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Fuzzy Controlled SVC for Reactive Power Control of Long Transmission Lines

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Abstract

Flexible AC transmission system (FACTS) devices are used to improve the existing transmission capabilities of the transmission system by making it more flexible and independent operating. The technology is used to achieve complete deregulation of power systems i.e generation, transmission and distribution. The loading capability of transmission system can also be enhanced nearer to the thermal limits without affecting the stability. The closed loop smooth control of reactive power can be achieved by using shunt connected FACTS devices. Static VAR Compensator (SVC) is one of the shunt connected FACTS device which is to be utilized here for the purpose of reactive power compensation. This paper attempts to design and simulate the Fuzzy logic control which is used to regulate the firing angle of SVC. With this scheme, it is seen that a better, smooth and adaptive control of reactive power has been achieved. The modelling and simulations are carried out for 750km long Transmission line and the compensation is placed at the receiving end (load end).

Keywords: Flexible AC transmission system (FACTS); Static VAR Compensator (SVC); Fuzzy Logic Controller (FLC).

1. Introduction

In power system, the reactive power generation and absorption is essential since the reactive power plays a vital role in keeping the voltage of power system stable. The main elements for generation and absorption of reactive power are transmission line, transformers and alternators. The transmission lines have distributed parameters throughout the line. On the light loads or at no loads, parameters become predominant and consequently the line supplies charging VAR (generates reactive power). In order to maintain the terminal voltage at the load bus adequate, reactive reserves are needed. FACTS devices like SVC can be used which helps in achieving better economy in power transfer.

In this paper transmission line (λ /8) is simulated using 4π line segments by keeping the sending end voltage constant. The receiving end voltage fluctuations were observed for different loads. In order to maintain the receiving end voltage constant, shunt inductor and capacitor are added for different loading conditions. SVC is simulated by means of Fixed Capacitor and Thyristor Controlled Reactor (FC-TCR) which is placed at the receiving end. The firing angle control circuit is designed and the firing angles are varied for various loading conditions to make the receiving end voltage equal to sending end voltage. Fuzzy Logic Controller (FLC) is designed to achieve the firing angles for SVC such that it maintains a flat voltage profile. All the results thus obtained, were verified and were utilized in framing of fuzzy rule base in order to achieve better reactive power compensation for the transmission line (λ/8). Based on observed results for load voltage variations for different values of load resistance, inductance and capacitance; a FLC is designed which controls the firing angle of SVC in order to automatically maintain the receiving end voltage constant.

2. Modeling of SVC

An elementary single phase thyristor controlled reactor [4] (TCR) shown in Fig.1 consists of a fixed (usually air core) reactor of inductance L and a two anti-parallel SCRs. The device brought into conduction by simultaneous application of gate pulses to SCRs of the same polarity. In addition, it will automatically block immediately after the ac current crosses zero, unless the gate signal is reapplied. The current in the reactor can be controlled from maximum (SCR closed) to zero (SCR open) by the method of firing delay angle control. That is, the SCR conduction delayed with respect to the peak of the applied voltage in each half-cycle, and thus the duration of the current conduction interval is controlled. This method of current control is illustrated separately for the positive and negative current cycles in Fig.2 where the applied voltage V and the reactor current $i_L(\alpha)$ at zero delay angle (switch fully closed) and at an arbitrary α delay angle are shown. When α =0, the SCR closes at the crest of the applied voltage and evidently the resulting current in the reactor will be the same as that obtained in steady state with a permanently closed switch. When the gating of the SCR is delayed by an angle α ($0 \leq \alpha \leq \pi/2$) with respect to the crest of the voltage, the current in the reactor can be expressed [4] as follows

$$V(t) = Vcoswt \quad (1)$$

$$i_L = (1/_L)\int_{\alpha}^{wt} V(t)\ dt = (V/_{wL})(sinwt - sin\alpha) \quad (2)$$

Since the SCR, by definition, opens as the current reaches zero, is valid for the interval $\alpha \leq wt \leq \pi - \alpha$ .For subsequent negative half-cycle intervals, the sign of the terms in equation (1) becomes opposite.

In the equation (1) the term $(V/_{wL})sin\alpha = 0$ is offset which is shifted down for positive and up for negative current half-cycles obtained at α = 0, as illustrated in Fig.2. Since the SCRs automatically turns off at the instant of current zero crossing of SCR this process actually controls the conduction intervals (or angle) of the SCR. That is, the delay angle α defines the prevailing conduction angle σ ($\sigma = \pi - 2\alpha$). Thus, as the delay angle α increases, the corresponding increasing offset results in the reduction of the conduction angle σ of the SCR, and the consequent reduction of the reactor current. At the maximum delay of $\alpha = \pi/2$, the offset also reaches its maximum of V/ωL, at which both the conduction angle and the reactor current becomes zero. The two parameters, delay angle α and conduction angle σ are equivalent and therefore TCR can be characterized by either of them; their use is simply a matter of preference. For this reason, expression related to the TCR can be found in the literature both in terms of α and σ [4].

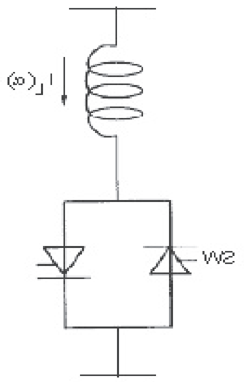

Figure 1. Basic Thyristor Controlled Reactor

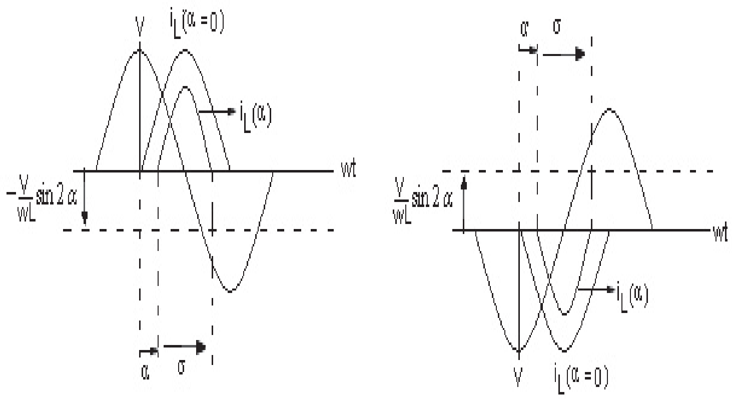

Figure 2. Firing delay angle

The amplitude $I_{LF}(\alpha)$ of the fundamental reactor current $i_{LF}(\alpha)$ can be expressed as a function of angle α [4].

$$I_{LF}(\alpha) = V/\omega L\,(1 - (2/\pi)\,\alpha - (1/\pi)\sin(2\alpha)) \quad (3)$$

Where V is the amplitude of the applied voltage, L is the inductance of the thyristor-controlled reactor and ω is the angular frequency of the applied voltage. The variation of the amplitude $I_{LF}(\alpha)$, normalized to the maximum current I_{LFmax}, ($I_{LFmax} = V/\omega L$), is shown plotted against delay angle α shown in Figure 3.

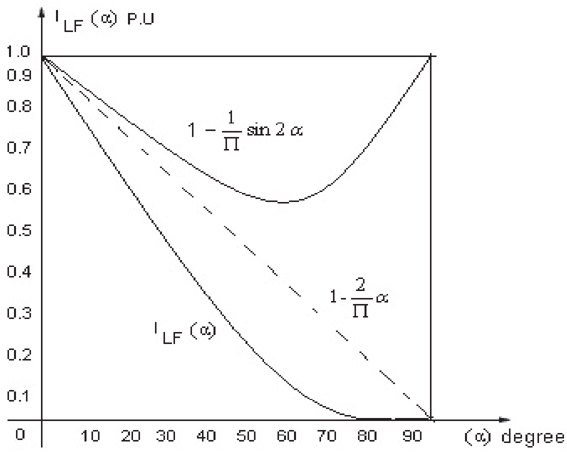

Figure 3 Amplitude variation of the fundamental TCR current with the delay angle (α)

It is clear from Figure 3, that the TCR can control the fundamental current continuously from zero (SCR open) to a maximum (SCR closed) as if it was a variable reactive admittance. Thus, an effective reactance admittance, $B_L(\alpha)$, for the TCR can be defined. This admittance, as a function of angle α is obtained as:

$$B_L(\alpha)=1/\omega L(1-(2/\pi)\alpha-(1/\pi)\sin(2\alpha)) \quad (4)$$

A basic VAR generator arrangement using a fixed capacitor with a thyristor-controlled reactor (FC-TCR) shown in Figure 4. The current in the reactor is varied by the previously discussed method of firing delay angle control. A filter network that has the necessary capacitive impedance at the fundamental frequency to generate the reactive power required usually substitutes the fixed capacitor in practice, fully or partially, but it provides low impedance at selected frequencies to shunt the dominant harmonics produced by the TCR. Figure 5 shows the dynamic V-I Characteristics of SVC with Load lines.

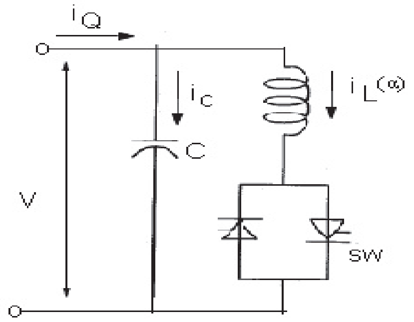

Figure 4. Basic FC-TCR type static generator

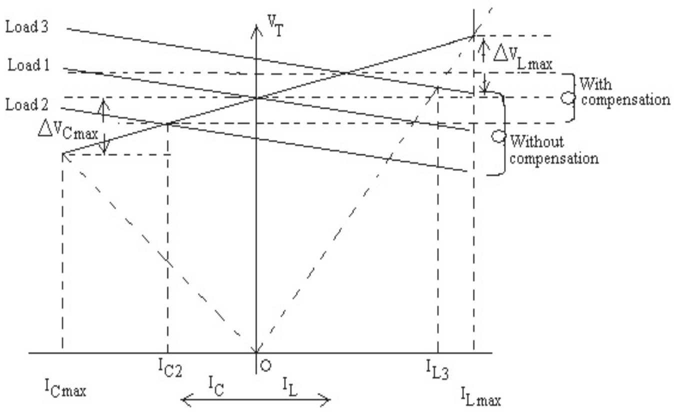

Figure 5. Dynamic V-I Characteristics of SVC with Load lines

V_{Cmax} = voltage limit of capacitor
B_C = admittance of capacitor
V_{Lmax} = voltage limit of TCR
I_{Cmax} = capacitive current limit
I_{Lmax} = inductive current limit
B_{Lmax} = max inductive admittance

3. SVC and its control system

The Static VAR Compensator (SVC) is a shunt device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids [14]. The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each capacitor bank is switched on and off by three thyristor switches TSC. Reactors are either switched on-off TSR phase-controlled TCR.

The figure below shows a single-line diagram of a static VAR compensator and a simplified block diagram of its control system.

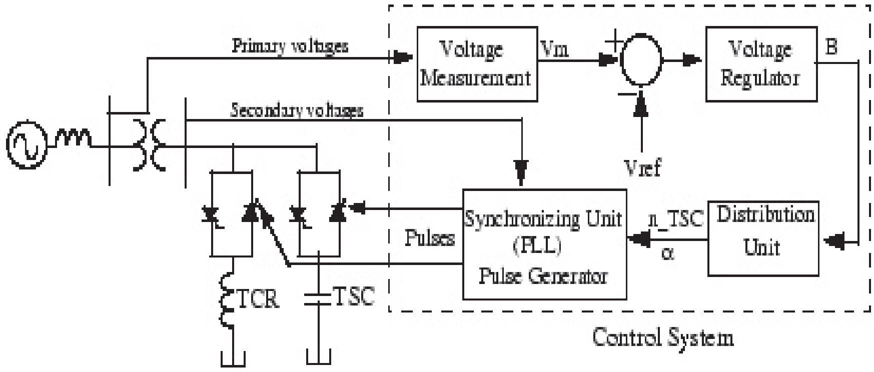

Figure 6. Single-line Diagram of an SVC and Its Control System Block Diagram

$V = Vref + Xs \cdot I$ SVC is in regulation range ($-Bc_{max} < B < Bl_{max}$)

$V = -\frac{I}{Bc_{max}}$ SVC is fully capacitive ($B = Bc_{max}$)

$V = \frac{I}{Bl_{max}}$ SVC is fully inductive ($B = Bl_{max}$)

Where V is Positive sequence voltage (pu)

I Reactive current (pu/Pbase) (I > 0 indicates an inductive current)

Xs Slope or droop reactance (pu/Pbase)

Bc_{max} Maximum capacitive susceptance (pu/Pbase) with all TSCs in service, no TSR or TCR

Bl_{max} Maximum inductive susceptance (pu/Pbase) with all TSRs in service or TCRs at full conduction, no TSC

P_{base} Three-phase base power specified in the block dialog box

3.1 SVC Dynamic Response

When the SVC is operating in voltage regulation mode, its response speed to a change of system voltage depends on the voltage regulator gains (proportional gain K_p and integral gain K_i), the droop reactance Xs, and the system strength (short-circuit level). For an integral-type voltage regulator (K_p = 0), if the voltage measurement time constant Tm and the average time delay T_d due to valve firing are neglected, the closed-loop system consisting of the SVC and the power system can be approximated by a first-order system having the following closed-loop time constant:

$$T_c = \frac{1}{Ki \cdot (Xs + Xn)}$$

where Tc Closed loop time constant

Ki Proportional gain of the voltage regulator (pu_B/pu_V/s)

Xs Slope reactance pu/Pbase

Xn Equivalent power system reactance (pu/Pbase)

The above equation demonstrates that you obtain a faster response speed when the regulator gain is increased or when the system short-circuit level decreases (higher X_n values). If you take into account the time delays due to voltage measurement system and valve firing, you obtain an oscillatory response and, eventually, instability with too weak a system or too large a regulator gain.

The transmission line without any compensation was not satisfying the essential condition of maintaining the voltage within the reasonable limits. The effect of increasing load was to reduce the voltage level at the load end. At light loads, the load voltage is greater than the sending end voltage as the reactive power generated is greater than absorbed. At higher loads the load voltage drops, as the reactive power absorbed is greater than generated, as shown in Table III. Fig.14 and Fig.15 indicates unequal voltage profiles. Fig.16 clearly shows the inductor current control.

Table 1- Load voltage before and after compensation

Tr Line Parameters for Lt=.10mh/km Ct =0.1µf/km R.= 0.001Ω		**Before compensation For Vs= 230V (peak)**		**After compensation for Vs=230V (peak)**		**Compensating inductor**	**Compensating capacitor**
R Ω	V_S (rms) Volts	V_R (rms) Volts	I_R rms Amp	V_R (rms) Volts	I_R (rms) Amp	L (H)	C (µF)
500	162.63	219.42	0.43	162.61	.32	.208	10
400	162.63	218.89	0.54	162.65	.40	.209	10
300	162.63	217.91	0.72	162.50	.54	.21	10
200	162.63	2215.63	1.07	162.49	.81	.214	10
180	162.63	214.78	1.19	162.82	.90	.217	10
160	162.63	213.66	1.33	162.55	1.016	.218	10
140	162.63	212.12	1.51	162.58	1.16	.221	10
120	162.63	209.92	1.75	162.58	1.355	.226	10
100	162.63	206.59	2.06	162.58	1.626	.234	10
80	162.63	201.13	2.51	163.47	2.032	.249	10
60	162.63	191.19	3.18	162.38	2.71	.289	10
50	162.63	182.88	3.65	162.24	3.252	.344	10

4. Fuzzy Logic Controller

Fuzzy logic is an approach with great potential for real time applications [2] [3]. Load voltage and load current taken as input to fuzzy system. For a closed loop control, error input can be selected as current, voltage or impedance, according to control type [7]. To get the linearity triangular membership function is taken with 50% overlap. The output of fuzzy controller taken as the control signal and the pulse generator provides synchronous firing pulses to thyristors. The Fuzzy Logic is a rule based controller, where a set of rules represents a control decision mechanism to correct the effect of certain causes coming from power system [8] [9]. In fuzzy logic, the five linguistic variables expressed by fuzzy sets defined on their respective universes of discourse. Table-2 shows the suggested membership function rules of FC-TCR controller. The rule of this table can be chosen based on practical experience and simulation results observed from the behavior of the system around its stable equilibrium points.

Table 2 – Rule base for M.F's

		Load voltage				
		NL	**NM**	**P**	**PM**	**PB**
Load current	**NL**	**PB**	**PB**	**NM**	**NM**	**NL**
	NM	**PB**	**PB**	**NM**	**P**	**NL**
	P	**P**	**PM**	**NM**	**NM**	**P**
	PM	**NM**	**P**	**NM**	**NM**	**PM**
	PB	**NL**	**NM**	**NM**	**NL**	**NL**

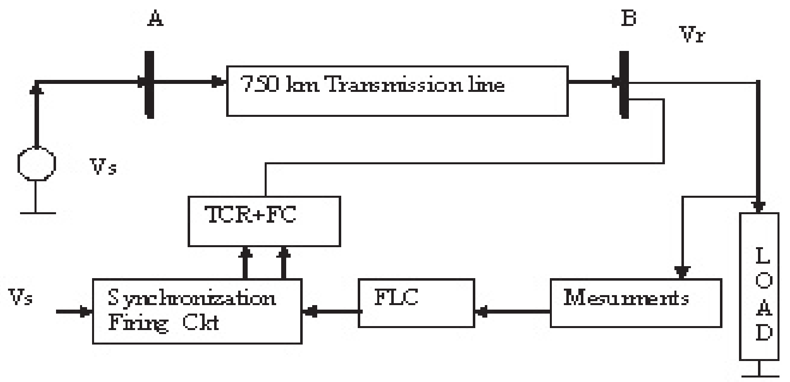

Figure 7. Single Phase equivalent circuit and fuzzy logic control structure of SVC

The Fuzzy logic block is developed using the data obtained from MATLAB simulation. Figure 7 shows the single line diagram for the TCR-FC with fuzzy logic controller and other components. The Fuzzy logic block senses the load current and accordingly gives the firing pulse delay to achieve the desired voltage at the load terminals. The use of Fuzzy logic has facilitated closed loop control. By using a simple set of rules the Fuzzy logic block decides by itself the firing angle to be given to attain the required voltage.
The Fuzzy logic block controls the firing angle circuit designed in MATLAB. The device TCR-FC is able to achieve flat voltage profile only for firing angles greater than 90 degrees. For firing angles less than 90 degrees TCR-FC is not able to control the voltage. The TCR model so designed is connected to the network to form the complete system with compensation. From the tabular forms and waveforms it is observed that the TCR-FC provides for an effective reactive power control irrespective of load variations.

5. Simulation Results

The simulation results were obtained using MATLAB software. Figure 8 shows the wave-forms without compensation for light loads with VR>VS that is the reactive power generated is greater than absorbed. Figure 9 shows the wave-forms without compensation for heavy loads with VR<VS that is the reactive power absorbed is greater than generated. Figure 10 represents the compensated rms and instantaneous voltage with fuzzy control.

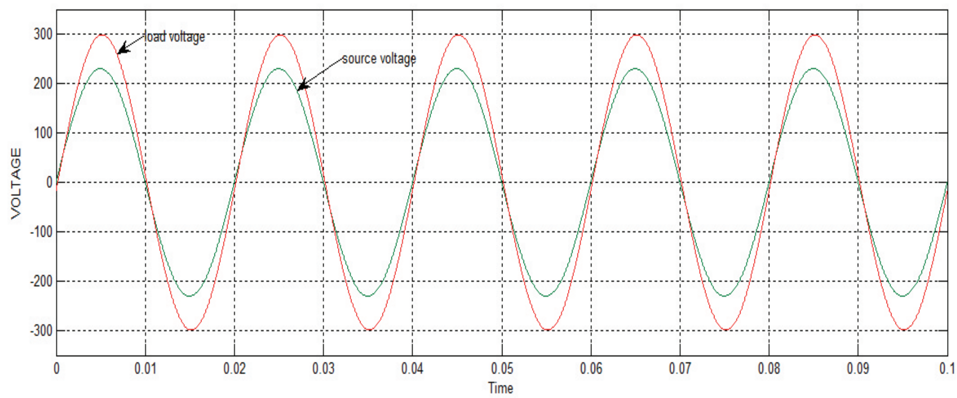

Figure 8: Wave-forms without compensation for light loads VR>VS as the reactive power generated is greater than absorbed

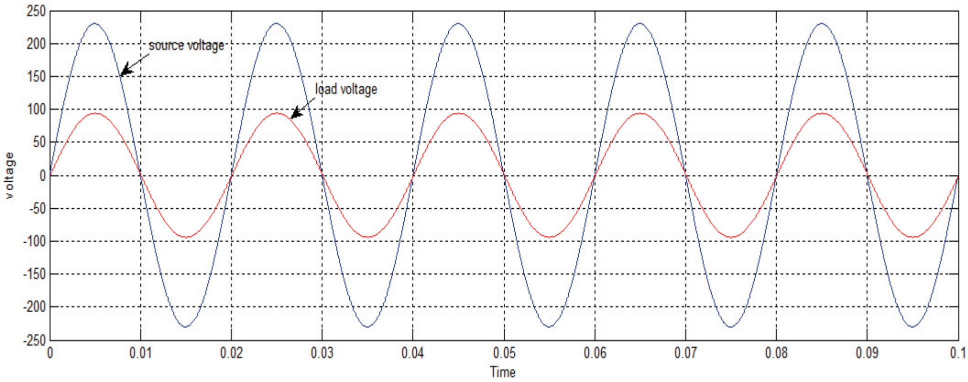

Figure 9: Wave-forms without compensation for heavy loads VR<VS as the reactive power absorbed is greater than generated

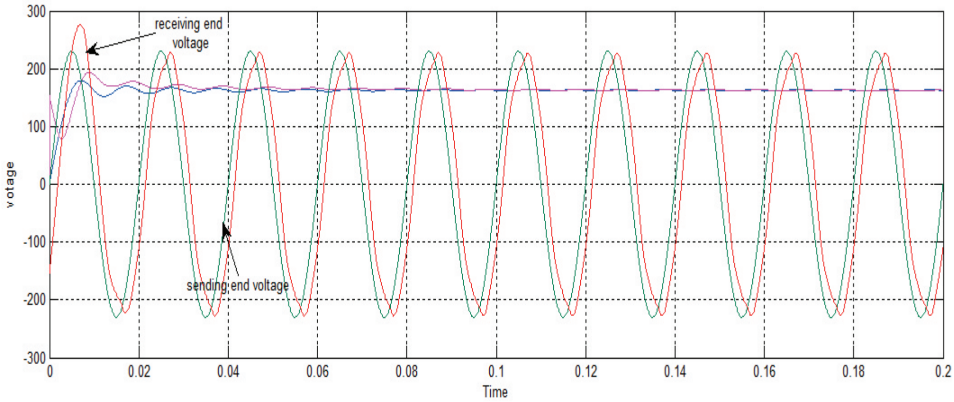

Figure 10: Compensated rms and instantaneous voltage with fuzzy control

Compensating voltages are shown in wave forms. The use of fuzzy logic has facilitated the closed loop control of system, by designing a set of rules, which decides the firing angle given to SVC to attain the required voltage. With MATLAB simulations and actual testing it is observed that SVC (FC-TCR) provides an effective reactive power control irrespective of load variations.

6. Conclusions

This paper presents an online Fuzzy control scheme for SVC. It can be concluded that the use of fuzzy controlled SVC (FC-TCR) compensating device with the firing angle control is continuous and effective. It is a simplest way of controlling the reactive power of transmission line. It is observed that SVC device was able to compensate both over and under voltages. The network without any compensation was not able to satisfy the essential condition of maintaining voltage within reasonable limits. The effect of increasing load led to a reduction of voltage at the load end. At light loads the load end voltage is greater than sending end voltage because of Ferranti effect. At higher loads the load voltage drops because the reactive power absorbed is greater than generated.

With the FC-TCR introduced the compensation of load voltage is fully controlled. The under voltages were compensated with greater firing angles while the over voltages at lower loads were brought to the required level by lowering firing angles. This is explained by the fact that for higher firing angles the angle or the time for which the inductor is in the circuit for the cycle of output voltage is lesser. For lower firing angles the inductor absorbs more reactive power and vice- versa. The output waveforms from MATLAB simulation clearly show the effect of introducing the inductor at the instant of firing. The voltage up to the firing instant was influenced by the network parameters and the fixed capacitor but from the instant of the firing angle the inductor also had its effect on the system voltage. It was observed that with FC-TCR in the circuit the load level up to which flat voltage profile is achieved is increased. If TCR alone is used without the fixed capacitor the compensation device would have been able to compensate the over voltages only. But due to the FC in circuit the SVC device was able to compensate for both over and under voltages.

It can be finally concluded that the use of TCR-FC compensating device with Fuzzy logic block serving the purpose of firing angle control is a continuous, effective and simplest way of controlling reactive power.

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