Enhancement of Power Quality in Power Distribution Systems Using FC-TCR Based Compensation Systems

DOI:10.36909/jer.15811

Okan Ozgonenel*, Secil Genc, Cenk Gezegin

Department of Electrical Electronics Engineering, Ondokuz Mayis University, Samsun, 55200, Turkey.

* Corresponding Author: okanoz@omu.edu.tr

ABSTRACT

The development of modern electronic systems and increasing number of application areas (computers, office equipment, rectifiers, converters, speed control devices, uninterruptible power supplies, switched power supplies) has led to harmonic generation and reduced energy efficiency. The majority of loads are inductive in nature and the draw of reactive power has increased in networks and transmission lines resulting in problems with power quality. In addition to efficient power flow in transmission systems, there is also a need to compensate for the reactive power flow in order the meet the requirements of the load and system. As an alternative to traditional solutions, FACTS (Flexible Alternating Current Transmission Systems) has been developed in order to operate electrical systems efficiently and improve stability and power quality. Technological applications such as SVC, STATCOM, SSSC and active harmonic filter are becoming widespread in order to improve power quality. In this study, applications within the scope of FACTS systems are explained and analysis of a fixed capacitor-thyristor controlled reactor (FC-TCR) to improve power factor is discussed. A circuit model of the FC-TCR is developed as a simulation and used to investigate how power factor may be kept within desired limits by adjusting the firing angle of the thyristors under different load conditions. A comparative evaluation has been carried out to determine the effect of FC-TCR by presenting results before and after the load compensation process is applied. From the simulation it is observed that reactive power compensation can be

achieved even for varying linear loads.

Keywords: Power factor correction, FACTS, reactive power, FC-TCR, SVC, STATCOM

1. INTRODUCTION

The development of modern power electronic systems and application areas (computers, office equipment, rectifiers, converters, speed control devices, uninterruptible power supplies, switched power supplies and arc furnaces) has led to an increase in harmonic generation and draw of reactive power in networks with resulting reduction in energy efficiency in transmission lines (Gandoman et al., 2018). The majority of loads in industry are inductive in nature. In addition to the increase in industrial load, the general demand for power is increasing (Gayakwad et al., 2014). The increase of reactive power to consumers is a significant influence on the voltage in the grid. Reactive power and the harmonics generated by consumer devices leads to issues that includes heating of electromagnetic devices, vibration and noisy operation in mechanical devices, low power factor in the network, malfunctions in electronic measuring devices, reduction of capacitor life by overheating, and losses etc (Desai, and Swapnil., 2017).

Reactive power compensation is one of the most effective and easiest ways to increase efficiency and save energy in electrical energy systems (Shahgholian and Faiz, 2010 and Miller, 1982). FACTS (Flexible Alternating Current Transmission Systems) have been developed as an alternative to conventional solutions in order to operate electrical systems efficiently, and improve stability and power quality. FACTS controllers may be implemented as, static VAR compensator (SVC), thyristor-controlled series compensator (TCSC), thyristor-controlled phase angle regulator (TCPAR), static synchronous compensator (STATCOM), also known as a static synchronous condenser (STATCON), and unified power flow controller (UPFC) (Kececioglu et al., 2016; Kowalak and Małkowski, 2011 and Edris, 2020).

In this paper, a new FC-TCR based compensating algorithm is proposed. Simulation results and theoretical solutions demonstrate that the methodology performs effectively correct power factor and improves voltage stability. The paper is organized as operation of FC-TCR, Material and Methods including non-varying and varying load cases.

2. OPERATION of FIXED CAPACITOR THYRISTOR CONTROLLED REACTOR (FC-TCR)

The FC-TCR comprises two components; a TCR module that monitors and controls reactive power and a FC (Fixed Capacitor) to apply compensation, and which may also include filters for higher harmonics. The TCR aims to compensate for the current in the inductance L by varying the firing angle of the thyristor from the highest value (thyristor always on) to zero (thyristor always off) (Gayakwad et al., 2014; Ahmed and Sekhar, 2017). A simplified model of single FC-TCR compensator is shown in Figure 1.

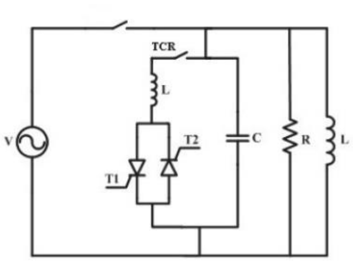


Figure 1. A simplified model of single FC-TCR compensator

The triggering of the thyristor is delayed according to the peak of the applied voltage in each half cycle. Current delays the voltage in the reactor by 90°, thus a firing angle of 90° causes the largest current through the reactor. For a 180° firing angle the current flowing through the reactor will be zero. Therefore, by controlling the phase angle of the thyristors in the range $90° \leq \alpha \leq 180°$ the TCR current can be changed from zero to a maximum value with respect to the peak of the voltage. When the TCR is off, the largest capacitive VAR output is achieved. The capacitive effect is reduced by increasing the current in the reactor by decreasing the angle α (Gayakwad et al., 2014; Martinez and Enjeti, 1996; Ma et al., 2009;

Shobha et al., 2016; Gelen and Yalcinoz, 2009; Gelen and Yalcinoz, 2007).

3. MATERIAL and METHOD

3.1 Non-Varying Linear Load Case

A simulation study of a FC-TCR based SVC structure for reactive power compensation for a non-variable load case has been undertaken and the flowchart for the compensation process is given in Figure 2.

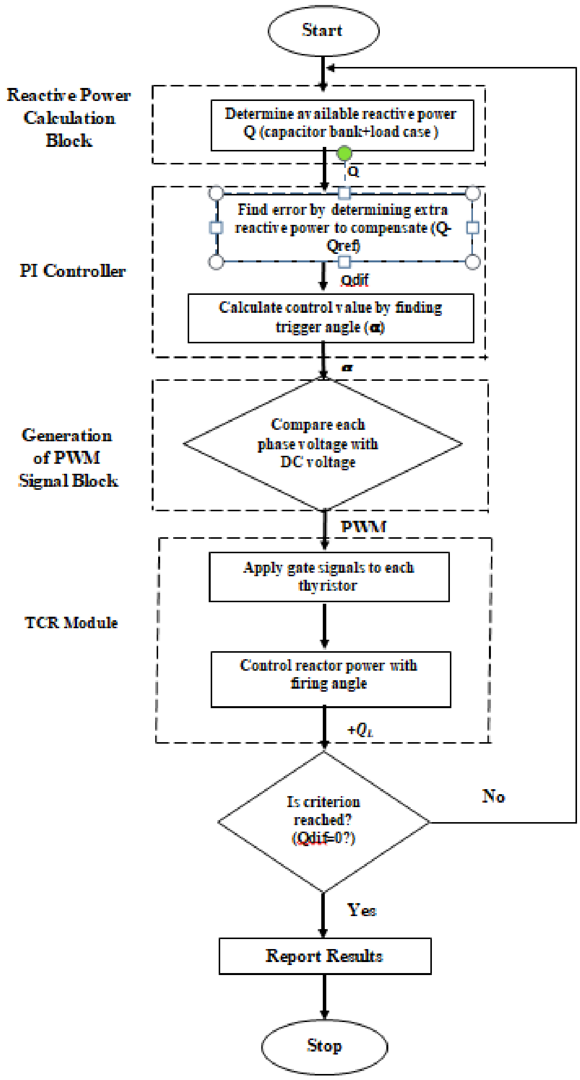


Figure 2. Flowchart of FC-TCR based compensation system

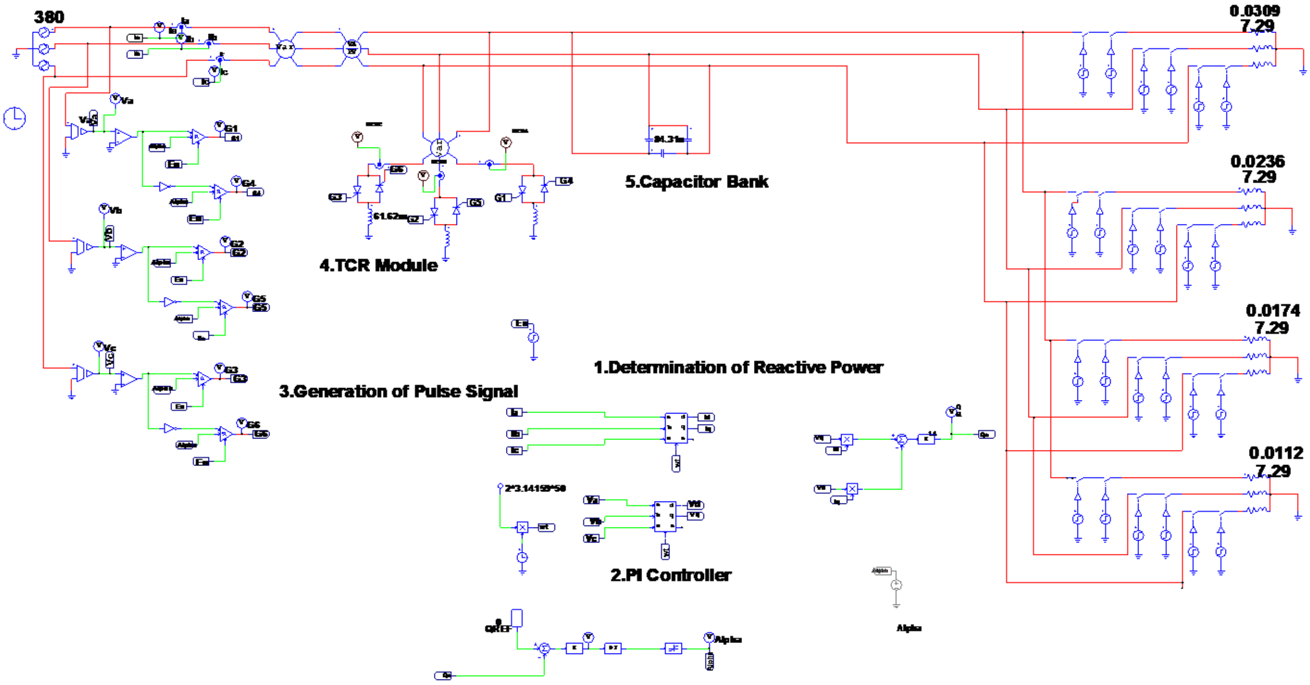


Figure 3. Simulation circuit of FC-TCR based SVC

The compensation circuit of Figure 3 comprises five parts: determination of reactive power, PI controller, generation of pulse signal, TCR module and capacitor bank. As the FC-TCR is used in a 380V, 50Hz low voltage transmission line, the capacitor bank is delta connected and the TCR is star connected. The reactive power of the load is given by Equation 1:

$$Q\_load=3*V*I*\sin\gamma \qquad (1)$$

Where:

V = rms voltage, I = rms load current and γ = load angle.

The reactive load Q_load is subtracted from the QC of the capacitor bank, with the remaining Q_dif being provided by the TCR. A voltage proportional to the difference between Q_load and QC, Q_dif, is given as the input to the proportional-integral (PI) controller and the firing angle to the TCR is adjusted to provide Q_dif. The output of the PI controller is a DC value representing the switching angle and is used to produce the pulses that are applied to the thyristor gates. The current in the reactors, ITCR, is directly related to the firing angle, α.

The value of the component B_TCR is given by Equation 2 (Zellagui and Chaghi, 2013):

$$B_{TCR}(a) = B_{Lmax}\left[1 - \frac{2a}{\pi} - \frac{1}{\pi}\sin(\alpha)\right] \quad (2)$$

Where; $B_{Lmax} = \frac{1}{L.\omega}$

In the first case, a fixed three phase ohmic-inductive load (R = 7.29 Ω and L = 0.03093 H) is connected in star to the the three-phase AC 380 V transmission line. The value for the components to provide a specific load and power factor may be calculated as Equation 3 and Equation 4, shown here to apply a load with power factor of 0.6.

For R = 7.29 Ω and cosØ = 0.6:

$$\emptyset = cos^{-1}(\emptyset) = 53.13^{\circ} \quad (3)$$

$$X_L = \tan(\emptyset)X_R = 9.72\ \Omega \quad (4)$$

The effect of the TCR compensation is observed by running the simulation for 0.2 s before compensation is applied. To generate the pulses at a certain angle to turn on reactive current, the following operations are implemented. The pulse signals applied to the thyristor gates are generated for each phase from the output of the PI controller applied to an alpha controller block, using the measured voltage and a comparator to detect zero crossing in PSIM software. G1, G2 and G3 control the reactor in the positive half cycle and G2, G4 and G6 in the negative half cycle. Figure 4, shows the 120˚ phase difference between the gate pulse applied to the thyristors in each phase of the reactor. The instantaneous current I_TCR of one phase over the positive half cycle is given by Equation 5 and the relation between the fundamental component of the reactor current and the firing angle α is given in Equation 6 (Gayakwad et al., 2014). These equations are valid between certain time limits (zero otherwise).

$$I_{TCR} = \left(\sqrt{2}V\right) / x_L(\cos\alpha - \cos wt) \quad (5)$$

$$I_1 = \frac{v_{rms}}{\pi\omega L}(2\pi - 2\alpha + sin(2\alpha)) \quad (6)$$

The phase control technique is used to control the thyristors, which are switched off at the zero crossing of the voltage in each cycle. Since the inductor current lags 90 ° from the voltage waveform, here the thyristor-controlled reactor is controlled at an angle in the range of 90 ° to 180°. The waveforms of TCR reactor currents are shown in Figure 5. Reactive power and power factor correction given by Figure 6.

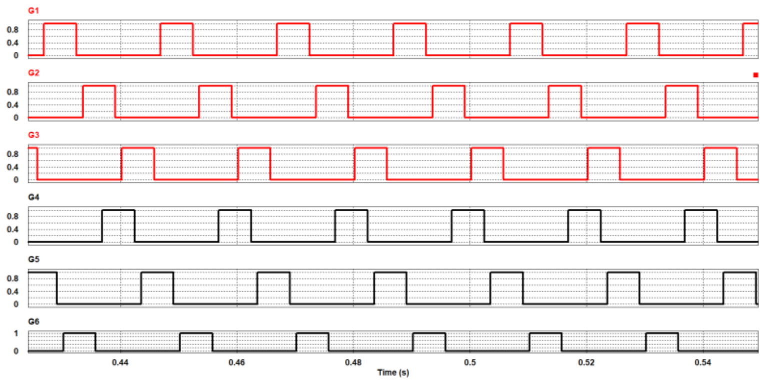


Figure 4. TCR gate signals waveform (146.65 ° triggering angle)

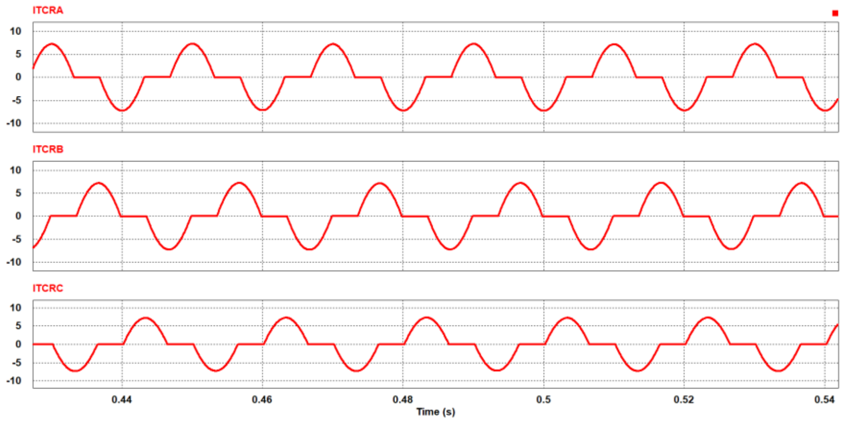


Figure 5. FC-TCR reactor phase currents

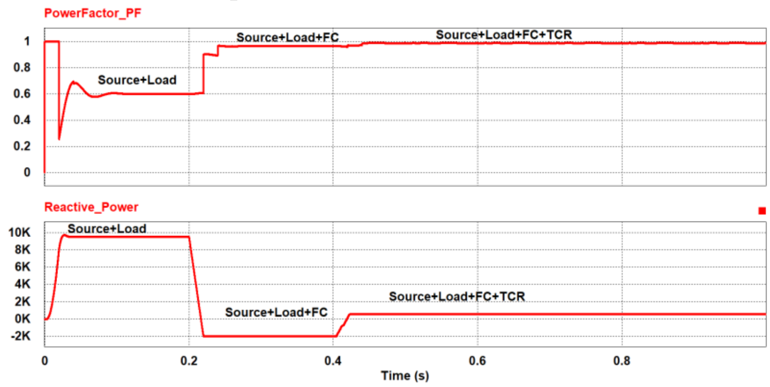


Figure 6. Reactive power and power factor

In the simulation, the lower limit of the limiter has been set to 90 and the upper limit as 180 with a limiter in order to change the angle between 90° and 180°. In order to observe the effect of the compensation, the power is applied for 0.2 s without the capacitor bank connected, and then it is connected. The capacitors have a value of 84.31 μF, which is sufficient to compensate a load with power factor of 0.6 as minimum. However, there is some overcompensation, which must be balanced by using the reactor. The detail of generating reactors gate signals and FC-TCR switching are shown in Figure 7 and 8.

Figure 7. Detail of generating reactor gate signals

The PWM applied to the thyristors is obtained by comparing the phase voltages measured by the instantaneous voltage ranges with the DC voltage (also the thyristor firing angle). The DC voltage is also the value obtained from the PI control output. Reactor control is provided with gate currents G1, G2 and G3 in the positive half period and with gate currents G4, G5 and G6 in the negative half period. Therefore, G1 and G4, G2 and G5, and G3 and G6 are connected to form gate signals with opposite sign.

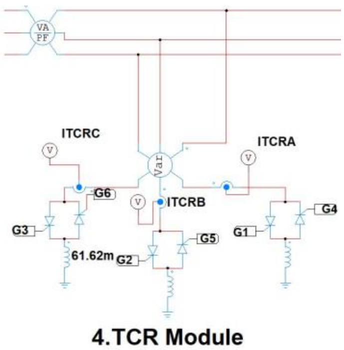


Figure 8. Detail of FC-TCR switching

The gate signals obtained in Figure 7 are used to control the thyristors connected to the TCR reactor. The over compensation situation is provided by the control of the triggering angles of the thyristors connected to the reactor. G1 and G4 gate signals are connected to phase A, G2 and G5 are connected to phase B, and G3 and G6 are connected to phase C. They control the inductive current flow in the positive and negative half-wave periods, respectively.

The reactive power drawn from the system may be determined by converting to the DQ axis using the ABC-DQ transformation. The reactive power is calculated using Equation 7 (Tahri and Draou, 2005). Detail of reactive power calculation is given as Figure 9.

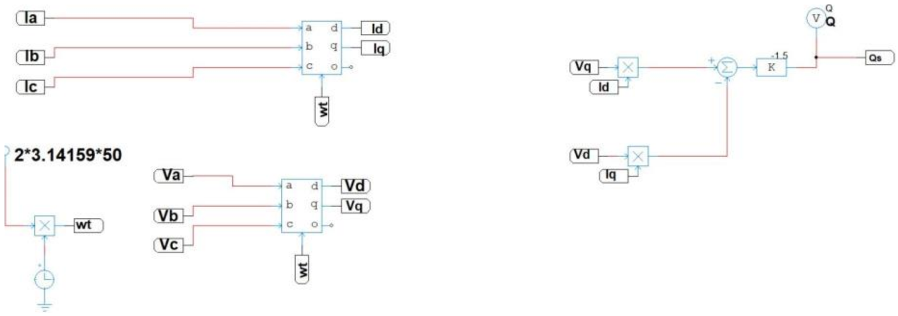


Figure 9. Detail of reactive power calculation

$$Q = \frac{3}{2}\left(v_q I_d - v_d I_q\right) \quad (7)$$

The error of the reactive power is determined by comparing the total drawn reactive power with the reference (zero) value. The error is applied to the PI controller and the appropriate thyristor angle, α, is determined, as shown in 10 and 11.

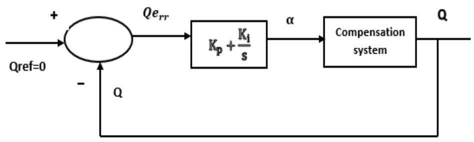


Figure 10. Closed loop block diagram of FC-TCR system with PI controller

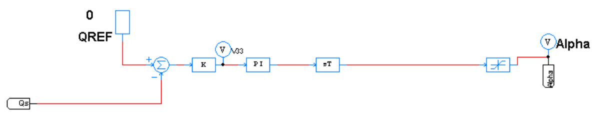


Figure 11. Closed loop of FC-TCR system with PI controller in PSIM software

The parameters for the PI controller are selected to provide the optimum solution. For low power factor (0.6) laods, the thyristor trigger angle must be large in order to compensate reactive power factor in the forward direction. Therefore, the trigger angle is calculated based on the lowest 0.6 power factor. Firstly, the reactors are not active in the system (when the system that calculates the trigger angle is active) in other words, closed loop will stop at particular value of alpha when both the value of Q will be matched and at that time alpha angle freeze. As the controller that calculates the trigger angle is disabled and reactors are active, obtained DC value is used to obtain the gate signals. It has been observed that as the controller gain decreases, the angle will decrease and more reactors will apply power to the system in the forward direction. The PI controller current gain is determined as Kp = 0.04 (proportional) and Ki = 100 (integral) to give enough reactive power with suitable trigger angle. These steps are done to determine the appropriate gain values of the PI controller. After determining the proper gain, the closed loop control loop is always active and automatic compensation is made.

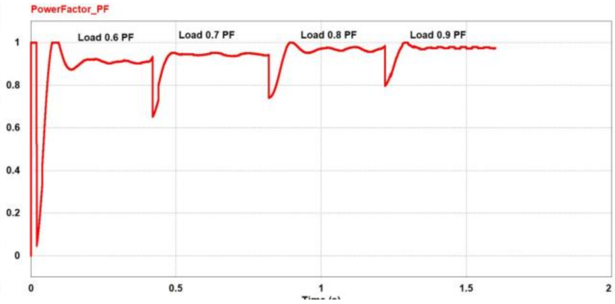
3.2 Varying Load Case

In the varying load case, a load with a power factor varying between 0.6 and 0.9 is connected successively to the circuit at 0.4 s intervals to investigate the performance of the FC-TCR to transient loads. Table 1 shows the load values for each power factor. Note that compensation beyond a power factor of 0.95 will require either a larger value of inductor or a smaller value of capacitor.

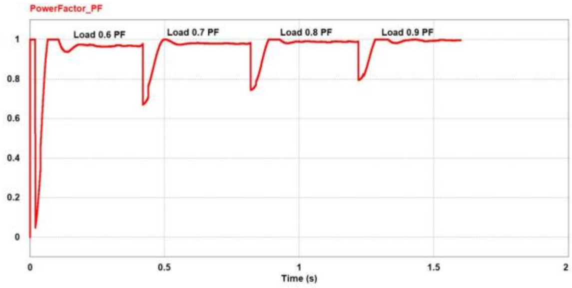
Table 1. Load values corresponding to power factor

Load value		Power factor
R (Ω)	**L (H)**	
7.29	0.03093	0.6
7.29	0.0236	0.7
7.29	0.0174	0.8
7.29	0.0112	0.9

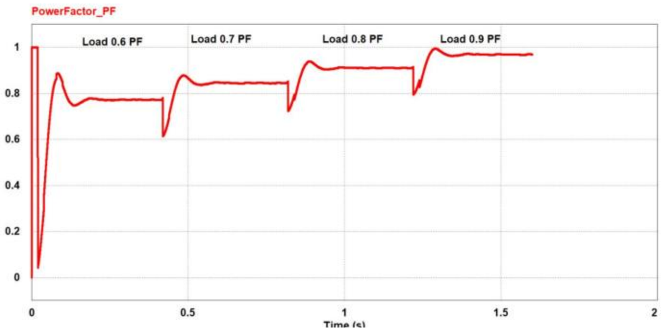
The thyristor angle is altered by the reactive power control circuit to keep the power coefficient at 0.99, even under varying load conditions. Power factor range under varying load and different controller (P, PI, and PID) are given by 12



(a)



(b)



(c)

Figure 12. Power factor under variable load with P controller (Kp=0.04) (a), PI controller (Kp=0.04, Ki=100) (b) and PID controller (Kp=0.04, Ki=100, Kd=0.01) (c)

The gain values of each controller are recorded, the values at which the controller operates best. As can be seen from the figures, the desired power factor of 0.99 can be reached with the PI controller in each of load conditions, but other controls cannot provide for all cases. Oscillation is highest with P controller. The shortest settling time is provided with PID controller. Rise times are equal in all. As a result, it has been determined that the best controller for best compensation with FC-TCR SVC is PI controller.

4. CONCLUSION

This study presents a FC-TCR based SVC structure that has been simulated to determine performance for static and variable load conditions. When compensation is done with different control methods, the best method is determined as PI controller. The controller gains operated best while Kp = 0.04 for proportional control, Kp = 0.04, Ki = 100 for PI control and Kp=0.04, Ki=100, Kd=0.01. Oscillation is highest with P controller. The shortest settling time is provided with PID controller. Rise times are equal in all. The simulation shows that reactive power compensation is performed correctly and maintains the power factor at 0.99 for static and varying linear load conditions, and responds well to the transient condition when the load is switched. Also, the results obtained in this study were compared with other authors working in the relevant field given by Table 2. Chaudhari et al. were simulated open loop study of fixed capacitor thyristor-controlled reactor (FC-TCR) system using Matlab/Simulink for various loading (Chaudhari et al., 2018). Khanmohammadi et al. were researched the fuzzy logic control strategy of SVC. Reactive loads were switched in different times. Performance of the proposed technique was demonstrated by using MATLAB/Simulink on a single machine infinite bus system. Results are given by Table 2 (Khanmohammadi et al., 2007). Szabó et al. were used Matlab/Simulink was to design SVC for the implementation in a three-phase 22 kV power line model. A compensation of power factor in each phase was done independently by using PID controller. Variation of power factor for desired phase with compensation given Table 2, also (Szabó et al., 2015). Farkoush et al. were done power factor correction by using TCR and TSC. Their simulation results were displayed with MATLAB/Simulink by using PI controller. When a load fault occurs and load was changed between from 0.6 to 0.8, they noted the results not given by Table 2. When power factor was 0.8, it was increased to 0.9 and also when SVC was not connected, power factor was 0.3, while the SVC was used, the variety level of power factor was changed to 0.5 (Farkoush et al., 2016). In this study, when variety level of power factor is between 0.6 and 0.9 demonstrated by Table 2. As can be observed from the results, the desired power factor is more improved in this study compared with the relevant studies by using PI controller in PSIM trial software.

Table 2. Overview of the other works performances

Work	Power factor	Power Factor with Compensation
Chaudhari's work	0.819	0.902
	0.801	0.9166
	0.781	0.9297
	0.792	0.942
	0.743	0.9537
	0.707	0.9732
Khanmohammadi's work	0.7	0.99
	0.6	0.97
	0.4	0.92
	0.5	0.96
Szabós's work	0.8	0.9
Current work	0.6	0.99
	0.7	0.99
	0.8	0.99
	0.9	0.99

REFERENCES

Gandoman, F. H., Ahmadi, A., Sharaf, A. M., Siano, P., Pou, J., Hredzak, B.& Agelidis, V. G. 2018. Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems. Renew. Sustain. Energy Rev 82: 502–514.

Gayakwad, D. R., Mehta, C. R.& Desai, S. P. 2014. Automatic reactive power control using FC-TCR. International Journal of Advanced Computer Research 4(2): 1–5.

Desai, D.& Swapnil, A. 2017. Reactive power compensation using FACTS device. Kalpa Publications in Engineering 1: 175–180.

Miller, T. J. E. 1982. Reactive power control in electric systems. New York, Wiley. Pp. 32-48.

Shahgholian, G.& Faiz, J. 2010. Static synchronous compensator for improving performance of power system: A review. Int. Rev. Electr. Eng 5(5): 2333–2342.

Kececioglu, O.F., Gani, A.& Sekkeli, M. 2016. A performance comparison of static VAR compensator based on Goertzel and FFT algorithm and experimental validation. SpringerPlus 5(1): 1-13.

Kowalak, R.& Małkowski, R. 2011. Shunt compensator as controlled reactive power sources. Acta Energetica 1(6): 13–20.

Edris, A. 2000. FACTS technology development an update. IEEE Power Engineering Review 20(3): 4-9.

Padiyar, K. R. 2007. FACTS controllers in power transmission and distribution. India, New Delhi. Pp.

Preethi, B.& Sumangala, B. V. 2013. Implementation of thyristor switched capacitor for reactive power compensation at secondary of distribution level feeders for voltage stability improvement. International Journal of Engineering Research & Technology (IJERT) 2(5): 322–329.

Chopade, P., Bikdash, M., Kateeb, I.& Kelkar, A. D. 2011. Reactive power management and voltage control of large transmission system using SVC (static VAR compensator). 2011 Proceedings of IEEE Southeastcon. Nashville, USA.

Patel, R., Bhatti, T. S.& Kothari, D. P. 2002. MATLAB/Simulink-based transient stability analysis of a multimachine power system. International Journal of Electrical Engineering Education 39(4): 320-336.

Ahmed, R. H.& Sekhar, C. P. 2017. Correction power factor of transmission lines using advanced FACTS controllers. Internetional Journal of Research and Innovation 4(1).

Martinez, R.& Enjeti, P. N. 1996. A high-performance single-phase rectifier with input power factor correction. IEEE Trans. Power Electron 11(2): 311–317.

Ma, W., Jiao, L., Shang, R.& Zhao, F. 2009. Medical image segmentation based on immune clonal optimization. 2009 IEEE International Conference on Intelligent Computing and Intelligent Systems. Shanghai, China.

Mane, S. R., Kolekar, A. A., Molaj, M. M., Patil, S. V.& Mestri, M. N. 2016. Arduino based power factor correction. International Journal of Electrical, Electronics and Data Communication 4(4): 4-8.

Gelen, A.& Yalcinoz, T. 2009. PI control of thyristor switched capacitor (TSC) and thyristor switched reactor-based static VAR compensator (TSR-Based SVC). Journal of the Faculty of Engineering & Architecture of Gazi University 24(2): 237-244.

Gelen, A.& Yalcinoz, T. 2007. Analysis of TSR-based SVC for a three-phase system with static and dynamic loads. 2007 Int. Conf. Electr. Eng. Lahore, Pakistan.

Zellagui, M.& Chaghi, A. 2013. Impact of SVC devices on distance protection setting zones in 400 kV transmission line. UPB Scientific Bulletin, Series C: Electrical Engineering 75(2): 249-262.

Tahri, A.& Draou, A. 2005. Instantaneous active and reactive power measuring method in three phase power system. Leonardo Electronic Journal of Practices and Technologies 4(6): 17-28.

Chaudhari, Y., Kalaskar, S., Patil, P., Patil, S., Shete, S.& Salvi, A. 2018. Performance analysis of FC-TCR. International Journal of Trend in Research and Development 5(3): 7.

Khanmohammadi, S., Hagh, M. T.& Abapour, M. 2007**.** Fuzzy logic based SVC for reactive power compensation and power factor correction. 2007 International Power Engineering Conference (IPEC 2007). Singapore.

Szabó, D., Regul'a, M., Bodnár, R.& Altus, J. 2014. Control of a SVC for power factor correction. 2014 ELEKTRO. Rajecke Teplice, Slovakia.

Farkoush, S. G., Park, S. N., Kim, K. H.& Rhee, S. B. 2016. Efficient Power factor improvement with SVC based on the PI controller under load fault in the smart grid. International Journal of Applied Engineering Research 11(1): 96-100.