Voltage Source Inverter Based Static Synchronous Series Compensator for Improved Available Transmission Capability in a Transmission Line

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Abstract: This paper deals with the active power flow control in a transmission line thus improving Available Transmission Capability (ATC) using Static Synchronous Series Compensator (SSSC). For the analysis, a generator supplying two parallel transmission lines connected to a load as 2-bus system is considered. When the load increases, active power flow in the transmission lines is shared based on their limits depending on ATC which is based on power handling capacity according to the demand. Therefore, for effective control of the active power flow considering the power handling capacity, SSSC is connected in series with one of the transmission lines. SSSC controls the active power flow in transmission line by injecting voltage in quadrature to the line current. SSSC designed in this work is a Voltage Source Inverter (VSI) which provides pulses and would help to inject the required voltage in quadrature to the line current. The PWM pulses of the VSI based SSSC is generated by dsPIC microcontroller. SSSC is modeled under both MATLAB / Simulink environment and implemented on a scaled down model of 150 km, 15.6 mH transmission lines connected in between generator and load.

Keywords: Static Synchronous Series Compensator (SSSC), Flexible Alternating Current Transmission System (FACTS), Voltage Source Inverter (VSI), Pulse Width Modulation (PWM).

1. Introduction

In the recent decades, drastic increase in power demand has resulted with the inclusion of many generating stations. But, with the existing transmission lines to handle huge generation and huge demand may lead to congestion of power flow. This alters the power flow through the transmission line systems and thus affects the network stability and security. It may even lead to cascaded failure of the system too. With the emergence of high power semiconductor switches, a number of control devices under the generic name of Flexible Alternating Current Transmission System (FACTS) are implemented to provide fast control over the power flow in a transmission system maintaining the power handling capacity of the lines within the limits [1]. FACTS devices significantly alters the way transmission systems are developed and controlled together with improvements in asset utilization, system flexibility and system performance. It provides flexible power system operation and control.

Among the different FACTS controllers [1], the most advanced type is the controller that employs Voltage Source Inverters (VSI) as synchronous voltage sources. Representative VSI type FACTS controllers are static compensators (STATCOM- shunt type controller), the static synchronous series compensator (SSSC- series type controller), and the unified power flow controller (UPFC -combined series-shunt type controller) which are used for power flow control and power stability enhancement in transmission lines [2-5]. In this work, for effective active power flow control on transmission line, SSSC is considered for the analysis. It is a series FACTS device connected in series with line and operates on the basis of thyristor based Voltage Source Inverter (VSI) that injects voltage in quadrature to line current. Thyristor based VSI operates with passive or active elements. Several researchers carried out their work on the operation of SSSC for inter area oscillations [7], damping of frequency oscillations [8-9], load

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frequency control [10-13]. SSSC is also applied for power system stability enhancement in a two-bus machine system [14-15], to control active and reactive power, along with damping of oscillations in a multi area power system [16-17]. The operation of SSSC for power flow control, its active and reactive compensation were carried out in the research extensively [18-27]. But, these researchers limited to simulation of the system with FACTS Devices. Therefore, in this work, hardware implementation of SSSC on a real time system for power flow control is taken into account. The work is support under both simulation and hardware for its validation. It deals with the development of a circuit based model of SSSC on a scaled down model of transmission line whose X/R ratio is 1, to study the control of active power flow for different load conditions.

The paper is organized as follows - section 1 deals with the introduction, section 2 deals with the active power flow in a transmission line, section 3 deals with operating principle and its effective control towards active power flow in line using SSSC. Section 4 discusses the results under both simulation and hardware implementation and finally section 5 concludes the work.

2. Active power flow control for improved Available Transmission Capability (ATC) in a transmission line

Power flow on transmission lines needs to be controlled in order to achieve the optimum utilization of transmission line capacity which is defined as Available Transmission Capability (ATC) of a line [25,28-30]. The distribution of the power flow between two parallel lines is dictated by their impedances. The line with smaller impedance carries more active power and vice-versa is expressed in Equation (1);

$$P_{L1} = \frac{V_S V_R}{X_L} \mathrm{Sin}(\delta_1 - \delta_2) \tag{1}$$

Thus, the active power transmitted can be controlled by; altering sending (V_S) / receiving end voltage(s) (V_R), lowering line impedance (X_L) and by controlling power angle (δ). A series compensator typically is used to increase or decrease the effective reactive impedance of the line, thus allowing control of real power flow between the two buses. The single line diagram of a system feeding via a double circuit transmission line feeding a load is shown in Figure 1.

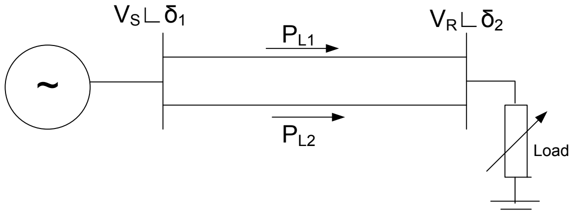

Figure 1. Two bus system connected via double circuit transmission line.

The active power flow control is one of the major problems in power sectors to limit the transmission line capability within limits which is resolved using SSSC Device.

3. Voltage Source Inverter (VSI) based Static Synchronous Series Compensator (SSSC) for active power flow control in transmission line

SSSC is a series FACTS device [2-3, 21], connected in series with the transmission line to control the real power flow in maintaining the transmission line limits. SSSC injects voltage in quadrature to the line current. Relating to the equation (1), the increased injected voltage results reduced impedance of the line, thereby increases the flow of active power in a line. The phasor representation of voltage injection by SSSC is as shown in Figure 2.

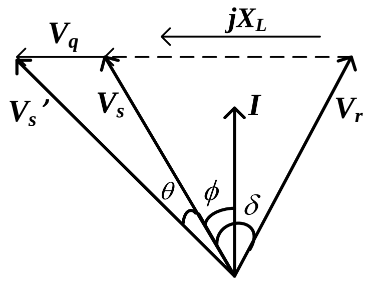

Figure 2. Phasor representation of voltage injection by SSSC.

Where; V_S and V_R are sending end voltage and receiving end voltage, δ is the angle between V_S and V_R. A small change in load, increases the voltage V_S by an angle V_S'. The function of SSSC is to compensate this increase in voltage by injecting a voltage V_q in quadrature to the line current I. By adjusting the injected voltage V_q of SSSC, the power flow through transmission line is controlled [24] and is given by Equation (2) and Equation (3);

$$P_{12} = P_{L1} - \Delta P_{SSSC} \tag{2}$$

where;

$$P_{12} = \frac{|V_S||V_R|}{X_L}(\mathrm{Sin}\delta_1 - \mathrm{Sin}\delta_2) - \frac{P_{L1}}{X_L I} V_q \tag{3}$$

The SSSC basically consists of a voltage source inverter (VSI) and dsPIC controller which would help to generate signal to VSI to generate PWM pulses accordingly to inject the required voltage. The dsPIC controller captures the line current to produce gating signals by VSI according to different control schemes. For the analysis, the SSSC is connected via an injection transformer in series with the transmission line 2, which is shown in Figure 3.

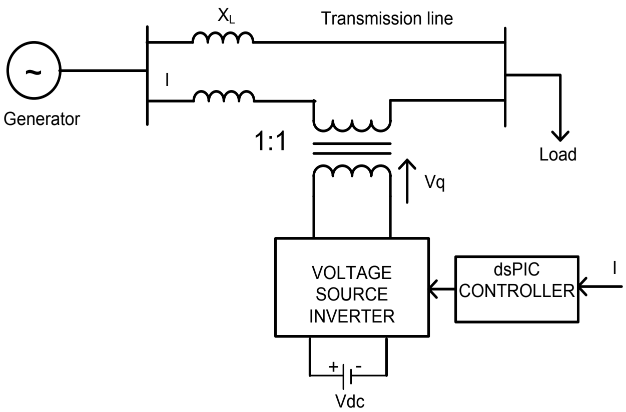

Figure 3. SSSC connected in series to transmission line 2.

The current from the transmission line is sensed and utilized by the control scheme to produce necessary gating signals for the VSI. The control scheme implemented for the active power flow control is as depicted in Figure 4.

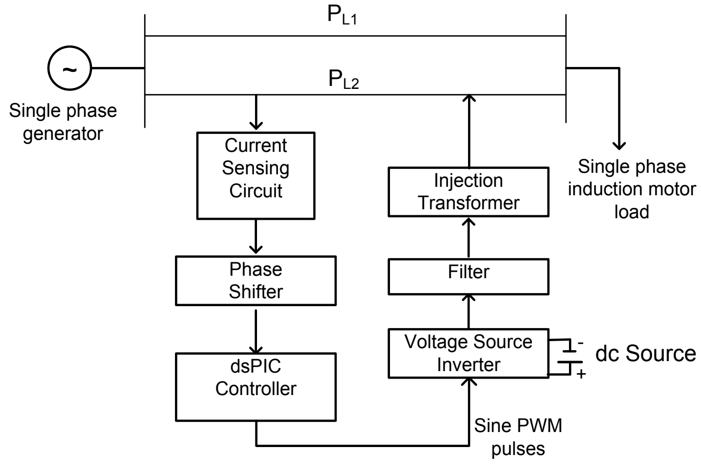

Figure 4. SSSC control circuit scheme.

The line current of the transmission line 2 is sensed using a current transformer. This current is phase shifted by the required angle in accordance with the load connected. The controller produces sine PWM pulses for the single phase inverter to switch accordingly to the phase shifted signal. Further, the output voltage is filtered using an LC filter to extract the fundamental sine wave at supply frequency. The filtered output is injected into the transmission line via an injection transformer to modify the power flow in that respective line.

4. **Simulation and experimental Results**

The proposed model of the system as explained in section 3 and developing the system shown in Figure 3 under MATLAB/ Simulink [31] and adopting the control scheme as discussed in Figure 4 is developed. A single phase induction motor of rating 1 hp, 0.8 pf is modelled with equivalent resistance and inductance. A single phase bipolar inverter with IGBT as switches is considered as VSI in SSSC configuration. A pulse width modulation technique is used for providing gating signals for the inverter switches. The output of the single phase inverter and filtered inverter output is as shown in Figure 5 and Figure 6 respectively.

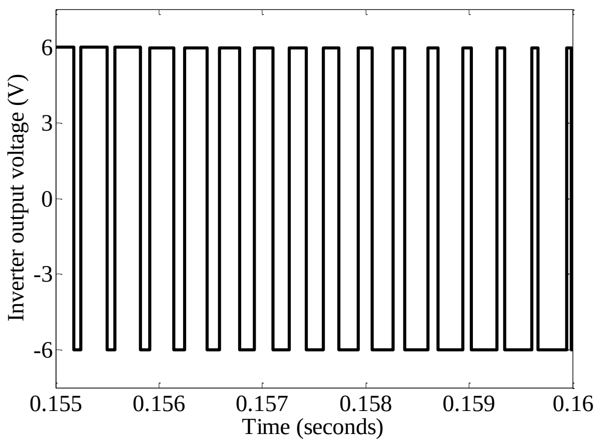

Figure 5. Single phase inverter output voltage.

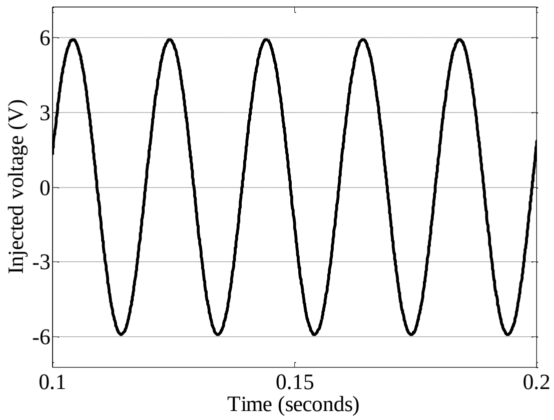

Figure 6. Output voltage of the LC filter.

The power flow through line 1 and 2 before connecting SSSC and after connecting SSSC is tabulated in Table 1.

Table 1. Simulation results of active power flow through transmission lines.

Active power flow in transmission lines	P_{L1} (W)	P_{L2} (W)	Total Power P (W)
Without SSSC	110.02	109.98	220
With SSSC	60.11	159.89	220

From Table 1, it can be inferred that, when SSSC is not connected to the system, the power flow through transmission lines are found to be identical. The impedance of both the lines is same hence same amount of power flows through both the lines. But, when SSSC is connected to line 2, the power flow through line 2 increases and line 1 decrease subsequently. It helps to maintain the transmission line power capability of line 1 thus meeting the total load demand requirement which shows the capacitive effect of the SSSC action. This is due to the reduction in effective line impedance of line 2 due to the surplus injection of voltage by SSSC as such the active power flow in line 2 is subsequently increased. The experimental setup of the Figure 3 was developed with the control scheme shown in Figure 4 on a scaled down laboratory model of transmission line having an inductance of 15.6mH and X/R ratio of 1 which replicates 220KV, 100MVA, 150 km having X_L=0.4794 Ohms/km. The output voltage of the single phase generator is connected via two transmission lines to a single phase induction motor load. The line current required for SSSC controller is sensed through a current transformer. The current transformer is designed using an LA 25NP [33] with a turns ratio of 1:1000, thus provides an output voltage of 5V. The SSSC controller is developed by designing a suitable phase shifter circuit using UA741 integrated circuit (IC) that provides 90 degree phase shift to the line current according to the nature of the load [32]. The logic for producing sine PWM pulses is generated by using a dsPIC30F4011 microcontroller [34]. The flow chart for generation of sine PWM code is shown in Figure 7. The phase shifted current signal is converted to digital signal by an Analog to Digital converter (ADC). This is compared with an internally generated triangular wave of switching frequency of 4.2 kHz to produce sinusoidal pulse width modulated output.

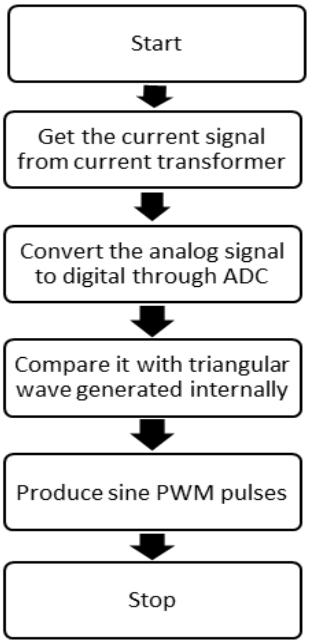

Figure 7. Flow chart for producing sine PWM pulses for the inverter

The sine PWM pulses obtained from DsPIC is shown in Figure 8. These pulses when given to a single phase inverter produces a square wave output.

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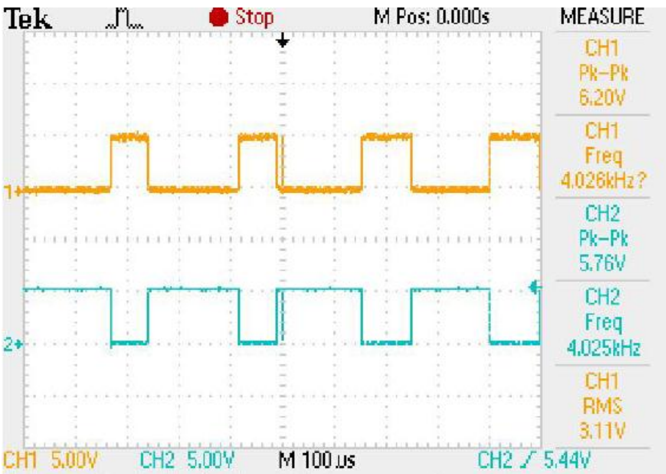

Figure 8. Sine PWM pulses for inverter

The single phase H bridge inverter is developed using an IRAMS20UPB module. IGBT's were used as switches and separate channels were made for supplying pulses to the switches. The inverter was fabricated in such a way that, it provides internal shunt resistors and gate drivers, giving matched propagation delay for all channels. The inverter produces a bipolar output which is filtered by an LC filter to produce the sine wave. The filter is designed to reduce the total harmonic distortion (THD) and extract the fundamental sinusoidal wave of system frequency, i.e., at 50 Hz. The filtered inverter output voltage is injected into the transmission line through an injection transformer connected having a turns ratio of 1:1. The hardware set up for the system is as show in Figure 9.

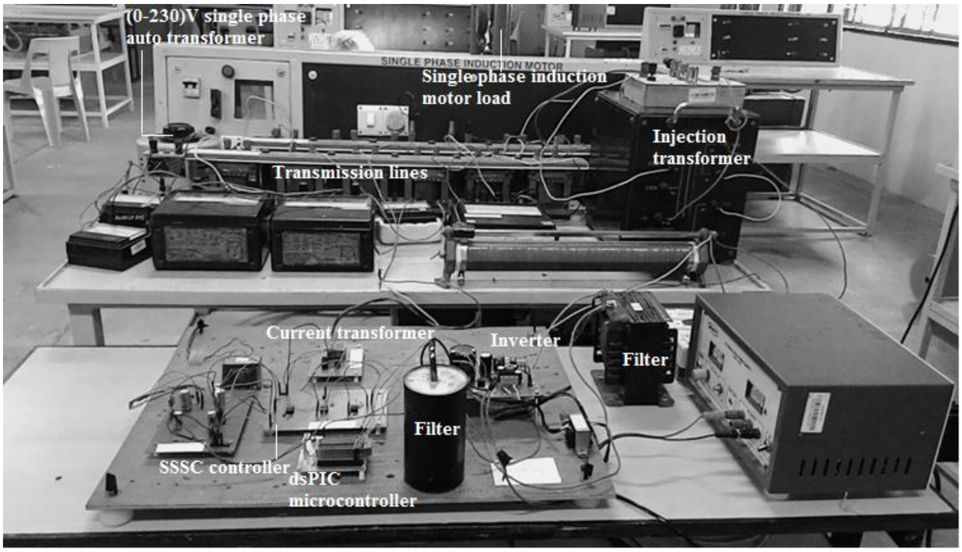

Figure 9. Hardware setup of the SSSC connected to a transmission line system

The hardware setup comprises of single phase generator replicated as single phase voltage source supplied through auto transformer (0-230V). The source is connected via two transmission lines of 15.6 mH to an induction motor of 1HP, 0.8pf. The current through the lines is sensed using Current Transformers (CT's) of 1:1000 ratio which is given to SSSC controller where the current signal is phase shifted and converted to digital signal by ADC.

This is compared in dsPIC with an internally generated triangular wave of switching frequency of 4.2 kHz to produce sinusoidal pulse width modulated output. The inverter produces a bipolar output which is filtered by an LC filter to produce the sine wave as shown in Figure 10.

The filtered inverter output voltage is injected into the transmission line through an injection transformer connected having a turns ratio of 1:1.

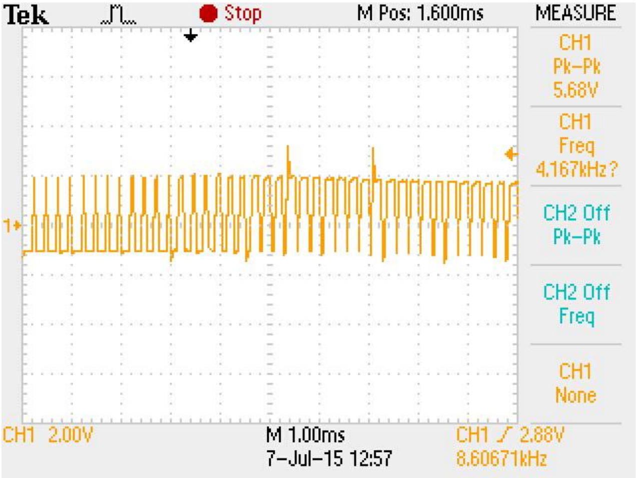

Figure 10. Inverter output signal.

The fundamental component of output voltage at system frequency of 50Hz is obtained from an LC filter is shown in Figure 11. For the inverter module used on analyzing the harmonics, the third and fifth harmonics are high. The total harmonic distortion (THD) is around 115%. The filter provides higher impedance to harmonic frequencies and lower impedance to fundamental frequency component. The designed values of inductor and capacitor of LC filter is of L=46mH and C=212μF based on the maximum voltage of the inverter which is 20V which is the voltage across the capacitor connected to the output of the inverter and current flowing through the inverter is 2A maximum. The THD is reduced to 4%.

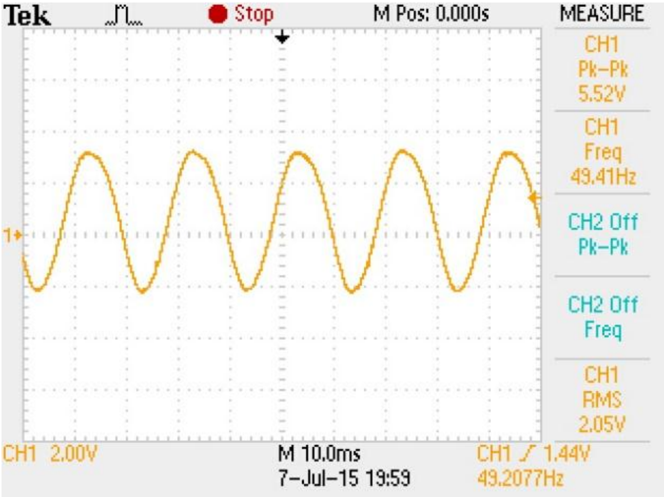

Figure 11. Output of LC filter

Table 2 shows the observed values of power flow through the transmission lines without connecting SSSC and after connecting SSSC for two loading conditions namely; No load and Full load operation of single phase induction motor.

Table 2. Hardware results of power flow through transmission lines

Condition of the load		P_{L1} (W)	P_{L2} (W)	Total Power P (W)
No - Load	Without SSSC	85	60	145
	With SSSC	50	100	150
Full - Load	Without SSSC	120	100	220
	With SSSC	60	160	220

From the above table it can be inferred that, under both no-load and full-load conditions, when SSSC is not connected to the system, the power flow through the transmission lines 1 and 2 are nearby, as the line impedance are identical. When a SSSC is connected to line 2, due to the capacitive action of SSSC, the power in line 2 increases and power in line 1 reduces thus maintaining the requirement of the total load demand. The SSSC injects voltage in series to the line; this in effect causes a reduction in line impedance causing an improvement in the active power flow. Thus, SSSC acts as a synchronous voltage source facilitating the regulation of active power in transmission lines.

5. Conclusion

The active power flow in a double circuit transmission line is regulated using a series FACTS device called as Static Synchronous Series Compensator. The active power flow through both the lines was shared equally in meeting with the load demand when no compensation was provided into the system. But, the transmission limit capability is the constraint on the transmission lines for its thermal stability to be maintained. By connecting SSSC in series with the transmission line provided series compensation thus improved the active power flow in the line. Thus, SSSC in line 2 helped in regulating the power flow in the line. The proposed system was simulated using MATLAB/Simulink and operation of SSSC was also verified experimentally. The operation of SSSC in effective active power flow control was observed on the transmission lines connected between the source and loads were verified under both no load and full load condition.

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