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Research Article

Performance Evaluation of an FCTCR-Based Reactive Power Compensation System Under Dynamic Load Conditions

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ABSTRACT

This work discusses modeling and performance analysis of a Fixed Capacitor-Thyristor Controlled Reactor (FCTCR) system for dynamic reactive power adjustment in AC power systems. The suggested compensator is a fixed capacitor branch and a thyristor driven reactor to control the reactive power under different load circumstances. A closed-loop firing angle control approach is used for dynamic adjustment of the reactor current according to the reactive power need of the system. The created model is tested for different values of inductive load in steps to study the reaction of active power, reactive power compensation features, load behaviour and performance of the thyristor controlled reactor. The simulation results illustrate the effectiveness of the proposed FCTCR system in providing capacitive reactive power support, improvement of reactive power balance and stable operation under dynamic loading situations. The compensator has good transient response and dynamic regulation performance, therefore it is applicable for low voltage reactive power compensation and power factor enhancement.

Keywords: FCTCR, Reactive Power Compensation, Power Factor Improvement, Flexible AC Transmission Systems, Dynamic Load Compensation

Introduction

Efficient reactive power management is essential for maintaining the stable and dependable functioning of modern electrical power systems. Inductive equipment, including motors, transformers, compressors, and power electronic devices, is frequently utilized in extensive industrial and commercial installations, hence increasing the reactive power demand within the network [1-3]. Elevated reactive power consumption results in a diminished power factor, increased line current, augmented power losses, voltage instability, and a decline in transmission efficiency. The rising trend in power consumption has rendered the preservation of acceptable power quality and the effective operation of the system a critical challenge in electrical distribution systems.

Reactive power compensation techniques [4-6] are widely utilized to improve the system performance and to avoid undesired effects due to inductive loading. The most popular compensation mechanisms employed are the conventional fixed capacitor banks [6-7] due to their simple design and economical implementation. Fixed capacitors are reactive power support [8-9], but their compensation capability is constant and cannot adjust to the continuously changing operating conditions. In actual systems with dynamic load demands, fixed compensation approaches may not give an acceptable performance which results in poor reactive power regulation and unstable power factor situations.

Dynamic compensating capability development is a priority for power system engineers and researchers with controllers of Flexible AC Transmission Systems for reactive power regulation [5, 10-11]. Among these compensators, the FCTCR [12-15] has gained much attention due to its relatively simple structure and effective compensating capabilities. The compensator is composed of a fixed capacitor branch and a thyristor driven reactor branch for reactive power control according to the load needs. The capacitor branch continually provides capacitive reactive power, and the reactor branch absorbs adjustable inductive reactive power by changing the thyristor firing angle. This method of operation allows for smooth and continuous control of reactive power under various system situations.

The dynamic operating features of the compensator increase the overall system performance by preserving better reactive power balance and improved power factor conditions [12-13]. Thyristor switching of the reactor current gives fast reaction to the load changes and reduces the reactive power strain on the source. This leads to a lower magnitude of source current, better voltage management and higher overall power system efficiency. These benefits make the compensator a good solution for reactive power management and power quality improvement in low voltage power systems.

In this paper, a closed-loop FCTCR system is built and examined for dynamic reactive power compensation applications. The proposed model contains a thyristor driven reactor branch, fixed capacitor unit, firing angle control circuit and changeable inductive load conditions. The system performance has been examined under different operating settings to evaluate the active power response, reactive power compensation capabilities, compensator features and dynamic system behavior. The simulation results show the effective reactive power regulation and steady compensating performance under different load circumstances.

Operating Principle And Mathematical Modeling Of Fctcr

The proposed compensator is based on the principle of dynamic reactive power compensation by coordinated operation of a fixed capacitor branch and a thyristor driven reactor branch. The mathematical modeling of the system is built to examine the reactive power compensation capacity, firing angle control behavior and power factor enhancement for different load scenarios.

A. Operating Principle of FCTCR

The FCTCR compensator concept is based on the premise of dynamically controlling the reactive power by controlling the fluctuation of the reactor current [16-17]. The compensator consists of a fixed capacitor branch in tandem with a thyristor driven reactor branch. The fixed capacitor provides capacitive reactive power to the system continuously while the reactor branch absorbs inductive reactive power in a regulated manner, depending on the system operating situation. Overall reactive power compensation is performed by changing the conduction angle of the thyristors linked to the reactor branch.

The thyristor controlled reactor consists of anti parallel thyristors in series with an inductor. The firing angle of the thyristors is varied to adjust the effective reactor current. Reducing the firing angle increases the conduction interval of the thyristors, therefore increasing the reactor current and increasing the inductive reactive power absorption. Likewise, an increase in the firing angle reduces the absorption of reactive power and the current of the reactor. This firing angle control arrangement allows for continuous management of reactive power under shifting load situations.

The reactive power absorbed by the thyristor-controlled reactor is expressed by eq. (1).

$$Q_{TCR} = \frac{V^2}{X_L}\left(\frac{2}{\pi}(\pi-\alpha)+\frac{1}{\pi}\sin(2\alpha)\right) \tag{1}$$

where V represents the supply voltage, X_L denotes the reactor inductive reactance, and α is the thyristor firing angle.

The total reactive power compensated by the compensator is obtained by the difference of the reactive power supplied by the fixed capacitor and the reactive power absorbed by the reactor branch, given by:

$$Q_{FCTCR} = Q_C - Q_{TCR} \tag{2}$$

where $Q_C$represents the reactive power supplied by the capacitor branch and Q_{TCR}denotes the reactive power absorbed by the reactor branch.

The suggested system has a closed loop operating mechanism which constantly monitors the system reactive power requirement and consequently the firing angle of the thyristors is automatically adjusted. This dynamic control capacity allows for consistent compensating performance during load variations and enhances the overall reactive power balance of the system.

B. Power Factor Improvement

Power factor is one of the major performance parameters in electrical power systems as it provides the effective utilization of electrical power. In systems with large inductive loads, increasing demand of reactive power leads the power factor to decrease which results in increased source current, greater transmission losses and poor voltage control. Hence reactive power adjustment is needed to maintain acceptable power factor conditions and enhance system efficiency [13, 17-18].

The power factor equation (3) describes the relationship between active power, reactive power and perceived power.

$$PF = \frac{P}{\sqrt{P^2 + Q^2}} \tag{3}$$

where $P$is the active power and $Q$is the system reactive power of the system.

In the proposed compensator, the fixed capacitor provides capacitive reactive power to compensate inductive reactive power absorbed by the load. The reactor current is dynamically controlled by the TCR according to the system operating parameters. This coordinated action decreases the net reactive power demanded from the source, and enhances the overall system power factor.

The reactive power demand varies continuously during dynamic load variations. The closed-loop firing angle control mechanism is employed to change the conduction angle of the thyristors to achieve a consistent compensation performance [19-21]. Hence the proposed technology minimizes the source current magnitude, improves the voltage regulation and increases the overall efficiency of power system. The dynamic compensating capacity of the compensator makes it suited for reactive power management applications under different operating situations.

FCTCR System Modeling and Control Strategy

The proposed compensation scheme is developed using FCTCR based Static Var Compensator setup for dynamic reactive power control under varied load situations. The overall system configuration consists of AC source, transmission line, fixed capacitor branch, thyristor controlled reactor branch, measurement unit, firing angle controller, gate pulse generation circuit and switching inductive load bank. The whole configuration and operating principle of the suggested compensator is shown in Figure1.

The AC supply system operates at a voltage of 230 V and frequency of 50 Hz. The load side is composed of dynamically varying inductive load branches connected by switching operation to provide multiple states of reactive power demand. The system reactive power requirement is continuously changing due to load variations, which results in variations in source current, power factor and reactive power flow. The proposed compensator is linked in shunt with the load to control the reactive power dynamically and to keep the enhanced operating conditions.

The compensator consists of two basic portions, a fixed capacitor section and a thyristor-controlled reactor section [12-16]. The fixed capacitor provides capacitive reactive power constantly to the system. The thyristor controlled reactor absorbs tunable inductive reactive power as per the system requirements. The reactor branch is an inductor with anti-parallel thyristors in series. The reactor branch absorbs inductive reactive power, which is controlled by adjusting the firing angle of the thyristors, which controls the conduction interval of the reactor current. A closed-loop firing angle control approach is adopted to achieve the automatic reactive power management. The measuring device continually measures the voltage and current signals of the main line and in real time calculates the relevant active and reactive power values. The firing angle controller creates the required control signals for the gate pulse generator based on the detected reactive power situation. The resulting gate pulses are applied to the thyristors of the reactor branch, regulating the reactor current and ensuring the necessary level of reactive power compensation.

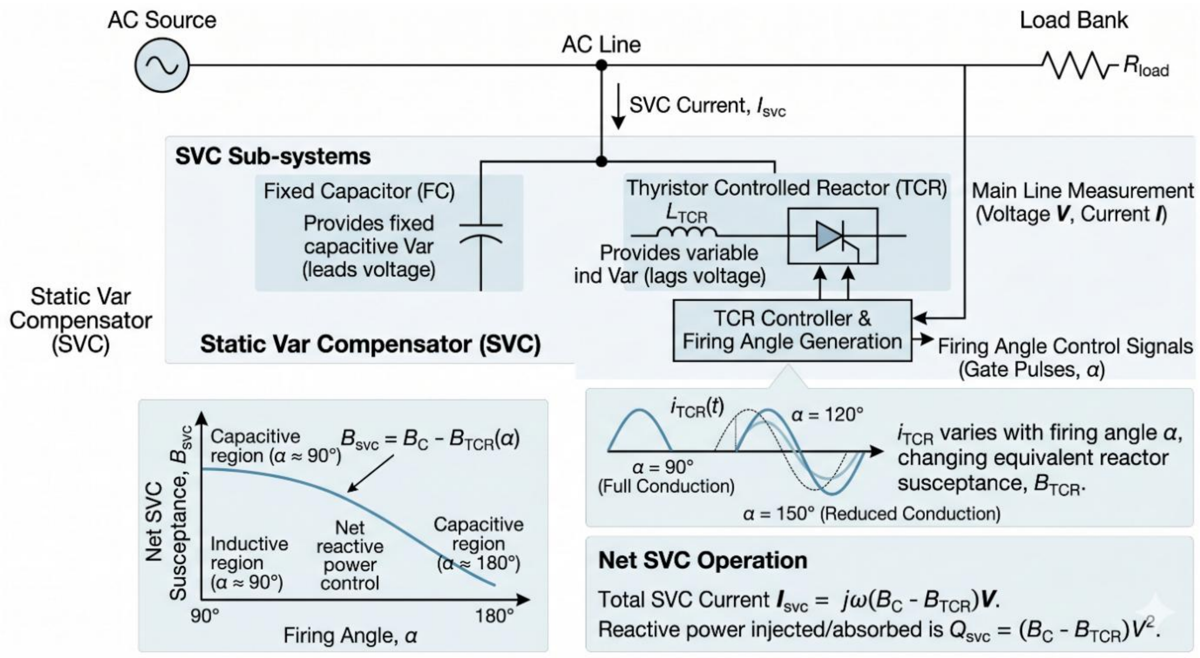

Figure 1. Schematic configuration and operational characteristics of the FC-TCR, including the net susceptance B_{SVC} as a function of firing angle α

Table 1. Electrical Parameters of Proposed FCTCR System

Parameter	Value
AC Source Voltage	230 V
Supply Frequency	50 Hz
System Type	Single Phase
Base Load Active Power	500 W
Initial Reactive Load	1000 VAR
Additional Reactive Loads	500 VAR, 1000 VAR, 500 VAR
Fixed Capacitor Configuration	Shunt Connected
Simulation Time	2 s
Simulation Type	Continuous

Table 2. **Control and Switching Parameters of Proposed FCTCR System**

Parameter	Value
Thyristor Forward Voltage	0.8 V
Thyristor ON Resistance	0.001 Ω
Snubber Resistance	500 Ω
Snubber Capacitance	250e−9 F
Pulse Generator Frequency	50 Hz
Firing Angle Control	Closed Loop
Compensation Technique	FC-TCR Based
Reactive Power Control	Dynamic

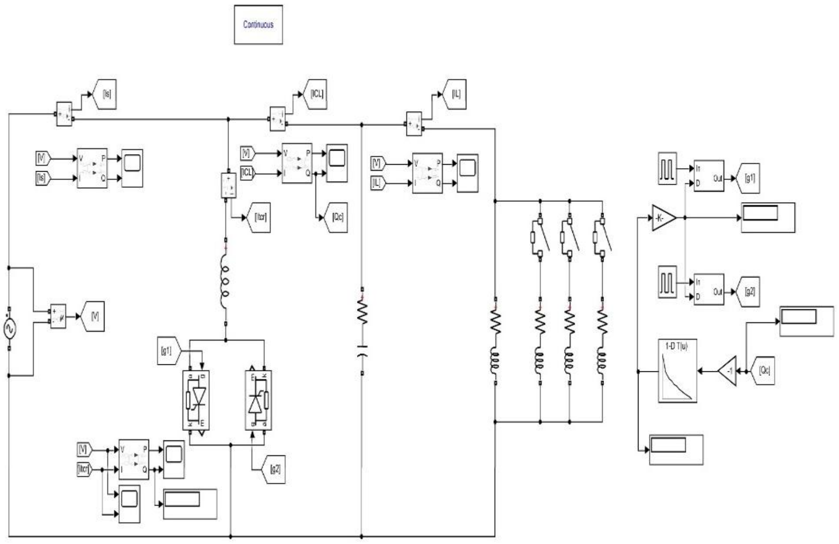

Figure 2. Simulation Model of the Proposed FCTCR Compensation System

The suggested system is modelled and analysed under the continuous simulation circumstances to assess the transient and steady state response . Different measurement scopes are provided to monitor the active power characteristics, reactive power compensation response, load power behavior and thyristor controlled reactor performance during dynamic load changes. The developed model is expected to provide a better reactive power balance, improved power factor and stable operation performance under different system situations. Figure 2 presents the created MATLAB/Simulink model of the proposed FCTCR compensation system. The proposed model includes an AC voltage source, fixed capacitor branch, thyristor controlled reactor branch, firing angle control circuit, measurement units and dynamically variable inductive load bank. The reactive power absorption is controlled by the thyristor-controlled reactor through the gate pulse signals generated by the firing angle controller depending on the system operating parameters. The model includes different measurement blocks and scopes to investigate active power response, reactive power compensation characteristics, load behavior, and compensator performance under different load situations. The primary electrical and control parameters used for execution of the proposed FCTCR compensation system are presented in Tables 1 and 2. The settings are selected based on the dynamic load condition of reactive power compensation operational needs. The specified system characteristics allow a dynamic study of the compensator behavior in different load scenarios. The created model is effective to analyze the reactive power compensation capabilities, transient response characteristics and operation of thyristor controlled reactor under sequential load fluctuations.

Simulation Results And Discussion

The reactive power compensation capabilities and operating features of the proposed FCTCR compensation system are investigated under dynamically changing load conditions. The simulation investigation is performed for total time of 2 s under steady state settings. The switching inductive load bank is used to induce variations of load in a stepwise manner, so that the transient and steady-state response of the compensator system may be studied.

The simulation model is operating with single phase 230 V, 50 Hz AC supply system. During the simulation interval, various inductive load levels are connected sequentially, which produces a change in the active and reactive power consumption. The proposed compensator controls the reactive power flow by dynamically adjusting the conduction angle of the thyristor driven reactor depending on the system operating condition.
The system performance is studied in terms of different scopes of measurement such as the active and reactive power response of the compensator, reactive power compensation characteristics, load power characteristics and the operational characteristics of the thyristor controlled reactor. The acquired results are applied to the effectiveness estimation of the suggested compensator in reactive power balance and stable operation of the system in load changes. The simulation findings show that the suggested compensator can provide capacitive reactive power support and dynamically control inductive reactive power absorption under different load circumstances. The firing angle control mechanism provides a suitable transient response and ensures stable operation of the compensator for the whole simulation interval. Furthermore, the compensator helps to improve the reactive power balance and adds to the better power factor performance under dynamic operating situations.

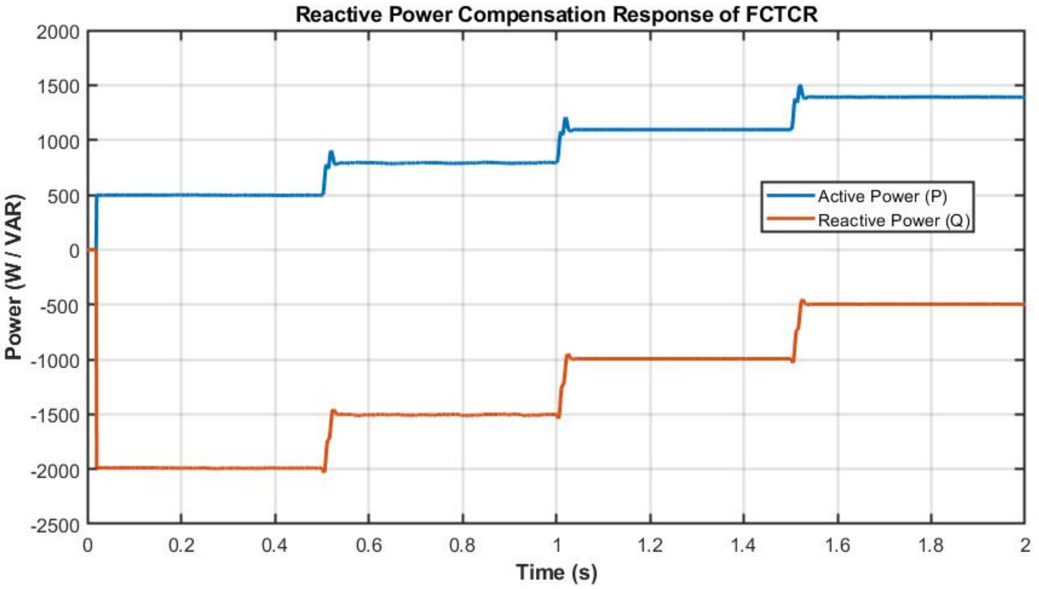

Figure 3. Reactive Power Compensation Response of FCTCR

A. Reactive Power Compensation Response

Figure 3 shows the reactive power compensation characteristics of the proposed FCTCR system for dynamic load variations. The waveform shows the active and reactive powers response of the compensator during the consecutive load changeover intervals during the simulation time of 2 s. The active power response is increased discretely depending on the operating situation and connected load demand. The small transients appear right after the instants of the load switching, due to the dynamic adjustment of the thyristor-controlled reactor firing angle. However, the system may attain stable operating condition in a short time after each transient period, which indicates the good dynamic response capabilities of the suggested compensator system. The reactive power response is negative for the whole simulation interval, representing capacitive reactive power injection on the compensator branch. At the beginning the compensator injects about 2000 VAR capacitive reactive power into the system. The magnitude of reactive power required for compensation steadily reduces as per the system needs as the inductive load demand grows. This behavior demonstrates the good dynamic regulation capacity of the suggested compensator under various load circumstances.

The findings obtained show that the proposed compensator is capable of maintaining the balance of reactive power effectively and providing steady compensation performance under dynamically changing operating situations. The coordinated functioning of the fixed capacitor branch and thyristor controlled reactor provides the continuous reactive power support and enhances the overall performance of the system.

B. Load Active and Reactive Power Characteristics

Figure 4 displays the active and reactive power characteristics of the load under dynamic operation conditions. The load demand is varied successively during the simulation interval using switching inductive load branches to test the performance of the suggested compensator system. With the connection of each additional load branch to the system, the active power waveform increases in steps. In the beginning the active power of the load is about 500 W and then it is increasing progressively to the higher operating levels in the next switching intervals. Small transient oscillations are noticed immediately after each load shift due to the abrupt change of system current and power demand. However, the wave structure is quickly stabilized after each switching operation, demonstrating a stable system performance. The reactive power requirement of the load likewise grows substantially with increasing inductive loading circumstances. The waveform of reactive power has stepwise increments for each load operating interval. The rise in reactive power consumption necessitates dynamic reactive power correction to ensure stable operating conditions and improved power factor performance.

The findings obtained confirm the success of the established load model in generating different operating situations for the evaluation of the compensator performance. The dynamic load variations validate the effectiveness of the proposed FCTCR system in regulating reactive power and maintaining stable operation under changing load conditions.

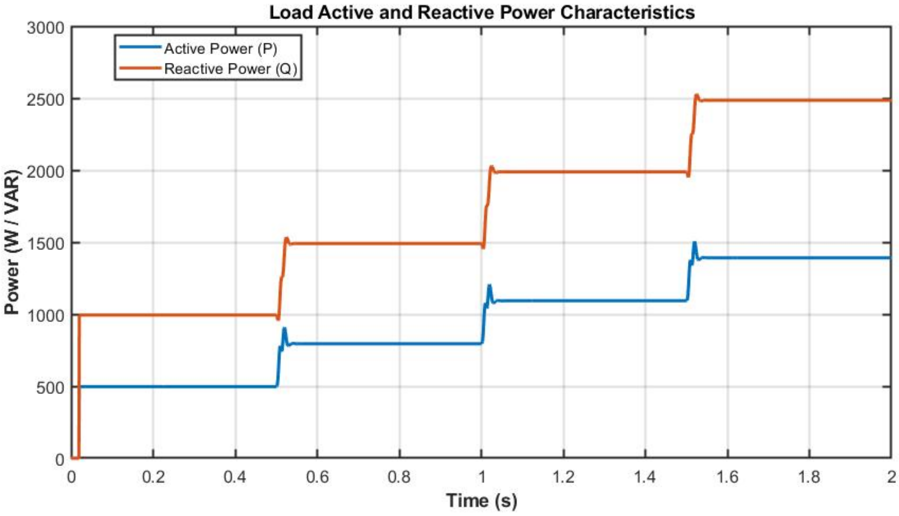

Figure 4. Load Active and Reactive Power Characteristics

C. TCR Active and Reactive Power Characteristics

The active and reactive power characteristics of the thyristor controlled reactor branch under different load situations are shown in Figure5. The firing angle of the thyristors is controlled to make the reactor branch dynamically absorb the inductive reactive power according to the system compensation

requirement.
Due to the fact that the thyristor controlled reactor is mostly involved in reactive power management, the active power of the thyristor controlled reactor is relatively small in the simulation interval. The load switching instants exhibit minor transient changes in active power. These transients are attributed to dynamic firing angle adjustment and switching action of the thyristors. After each transient period the waveform settles fast and remains in steady state. The reactive power waveform shows the reactor branch absorbing a controlled amount of inductive reactive power. Initially, the reactor absorbs more reactive power to balance the compensatory process. With change in operating condition, the reactive power absorption steadily reduces depending upon the compensating required of the system. The behavior shows the effective regulation of the firing angle in the reactor branch under different load situations.

The obtained results demonstrate that the thyristor controlled reactor is a very effective method to regulate the inductive reactive power absorption and to keep the stable compensation performance during the simulation interval. The simultaneous functioning of the reactor branch and the fixed capacitor branch allows for contin

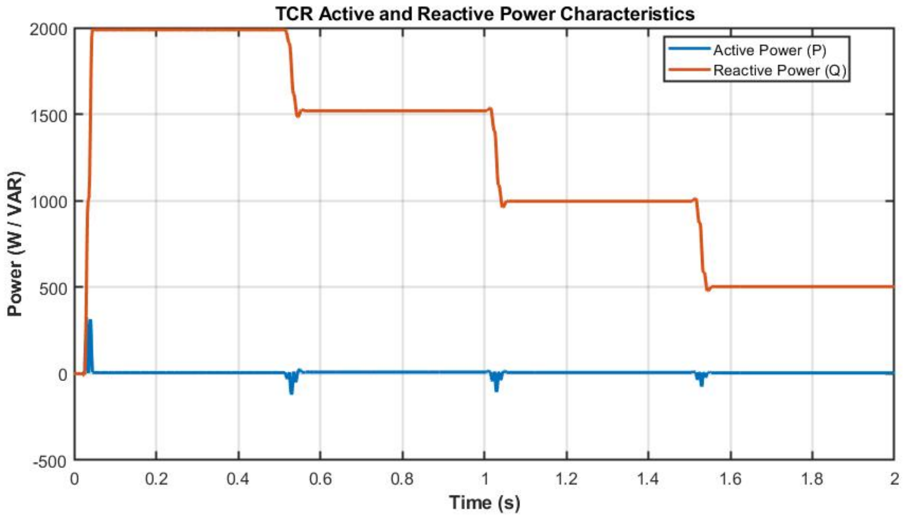

Figure 5. TCR Active and Reactive Power Characteristics

D. Active and Reactive Power Response of FCTCR

Figure 6 depicts the overall active and reactive power response of the proposed FCTCR system in different loading circumstances. The waveform depicts the dynamic operating behavior of the compensator during sequential load switching intervals during the simulation period. The active power response steadily increases based on the linked load demand and compensator working condition. The varied operating periods show active power step adjustments, which demonstrate the effect of dynamic load variation on overall system performance. There will be some transitory oscillations just after the load switching operations, due to the dynamic adjustment of the compensator control mechanism. Nevertheless, the system converges to a steady state quickly after each transient period, showing a satisfactory dynamic response capability. The reactive power waveform displays the compensation performance of the proposed system at different operating situations. Reactive power undergoes temporary changes during switching instants due to firing angle adjustment and transient reactor current variation. The compensator is able to control the reactive power flow and keep stable operating conditions during the simulation interval.

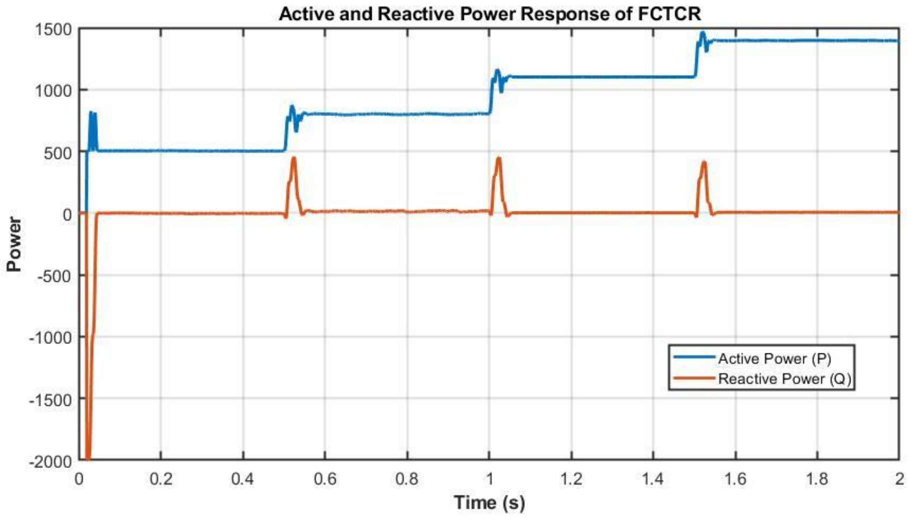

Figure 6. Active and Reactive Power Response of FCTCR

The collected findings show that the suggested compensator system provides an effective reactive power control and stable dynamic performance under varied load situations. The fixed capacitor branch, thyristor controlled reactor and firing angle controller work in synchronism to give better reactive power balancing and overall system operation.

Conclusion

In this work, a reactive power compensation system based on FCTCR has been constructed and assessed under dynamically varying load conditions. The proposed compensator ensures continuous reactive power regulation and better system operating performance with a fixed capacitor branch and a thyristor driven reactor branch. The reactor current is dynamically controlled via a closed loop firing angle control approach based on the reactive power needs of the system. The simulation results show that the proposed compensator can keep the reactive power balance well under different load situations. The reactive power compensation features prove that the compensator delivers the capacitive reactive power successfully and dynamically controls the inductive reactive power absorption via the firing angle control of the thyristor-controlled reactor. The results obtained also show good transient responsiveness and stable operation performance under sequential load switching situations.

The load active and reactive power characteristics verify the capacity of the created system to work under dynamic settings. Besides, the thyristor controlled reactor features show good reactive power management and stable compensation characteristic throughout the simulation interval. The overall active and reactive power response indicates that the suggested system can maintain better power factor and steady compensation performance under varying load demand.

The designed compensator system can be considered as an effective solution for reactive power management and power quality improvement in low voltage power systems. For further improvement of the performance of dynamic compensation, the future work can involve the application of advanced intelligent control approaches and hardware-based experimental validation.

Conflict Of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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