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Full Length Research Paper

Enhanced power transfer capability by using SSSC

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Static Synchronous Series Compensator (SSSC) is a voltage sourced converter based series FACTS device that provides capacitive or inductive compensation independent of line current. This paper presents the achievement of the required active and reactive power flow into the line for the purpose of compensation as well as validation of enhancement of the power transfer capability of a transmission line when Interline Power Flow Controller acts as standalone as SSSC. The effect of variation of the phase angle of the injected voltage on the power system parameters such as effective sending end voltage, effective transmission angle, active power, reactive power, and overall power factor with and without SSSC have also been incorporated. The numerical results for the test case have been presented to demonstrate the performance and its applicability on a transmission line.

Key words: Coupling transformer, flexible ac transmission (FACTS), interline power flow controller (IPFC), static synchronous series compensator (SSSC), voltage sourced converter (VSC), static compensator (STATCOM).

INTRODUCTION

The static synchronous series compensator (SSSC) can be operated without an external energy source as reactive power source with and fully controllable independent of transmission line current for the purpose of increasing or decreasing the overall reactive voltage drop across the transmission line and thereby controlling the electric power flow (Li et al., 2000; Sedraoui et al., 2001). The SSSC device can provide either capacitive or inductive injected voltage compensation. If AC injected voltage in SSSC lags behind the line current by 90°, capacitive series voltage compensation is obtained in the transmission line. On the contrary, if AC injected voltage of the SSSC leads the line current by 90°, an inductive series compensation is achieved (Padiyar, and Nagesh 2007; Padiyar, and Prabhu, 2003; Padiyar, and Prabhu, 2004). The injection of the voltage into the line must take place only when the power is to be subtracted from or added into the line.

The SSSC (Fardanesh, 2004) is connected to the line using a quasi-resonant DC supply to provide the soft switching and close loop control for synchronization, compensation and PWM signal generation. The quasi-resonant topology is used in the system which is deviated DC supply in the sense that the output voltage is not constant value but occasionally goes down to zero when a resonance is triggered. However, it is incorporated into the power system through a series coupling transformer as contrary to the shunt transformer found in STATCOM topology (Taha and Saad, 2009; Panigrahi et al., 2006; Narain and Laszlo, 2007; Padiyar, 2008). The series transformer is used to inject an independently controlled voltage in quadrature with the line current for the purpose of increasing or decreasing the overall voltage drop across the line and thereby controlling the transmitted power (Laszlo et al., 1999; Erwan et al., 2007; Fardanesh, 2004; Laszlo et al., 1997).

In essence, the SSSC can be considered to be controllable effective line impedance (Taha and Saad, 2009; Panigrahi et al., 2006; Narain and Laszlo, 2007; Padiyar 2008; Laszlo et al., 1999). Since SSSC has a VSC topology, the DC capacitor is used to maintain the DC voltage enabling the SSSC to increase or decrease

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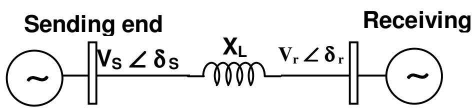

Figure 1. Basic transmission system.

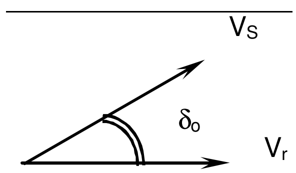

Figure 2. Phasor diagram.

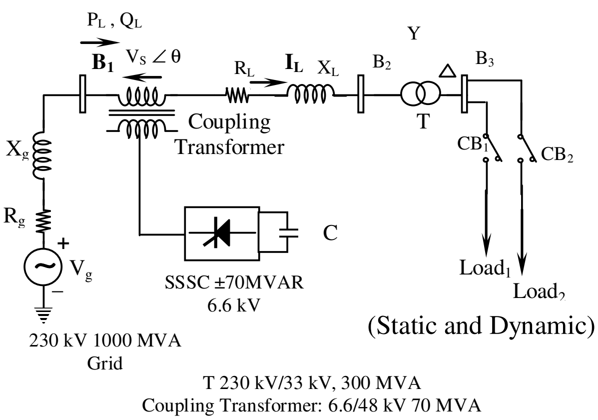

Figure 3. Schematic diagram of SSSC.

the transmitted power across the line by a fixed fraction of maximum power (Cai et al., 2002; Xia et al., 2010; Naresh et al., 2010; Akhilesh and Panigrahi, 2009). Since the SSSC has the ability to absorb or supply reactive power from or to the line, it makes the surrounding power system impervious to classical sub synchronous resonance (SSR) (Taha and Saad, 2009).

This paper presents the enhanced power transfer capability of a transmission line by static synchronous series compensator (SSSC). It is organized as follows: section II focuses the basic concept of series reactive compensation, section III formulates the problem, solution methodology is given in section IV, case study and simulation results are given in section V. Section VI highlights the conclusion.

SERIES REACTIVE COMPENSATION

The desired power flow through the line is translated into the required injected voltage. The control of DC bus voltage plays a vital role in power flow into the line. The operating principle of SSSC and the corresponding phasor diagram have been shown in Figures 1 and 2 respectively. It acts as resistor when DC capacitor is charging and as generator while discharging. The power flow control is achieved through reactive part of the voltage injected. It is also noted that SSSC acts as capacitor when power flow through the line is increased and as an inductor when power flow is to be decreased (Taha and Saad, 2009). The system shown in Figure 3 describes the basic configuration of static synchronous series compensator using 48 pulse static synchronous series compensator. The capacity of SSSC is ± 70 MVAR whereas the main transformer has the capacity of 300 MVA (approximately 4 to 5 times). They have represented the model of SSSC by an equivalent Thevenin's circuit at bus B_1.

The other major challenge in the implementation of VSC based SSSC (Cai et al., 2002) is sufficiently high value of storage capacitor and therefore not cost effective. With the passage of time, the charge on capacitor decreases on account of increased real power demand at the receiving end and reactive power compensation for the line. The high value of storage capacitor is suitable for long line compensation in order to sustain the long term and dynamic stability. In case of distribution Static Synchronous Series Compensator (D-SSSC), there is a need to bring down the value of storage capacitor which aims at achieving the cost-effectiveness and short and long term dynamic stability to suppress sub synchronous resonance.

$$P = \frac{V_S V_r}{X_L}\sin(\delta_S - \delta_r) = \frac{V^2}{X_L}\sin\delta \tag{1}$$

$$Q = \frac{V_S V_r}{X_L}[1-\cos(\delta_S - \delta_r)] = \frac{V^2}{X_L}(1-\cos\delta) \tag{2}$$

$$\delta = (\delta_S - \delta_r) \tag{3}$$

$$|V_S| = |V_r| = |V| \tag{4}$$

$$P_q = \frac{V^2}{X_{eff}}\sin\delta = \frac{V^2}{X_L\left[1-\frac{X_q}{X_L}\right]} \tag{5}$$

$$Q_q = \frac{V^2}{X_{eff}}[1-\cos\delta] = \frac{V^2}{X_L\left[1-\frac{X_q}{X_L}\right]}[1-\cos\delta] \tag{6}$$

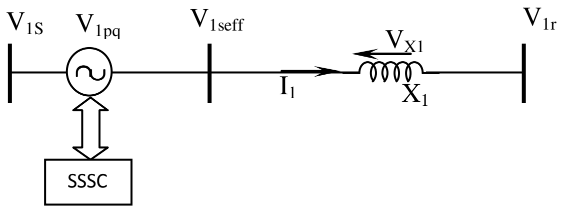

Figure 4. Effect of injected voltage.

Where,
P: Active power in p.u.
Q: Reactive power in p.u.
V_s: Sending end voltage in p.u.
V_R Receiving end voltage in p.u.
X_L Line reactance in p.u.
δ_s Voltage angle at sending end
δ_r Voltage angle at receiving end
P_q Active power at bus B_2 p.u.
Q_q Reactive power at bus B_2 in p.u.
X_{eff} Effective total transmission line reactance between its sending end and receiving end power system.

The series connected FACTS device can control active or reactive power flows in the line to share power between lines. This serves two purposes namely: reduce line losses and avoids overloads for an instance. Several SSSCs when combined together with their storage capacitors can be regarded as Interline Power Flow Controller (IPFC). An IPFC employs a number of inverters with a common DC link, each to provide series compensation for a selected line of the transmission system.

PROBLEM FORMULATION

At selected transmission angle, δ_o the initial rotor angle is 30°. The uncompensated system transmits $P_{r,30°}$ = 1.0 pu real power to and absorbs $Q_{r,30°}$ = 0.268 pu reactive power from the receiving end. The rotation of injected voltage $V_{1pq\ max}$ over 360° produces a circular locus for P_{1r} and Q_{1r} with a radius of $(P_{1pq}^2 + Q_{1pq}^2)^{1/2}$, where

P_{1pq} – Real power supplied by series voltage source.
Q_{1pq} – Reactive power supplied by series voltage source.

$$P_{1r30^o} = \frac{V_{1S}V_{1r}}{X_1}\sin\delta_1 = \frac{1x1}{0.5}\sin 30 = 1.0\ pu.$$

$$Q_{1r30^o} = \frac{V_{1S}V_{1r}}{X_1}[1-\cos\delta_1] = \frac{1x1}{0.5}[1-\cos 30] = 0.268 pu.$$

$$P_1 = P_{1r} + \frac{VV_{1p}}{X_1}\sin\left(\frac{\delta_1}{2}-\phi_1\right) + \frac{VV_{1q}}{X_1}\cos\left(\frac{\delta_2}{2}-\phi_1\right)$$

$$Q_1 = Q_{1r} - \frac{VV_{1p}}{X_1}\cos\left(\frac{\delta_1}{2}-\phi_1\right) + \frac{VV_{1q}}{X_1}\sin\left(\frac{\delta_2}{2}-\phi_1\right)$$

Where, $$\sin\phi = \frac{V_{1p}}{2V\sin\frac{\delta}{2}}$$

The Figure 4 shows the effect of injected voltage ϕ_1 changes, as the value of V_{1pq} (magnitude or phase) changes. If V_{1pq} is added in phase with the sending end uncompensated voltage V_{1s}, V_{1pq} can be expressed as:

$V_{1pq} = V_{inj}\angle(\delta_1 + \rho_{1pq})$.

SOLUTION METHODOLOGY

The voltage source is a 230 kV with 1000 MVA short circuit level (resistance 0.1 pu and an equivalent reactance of 0.3 pu) followed by a 230 kV radial transmission line connected to bus B_2 (Taha and Saad, 2009). The other data for reference are given in Table 1. To observe the effect of variation of injected voltage source, they are controllable within ($0 \le V_{1pq} \le V_{1pqmax}$) and angle ($0 \le \rho_{1pq} \le 360°$). The rotation of phasor V_{1pq} with angle ρ_{1pq} varies both magnitude and angle of phasor in a cyclic manner and as a result, both the transmitted real power P_{1r} and the reactive power Q_{1r} also vary with ρ_{1pq} in a sinusoidal manner.

At ρ_{1pq}= 0°;$|V_{inj}|$ = 0.2 pu ; $V_{1pq}= V_{inj}\angle(\delta_1+0°) = 0.2\angle 30°$ pu.

It is to be noted that the angle of injected voltage is considered zero when it is in phase with the sending end voltage with an initial transmission angle of 30°.

Real (V_{1pq}) = V_{1p} = 0.2 cos 30° = 0.1732 pu.
Imag (V_{1pq}) = V_{1q} = 0.2 sin 30° = 0.1 pu.

Thus $$\sin\phi_1 = \frac{0.1732}{2\,x\,1\,x\sin\left(\frac{30}{2}\right)} = 0.3342 \quad or$$

ϕ_1 = 19.52° degrees.

$$P_1 = 1.0 + \frac{1x0.1732}{0.5}\sin[15-19.52] + \frac{1x0.1}{0.5}\cos[15-19.52]$$
$$= 1.0 - 0.027267 + 0.1993 = 1.1721\,pu$$

$$Q_1 = 0.268 - \frac{1x0.1732}{0.5}\cos[15-19.52] + \frac{1x0.1}{0.5}\sin[15-19.52]$$
$$= 0.268 - 0.3449 - 0.01576 = 0.09266\,pu$$

$$V_{1Seff} = (V_{S1}\angle+\delta) + V_{pq}\angle(\delta_1+\rho_1)$$
$$= 1.0[\cos 30 + j\sin 30] + 0.2[\cos 30 + j\sin 30]$$
$$= 1.03923 + j0.6 = 1.1999\angle 30^o \quad pu$$

Here , δ_{1eff} = 30° same as initial value. Since ρ_{1pq} = 0°, where

Table 1. Case study.

Voltage source		SSSC	
Rated volts	230 kV	Valves	GTO
MVA S.C.	10^3 MVA	No. of pulses	48
Resistance	0.1 pu	DC voltage	1 kV
Reactance	0.3 pu	Rated power	± 2 x 35 MVAR
Rated voltage	230 kV	GTO (Rf)	1 mΩ
Transmission line		Capacitor bank (DC)	
X_L	0.25 pu	[1]Capacitance	20 mF
R_L	0.05 pu	DC volts	1 kV
Rated volts	230 kV		
Transformer		Coupling transformer	
Rated volts	230/33 kV	Rated volts	6.6/36 kV
Rated power	300 MVA	[2]Rated power	35 MVA
X_L	0.01 pu	Resistance	0.001 pu
		X_L	0.02 pu

[1] – Capacitance is a reliable bank for compensation.
[2] - SSSC has capacity of 70 MVAR whereas coupling transformer has 35 MVA capacity.

$$\delta_{1eff} = \sin^{-1}\left[\frac{P.X_1}{V^2}\right]$$

At ρ_{1pq}= 30°;$|V_{inj}|$ = 0.2 pu ; $V_{1pq}= V_{inj} \angle (\delta_1+30°) = 0.2\angle 60°$ pu.
Real (V_{1pq}) = V_{1p} = 0.2 cos 60° = 0.1 pu.
Imag (V_{1pq}) = V_{1q} = 0.2 sin 60° = 0.1732 pu.

Thus

$$\sin\phi_1 = \frac{0.1}{2\,x\,1\,x\sin\left(\frac{30}{2}\right)} = 0.19318 \quad or$$

ϕ_1 = 11.138° degrees.

$$P_1 = 1.0 + \frac{1x\,0.1}{0.5}\sin[15-11.138] + \frac{1x\,0.1732}{0.5}\cos[15-11.138]$$
$$= 1.0 + 0.01347 + 0.34521 = 1.3586 \; pu$$

$$Q_1 = 0.268 - \frac{1x0.1}{0.5}\cos[15-11.138] + \frac{1x0.0866}{0.5}\sin[15-11.138]$$
$$= 0.268 - 0.19954 + 0.01166 = 0.08012 pu$$

$$V_{1Seff} = (V_{S1}\angle +\delta) + V_{pq}\angle(\delta_1 + \rho_1)$$
$$= 1.0[\cos 30 + j\sin 30] + 0.2[\cos 60 + j\sin 60]$$
$$= 0.966 + j0.6732 = 1.1774\angle 34.8724^o \quad pu$$

SIMULATION RESULTS

The variation of P_{1r} and Q_{1r} with rotating V_{1pqmax} can be illustrated in the (P_{1r} ; Q_{1r}) plane shown in Figure 6. It is evident from Figure 7 that the active power at the receiving end of the line 1 increases as the magnitude of the injected voltage is increased. Figure 8 shows the reactive power variation with the variation in injected voltage angle. Figure 9 shows the overall power factor variation and Figure 10 shows the effective sending end voltage with variation in injected voltage angle. The graphical study reveals that if the injected voltage source of constant magnitude is added with sending end voltage with the constraints ($0 \leq \rho_{1pq} \leq 360°$), it was observed that the reactive voltage drop increases when ($0 \leq \rho_{1pq} \leq 90°$, maximum at 90°) and decreases when ($90 \leq \rho_{1pq} \leq 270°$, minimum at 270°). The magnitude of the reactive voltage drop greatly depends upon the line current. The variation of injected voltage in phase also gives a controllable region for effective transmission angle as indicated in Table 2. The algorithm has been implemented in MATLAB 7.0 on a Pentium IV, 2.2 GHz, 3.46 GB processor to get the simulation result. The optimum region to choose the ρ_{1pq} is from 0 to 90° for enhanced transmission capacity. All the observations are shown from Figures 5 to 11 and validated with the results for compensation using SSSC (Taha and Saad, 2009).

The effect of SSSC compensation such that the real power to reactive power ratio reaches to 5.0 compared to its value of 0.55 under uncompensated situation. There is

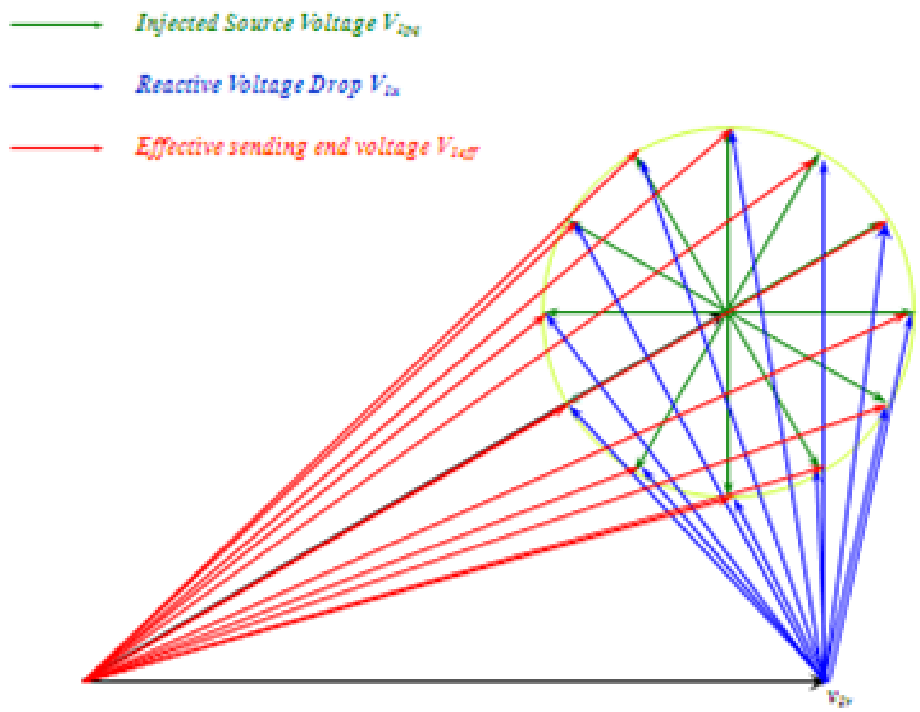

Figure 5. Phasor diagram

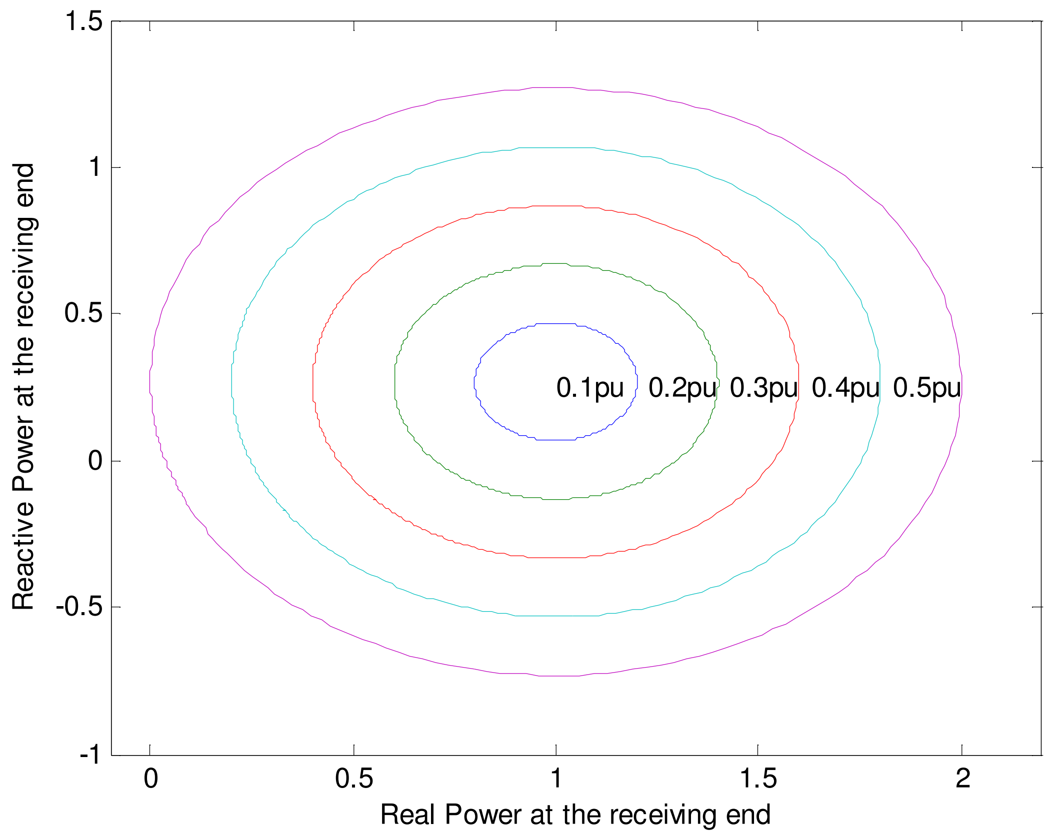

Figure 6. P-Q Plane at receiving end with variation in injected voltage magnitude and phase.

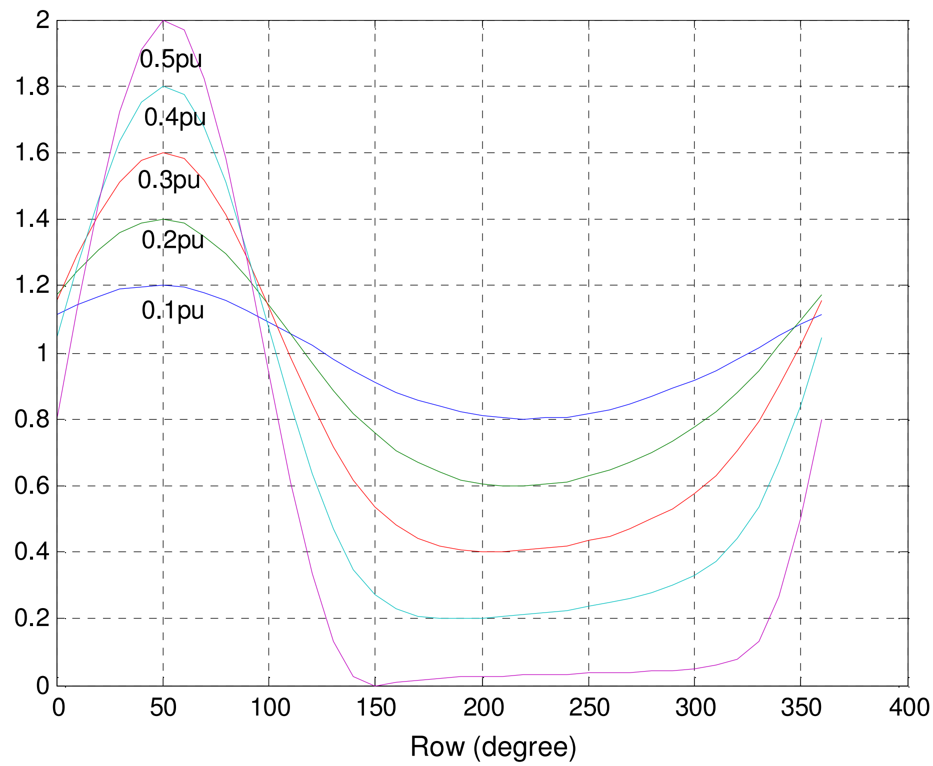

Figure 7. Active power at the receiving end of line 1.

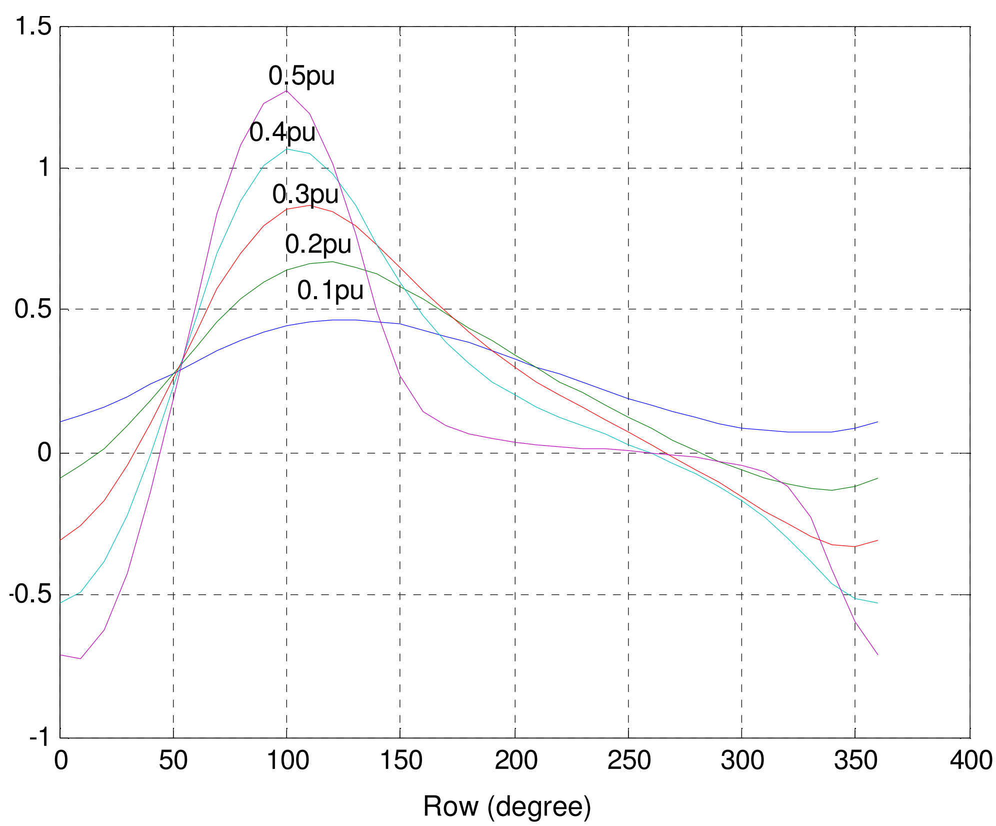

Figure 8. Reactive power at the receiving end of line 1.

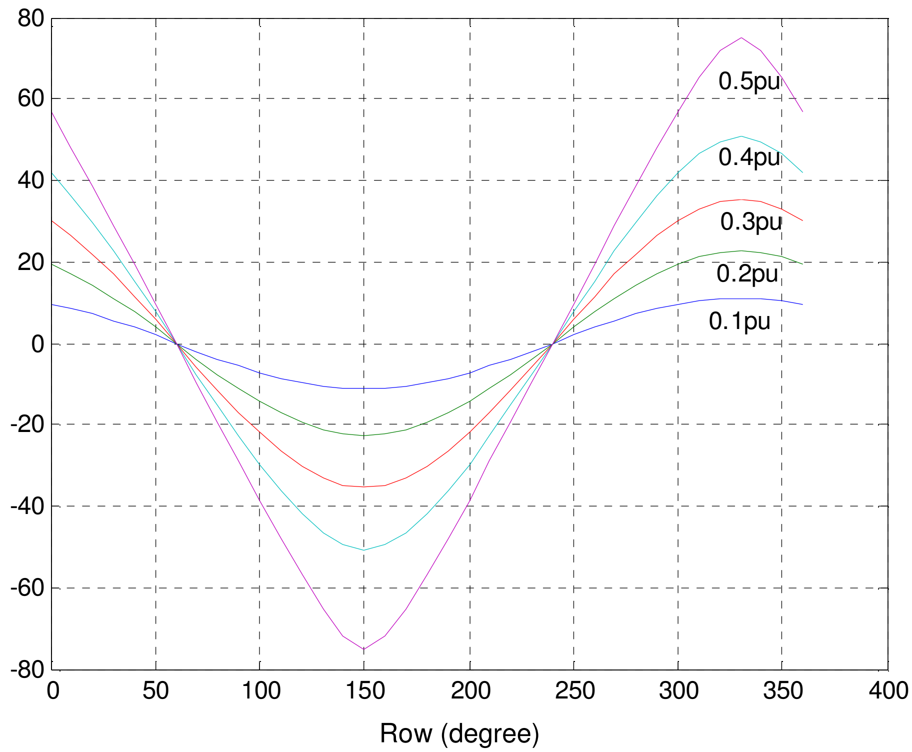

Figure 9. Overall power factor angle variation.

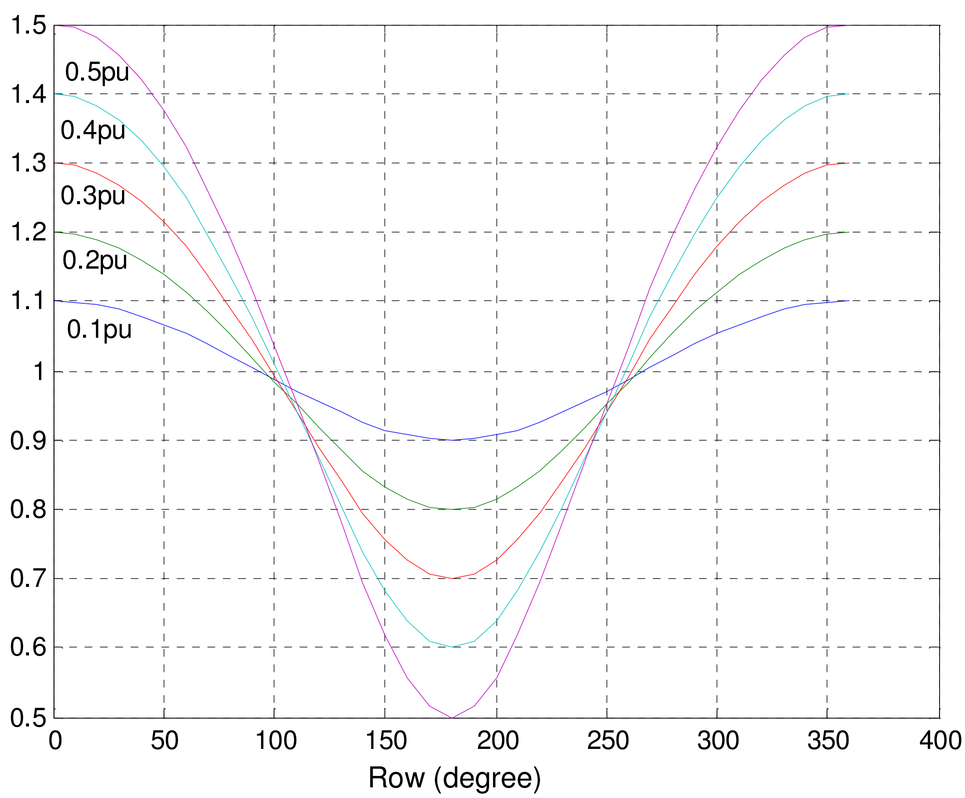

Figure 10. Effective sending end voltage with variation in magnitude and phase of injected voltage.

Table 2. Simulation results involving power transmission capability (with SSSC).

Injected voltage = 0.2 per unit					
ρ_{1pq} *	PF	$P_{1(new)}$	$Q_{1(new)}$	V_{1seff}	δ_{eff}
*0.00	19.5486	1.17190	-0.09318	1.200	30.000
10.000	17.2161	1.24507	-0.04813	1.19747	31.66196
20.000	14.3801	1.30918	0.01421	1.18991	33.29557
30.000	11.1387	1.35909	0.09178	1.17746	34.87192
40.000	7.5936	1.39038	0.18079	1.16035	36.36096
50.000	3.8470	1.39992	0.27605	1.13891	37.73101
60.000	0.0000	1.38637	0.37153	1.11355	38.94828
70.000	-3.8470	1.35036	0.46099	1.08481	39.97660
80.000	-7.5936	1.29447	0.53872	1.05331	40.77736
90.000	-11.1387	1.22287	0.60016	1.01980	41.30993
100.00	-14.3801	1.14087	0.64237	0.98516	41.53277
110.00	-17.2161	1.05417	0.66431	0.95036	41.40566
120.00	-19.5486	0.96828	0.66674	0.91652	40.89339
130.00	-21.2888	0.88781	0.65194	0.88481	39.97131
140.00	-22.3647	0.81614	0.62324	0.85649	38.63257
150.00	-22.7288	0.75523	0.58437	0.83282	36.89637
160.00	-22.3647	0.70573	0.53893	0.81494	34.81495
170.00	-21.288	0.66726	0.49000	0.80379	32.47637
180.00	-19.5486	0.63882	0.43990	0.80000	30.00000
190.00	-17.2161	0.61911	0.39017	0.80379	27.52363
200.00	-14.3801	0.60685	0.34172	0.81494	25.18505
210.00	-11.1387	0.60091	0.29494	0.83282	23.10363
220.00	-7.5936	0.60041	0.24990	0.85649	21.36743
230.00	-3.8470	0.60476	0.20648	0.88481	20.02869
*240.00	0.00000	0.61363	0.16447	0.91652	19.10661
250.00	3.84700	0.62695	0.12366	0.95036	18.59434
260.00	7.5936	0.64489	0.08388	0.98516	18.46723
270.00	11.1387	0.66784	0.04513	1.01980	18.69007
280.00	14.3801	0.69638	0.00759	1.05331	19.22264
290.00	17.2161	0.73123	-0.02825	1.08481	20.02340
300.00	19.5486	0.77316	-0.06146	1.11355	21.05172
310.00	21.2888	0.82284	-0.09063	1.13891	22.26899
320.00	22.3647	0.88062	-0.11377	1.16035	23.63904
330.00	22.7288	0.94621	-0.12837	1.17746	25.12808
340.00	22.3647	1.01839	-0.13158	1.18991	26.70443
350.00	21.2888	1.09481	-0.12060	1.19747	28.33804
360.00	19.5486	1.17190	-0.09318	1.20000	30.00000

* The angle of injected voltage is considered zero when it is in phase with the sending end voltage.

a considerable improvement in the overall power factor of the line after compensation.

Conclusion

This paper presents the enhanced power transfer capability of a transmission line by static synchronous series compensator (SSSC). The enhanced power transfer capability has been found for an injected voltage magnitude of 0.2 per unit within the angle variation of 0° to 90°. The real power P demanded by the load is supplied by the three phase source and transmitted by the line.

Static synchronous series compensator is operated to decrease the reactive power flow over the line by

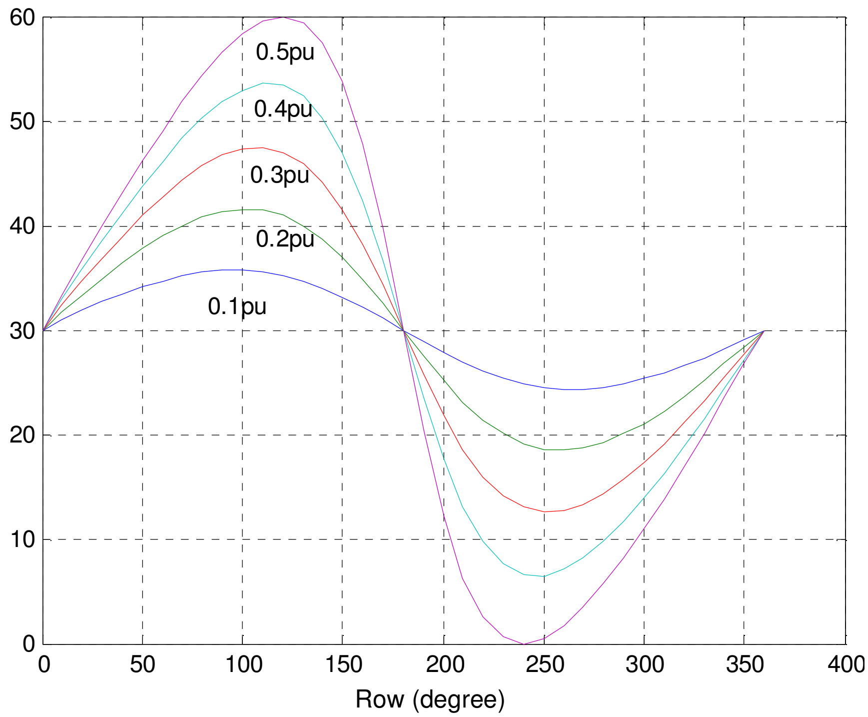

Figure 11. Overall transmission angle.

compensating the reactive power demanded by the line inductance. The numerical results for the test case have been presented to demonstrate the performance and its applicability on a transmission line.

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