSSC

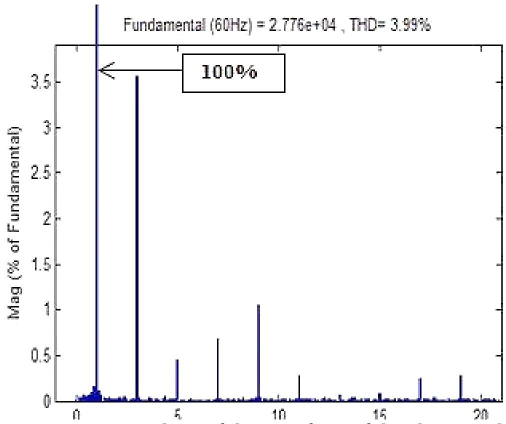

Fig. 10. FFT analysis of the waveform of the phase a voltage

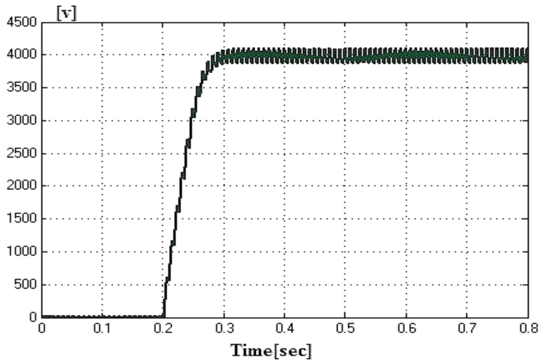

Fig. 11. Dc link voltage of each bridge of the inverter in phase a

Table.1.
The characteristics and parameters of the proposed system

Modulation index	***m***	***1***
Bus bar 1 voltage (phase-phase)	V_{s1}	132 kv ∠0
Bus bar 3 voltage (phase-phase)	V_{s2}	152 kv∠13
Power system frequency	f	60 HZ
Carrier frequency	f_{cr}	180 HZ
Series reactance of 1-2 line	X_{L1}	90Ω
Series reactance of 2-3 line	X_{L2}	40Ω
Bus bar 2 Active power	P	78 MW
Bus bar 2 Active power	Q	58 MVar
Reference reactive power	q_{ref}	11.03MVar
On a three-phase 230 Kv, 60HZ, 162MVA base		

7. Conclusion

In this study, a novel method is proposed to employ SSSC to increase transmission line capacity. This method is based on elimination of coupled transformer, so it helps to reduce costs of transformer construction, installation and maintenance. The proposed method, despite of elimination the transformer, was proved to compare with series compensators with transformer in terms of power quality and response speed.

To connect the transformerless SSSC to grid, a 15-level CHB inverter was used with instantaneous p-q power control and P-S PWM technique. This project was also simulated for a 230kv transmission line. Results obtained from the simulation indicated that for decrease of 70% in reactive power losses of the transmission line transmitted active power increase from 53.24 to 74.09 MW. This value is equal to 39% of active power increasing in the line. Unbalance of dc-link voltage in capacitors was restricted to 6% by proposed control method; also, no over voltage is not applied to the switches. The P-S PWM technique used in the inverter is appropriate so that the THD of inverter's output voltage is 3.99%.

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