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Substations power quality improvement by flexible alternating current transmission system devices

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ABSTRACT

The increase in load demand has a negative impact on power system quality, reliability, and stability. Transporting reactive power from the generating side to the distribution side reduces the transmission line's capacity to deliver active power to loads. In conventional power systems, during faults or sudden loads, the load flow changes and causes extra voltage drop. Reactive power compensation at the load side can improve voltage quality at distribution busbars, but the conventional compensation method doesn't offer the required flexibility. With the development of the power electronics industry, flexible alternating current transmission system (FACTS) devices have been introduced. There are many categories for FACTS controllers, including series, shunt, and hybrid, which can exhibit dynamic operating characteristics. In this paper, two types of FACTS devices (STATCOM and fixed capacitor-thyristor-controlled reactors (FCTCR)) have been used to improve voltage profile in a part of Iraq's high voltage power system during unusual operating conditions, such as sudden loads and the absence generation. Load flow calculations were conducted to determine the critical bus, and then the performance of the FACTS devices was investigated during heavy loading when the devices were connected separately to the critical bus. The voltage drop in the bus was 1.58%, which reduced to 0.78% with STATCOM and 0.96% with FCTCR.

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1. INTRODUCTION

Iraq's high-voltage power system operates using basic custom power devices (CP), such as reactive power compensation units and analog protections. However, these installations have limited capabilities to support the power system during unusual operating conditions. Additionally, power plants in Iraq use conventional generation units, like fuel-based ones, which have low efficiency. Most of the time, when faults occur in transmission lines or power plants, the loads in the affected regions are supplied by other substations in the power system. This leads extra power losses in transmission lines and voltage drops in system nodes.

Reactive power is the imaginary component of the apparent power, which is stored as an electrical filed in capacitors and inductors. This power is an essential aspect of AC power flow through the system because it's necessary for voltage profile stability and regulation in the system's busbars. Additionally, voltage on the receiving side is affected by reactive power within the system. Many installations inject or absorb reactive power in the power system, including generation units in distributed generation systems, inductive loads, or load demand [1]. However, the voltage in the buses varies according to operating conditions. Using appropriate voltage controllers and reactive power compensation installations leads to an improvement in the performance of the power system. Flexible alternating current transmission systems (FACTS) are installed in AC transmission power systems to increase power transfer capability, stability, and controllability of the power system. By applying FACTS in the power system there will be smooth regulation of impedances, bus voltages, and phase angles [2]. These installations can be connected to any bus or line within the system, but their performance varies depending on the point of common connection (PCC). FACTS controllers are typically used for series and/or shunt compensation. When FACTS is connected in parallel with a transmission line, it provides dynamic voltage regulation, improvement of system stability, and reactive power consumption. Shunt FACTS devices can be divided into two categories: the static var compensator (SVC) and the static synchronous compensator (STATCOM) [3].

STATCOM can be used for voltage regulation and reactive power compensation. Nimbalkar and Thakre [4], pulse voltage source inverter (VSI) serves as a STATCOM for a 230 kV utility grid, maintaining the voltage at the PCC at 236.9 kV with a 1.03 per unit (PU) factor under various load conditions. Campaña *et al.* [5], STATCOM was applied to improve power quality in the IEEE-14 bus system. A newton-raphson algorithm mathematical model for power flow calculation was developed in MATLAB to compensate for reactive power and enhance the voltage profile of critical busbars, maintaining it at 1 PU.

FACTS controllers can be used with power systems integrated renewable energy sources (RES). Jamil *et al.* [6], voltage regulation for a grid-connected wind turbine with an induction generator using 6MVA STATCOM is presented. The device was simulated under variable wind speeds. Also, Kumar *et al.* [7], a wind turbine based on a doubly fed induction generator (DFIG) and high voltage direct current (HVDC) transmission lines with STATCOM performance was investigated under different faults. The STATCOM was able to compensate for voltage dips from 75% to 100% and improve DC voltage mitigation. Khan *et al.* [8], genetic algorithm (GA) was used to optimize STATCOM performance for voltage regulation in a microgrid with 200 kw photovoltaic PV panels and a 2 MW wind turbine. The STATCOM was able to reduce voltage fluctuations in the connected bus to less than 8%.

Kadri and Makhloufi [9], fuzzy logic type 2 has been employed for current and voltage regulation in the STATCOM controller, and its performance has been compared to that of PI and fuzzy logic controller type 1. The STATCOM operated within a 6-busbar system with a wind turbine generating unit. Additionally, a STATCOM with a fuzzy logic type 2 controller was utilized to enhance the voltage profile in a power system with a high penetration of photovoltaic units [10]. STATCOM can be used with low-voltage grids, and in this case, it's called a distribution static synchronous compensator (D-STATCOM) [11]. Saradva [12], STATCOM, with voltage and current control strategies used in a microgrid that has RES, injects active and reactive power to improve power quality, especially the power factor at PCC. Ribeiro and Simonetti [13], a fuzzy-PI controller is applied to STATCOM with photovoltaic panels as the DC source. The results show an improvement in response speed when using the fuzzy-PI controller instead of a conventional controller.

Tamboli and Jadhav [14], a hybrid structure for STATCOM (combining SVC and STATCOM) was applied to improve power quality under various loading conditions, voltage sags, and unbalanced currents for different types of loads. Additionally, Al-Mamoori [15], STATCOM was used to enhance the voltage of the 132 kV power system in Diyala City, Iraq. Nakka *et al.* [16], a six-phase STATCOM with a PI controller has been used for voltage regulation during abnormal conditions such as faults, which caused a 20% voltage swell. The STATCOM mitigates the voltage swell and maintains its magnitude at an acceptable value.

SVC has various installations in power systems. Thyristor-controlled reactors (TCR) and fixed capacitor-thyristor-controlled reactors (FCTCR) are the most popular types of SVC. Mohammed *et al.* [17], FCTCR is used for dynamic reactive power compensation in a three-phase, three-wire smart grid system. The injected reactive power from FCTCR was calculated according to instantaneous power theory. Tariq *et al.* [18], a comparative study is presented for STATCOM and SVC in a 220/132 kV substation with very restricted reliability conditions. FACTS systems aim to improve power factor, but SVC introduces odd harmonics (specifically, the 5^{th} and 7^{th}). However, the installation cost of STATCOM is higher by 17%. Omeje [19], both TCR and UPFC were simulated for reactive power compensation. The comparison focused on efficiency and reactive power consumption, revealing that UPFC absorbed less reactive power than TCR for the same response. Ali *et al.* [20], a power quality improvement method is presented using a TSC controller under a heavy 11 KV grid load. The power factor improved to a range of 0.95-1, and voltage regulation was within ±10%. Barbosa and Filho [21], sigmoid functions were used to optimize SVC performance with 200 kVAR installed power. The proposed method is based on load flow and voltage drop calculations using the newton-raphson algorithm for a medium-scale IEEE power system. This method regulates voltage within ±5% of the nominal value. This work presents a comparison study for STATCOM and SVC devices, for power quality improvement, voltage regulation, and reactive power compensation for part of Iraq's high voltage utility grid, the critical busbar was assigned after load flow, and the power system response will be investigated under heavy loading which can be caused by faults in other transmission lines, or the absence for some generating units.

2. METHOD AND MATERIALS

The studied power system is part of Iraq's high-voltage grid, and the chosen system consists of 9 buses. First, load flow, power losses, and voltage drop will be calculated for ordinary operating conditions at each node to identify the critical busbar in the system. Then, the power system will be studied under high loading conditions with some generation units out of service. After that, the response of both STATCOM and FC-TCR will be investigated during these conditions.

2.1. The proposed power system

The chosen power system is a part of Iraq's utility power grid. The Al-Qadisieah power station serves as the slack busbar for the system, and the entire system is illustrated in Figure 1. The line parameters are as (1), (2):

$$Z = 0.048 + 0.2725i \ \Omega/km \tag{1}$$

$$Z0 = 0.2825 + 1.159i \ \Omega/km \tag{2}$$

the load and generated power for each bus in the selected part of case study power system are illustrated in Figure 1.

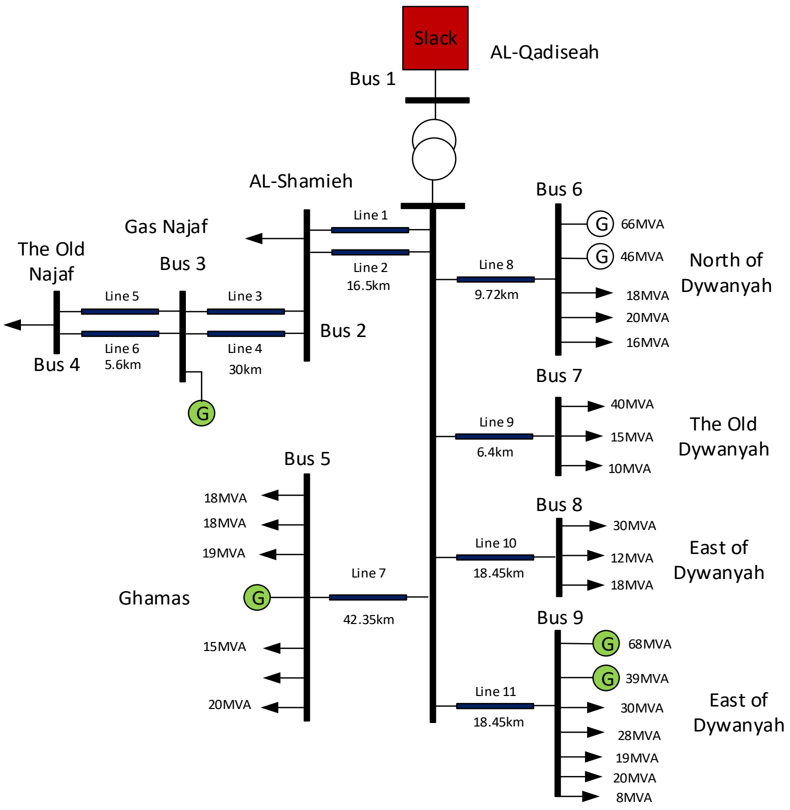

Figure 1. The studied power system structure

2.2. Load flow in ordinary operating conditions

For normal operating conditions, the power factor for the system is assumed to be 0.8, and the load factor for the transformers is set at 80%. MATLAB/Simulink can be used to calculate load flow and voltage profiles in PU for the power system [22]. Figure 2 depicts the complete simulation of the power system in MATLAB/Simulink. Figure 3 shows voltage root mean sequre (RMS) for each bus during simulation in ordinary operating conditions. Calculated by using MATLAB/Simulink. Figure 4 shows the voltage profile for the power system in ordinary operating conditions. Calculated by using MATLAB/Simulink. Table 1 shows the calculated voltage RMS in PU by using MATLAB/Simulink, and it shows that bus 5 has the lowest voltage magnitude. It is 0.994 as the voltage per unit.

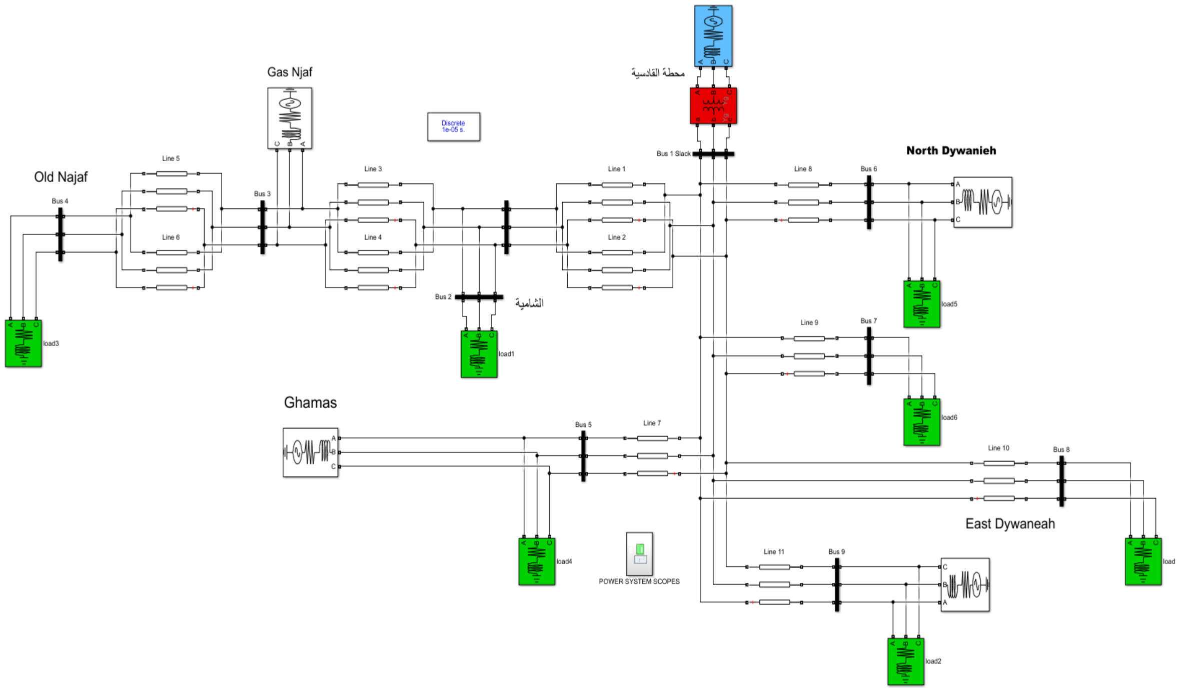

Figure 2. Power system simulation in MATLAB/Simulink

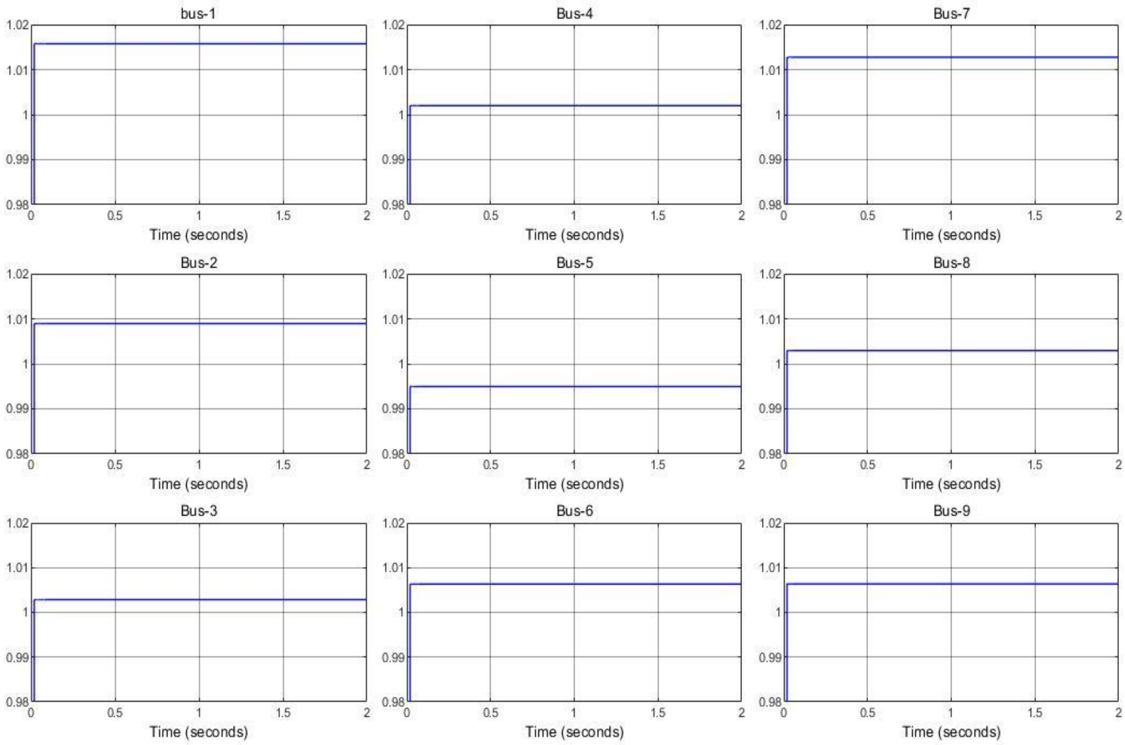

Figure 3. Voltage RMS in PU for each bus

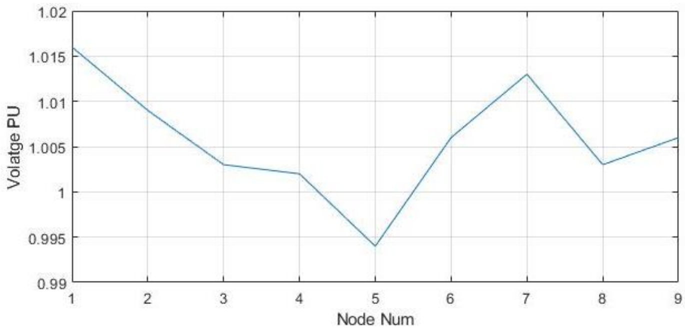

Figure 4. Voltage profile for the power system

Table 1. Buses voltage in PU calculated by MATLAB/Simulink

Bus number	Voltage (PU) MATLAB/Simulink
2	1.009
3	1.003
4	1.002
5	**0.994**
6	1.006
7	1.013
8	1.003
9	1.006
5	1.009

2.3. Load flow with high load operating conditions

Based on the load flow calculation results, it's evident that the voltage drop exceeds 1% at bus 5 (Ghamas), which is considered high for a high-voltage power grid. This paper investigates the FACTS response under challenging operating conditions. Initially, the generating units at bus 5 will be taken out of service. Subsequently, a sudden load of 30 MW and 5 MVAR will be added sequentially while maintaining steady-state loads. This sequence will lead to continuous voltage drops during the simulation. The loads will be added in sequence as illustrated in Figure 5, where three-phase breakers are closed at different times to connect loads to bus 5.

Applying these changes to the power system may result in very challenging operating conditions, potentially leading to voltage drops or asynchronization between generating units [23]. The first load will be added after 2 seconds, the second after 4 seconds, and the third after 5 seconds. Using a three-phase fault block does not have the required impact on the critical busbar. Figure 6 displays the voltage for each bus during the simulation under abnormal operating conditions.

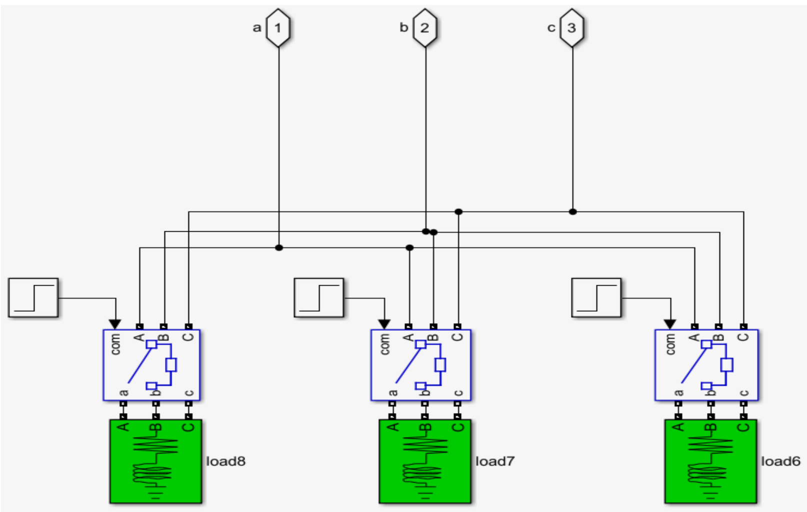

Figure 5. Adding loads in bus 5 using Simulink

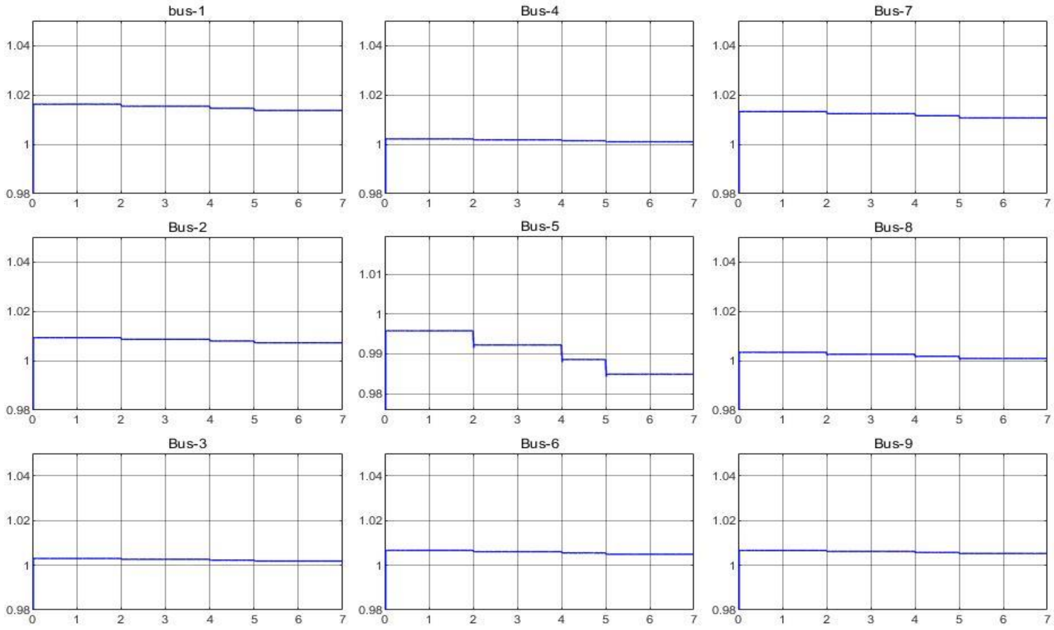

Figure 6. Voltage for each bus during the simulation

Table 2 shows the voltage in PU for each bus during high loading conditions, and it is clear that bus 5 has the lowest voltage. Figure 7 shows voltage drop during simulation with high load operating conditions, and Figure 7 shows that the voltage drop exceeds 1.5%, which is beyond the acceptable range. Figure 8 shows voltage profile for each node in the power systems without FACTS, using MATLAB/Simulink. Figure 7 shows voltage drop during simulation with high load operating conditions. It also shows us the problem in bus 5 without FACTS devices. That the voltage drop exceeds 1.5%, which is beyond the acceptable range. Figure 8 shows voltage profile for each node in the power systems without FACTS devices, using MATLAB/Simulink.

Table 2. Bus voltage in the power system with the high load in bus 5 without generating

Bus number	Voltage (PU) MATLAB/Simulink
2	1.009
3	1.003
4	1.002
5	**0.994**
6	1.006
7	1.013
8	1.003
9	1.006
5	1.009

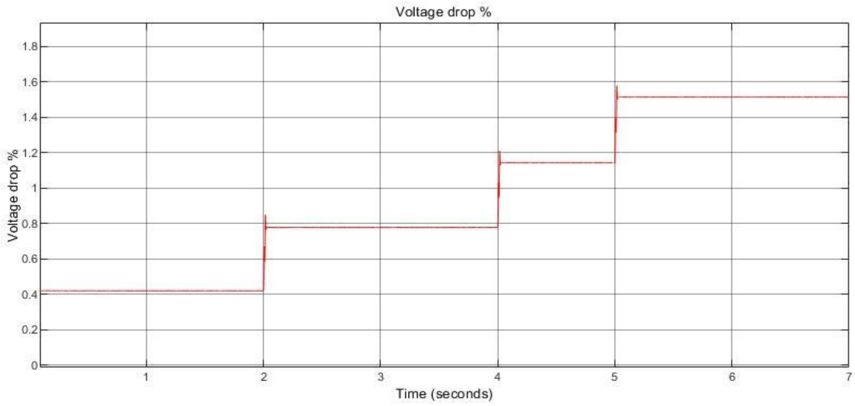

Figure 7. Voltage drops in bus 5 without FACTS

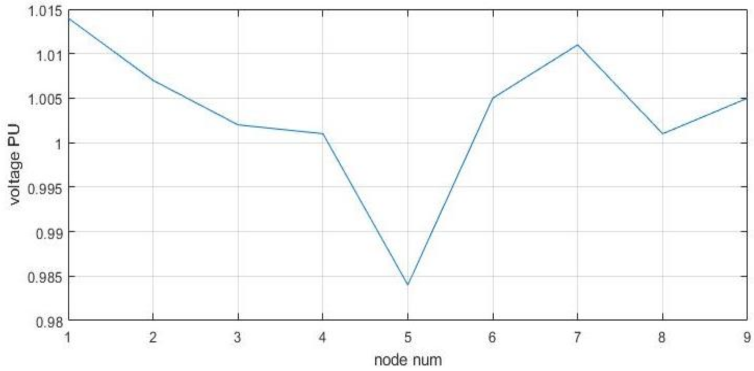

Figure 8. Voltage profile for the power system using MATLAB/Simulink without FACTS

3. MODELING STATCOM IN MATLAB/SIMULINK

After performing load flow calculations for the power system, it's evident that bus-5 is the critical bus in the system. We will now study the performance of STATCOM to support the voltage profile of the system. The STATCOM simulation has two main parts. The first is the equivalent power circuit, which includes the inverter and DC voltage source, and the second is the main controller, consisting of the active power controller, reactive power controller, and outer controller [24].

3.1. STATCOM structure

The STATCOM equivalent circuit, illustrated in Figures 9 and 10, comprises a full-bridge three-phase inverter (utilized to reduce total harmonic distortion, or THD) and two capacitors serving as the DC voltage source. The use of two capacitors improves STATCOM compensation capability. These capacitors are connected between the terminals (+, -, N), and the output side for the inverter is labeled as (a, b, c) [25].

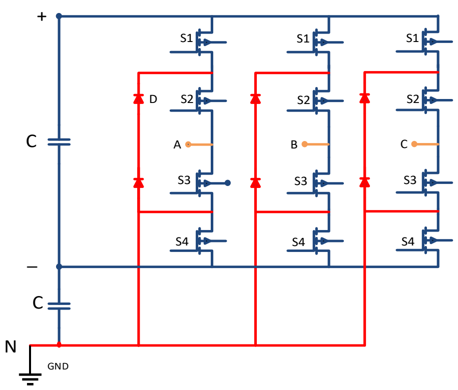

Figure 9. Equivalent circuit for STATCOM inverter

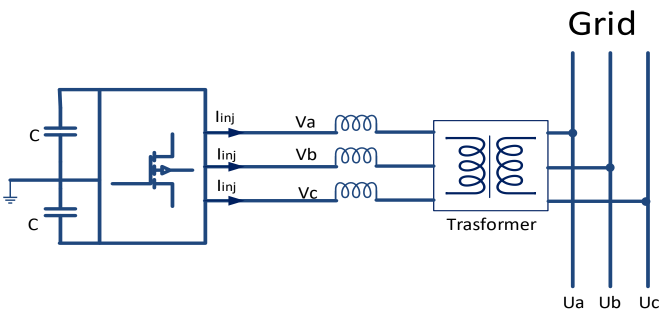

Figure 10. STATCOM connection with grid

3.2. STATCOM controllers

The control scheme is based on clark and park transformations, using clark's transformation is the first step for transitioning from abc system to dqo system, two main advantages can be obtained by employing these transformations. The first advantage is dealing with two components (x_d, x_q) instead of three (a, b, c), and linearizing the signals to use simple controllers like PI [26]. Clark's transformation is given by:

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{4}$$

After calculating αβ components, we can determine the d-q component using θ, obtaining from the PLL technique for the fundamental component of the electrical grid. Using these transformations has two main benefits: first, it deals with two components (d, q) instead of three (a, b, c); second, it simplifies the system's controllers, such as PID or PI controllers. These transformations are given by:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} Cos\,\theta & sin\,\theta \\ -sin\,\theta & Cos\,\theta \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \tag{5}$$

3.2.1. Active power controller

This controller is associated with the capacitors' DC voltage state. When the voltage is lower than the reference DC voltage, the inverter will consume active power to recharge the capacitors. Active power is connected with the Id-ref component value, where Id-ref is the reference value for the d sequence of the current. This current value will be compared with the injected current from the inverter after the output filter to calculate the error for the outer controller. The control scheme and the controller simulation are illustrated in Figure 11.

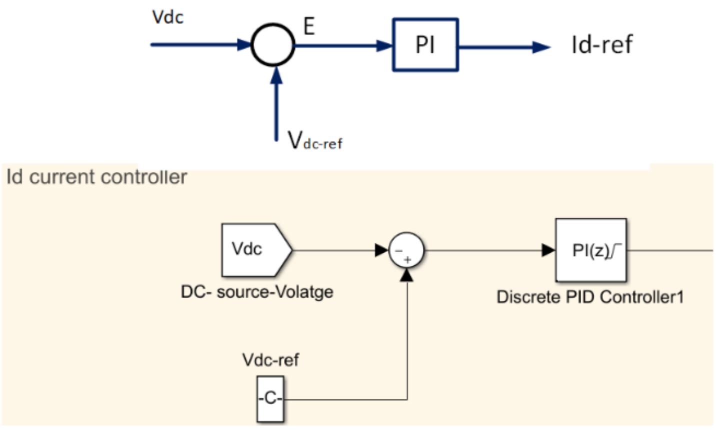

Figure 11. Id component controller scheme and simulation

3.2.2. Reactive power controller

This controller is responsible for the AC voltage amplitude in the PCC. First, the RMS value of the voltage amplitude will be calculated in PU. Subsequently, it will be compared to the reference voltage (1 PU) to determine Iq-ref and the reactive power state for the inverter, adjusting the power factor in the PCC to either lag or lead in order to regulate the voltage. Figure 12 shows the control scheme and simulation for the Iq controller [27].

3.2.3. STATCOM overall controller

This controller, also called outer controller, is connected in series with both previous controllers. Its responsibility is to generating pulses for the switches based on the error between the injected Id. Iq values and the references Id_ref, Iq_ref. The references are calculated by active power controller and reactive power controller. The outer controller then adjusts the modeled wave for pulse width modulation (PWM). From Figure 13, we can calculate the output voltage from the VSI at the PCC point as follows:

$$V_a - U_a = R_f I_a - L_f \frac{dI_a}{dt} \tag{6}$$

$$V_b - U_b = R_f I_b - L_f \frac{dI_b}{dt} \tag{7}$$

$$V_c - U_c = R_f I_c - L_f \frac{dI_v}{dt} \quad (8)$$

where V_a, V_b, and V_c represent the inverter output voltage, while U_a, U_b, and U_c denote the grid voltages at the PCC. R_f and L_f are filter parameters, and I_a, I_b, I_c are the injected currents. Figure 13 shows the simulation of the Id controller, Iq controller, outer controller, and the d, q to a, b, c transformation in MATLAB/Simulink.

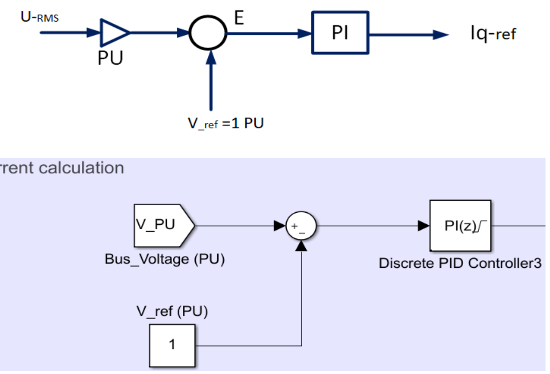

Figure 12. Iq component controller scheme and simulation

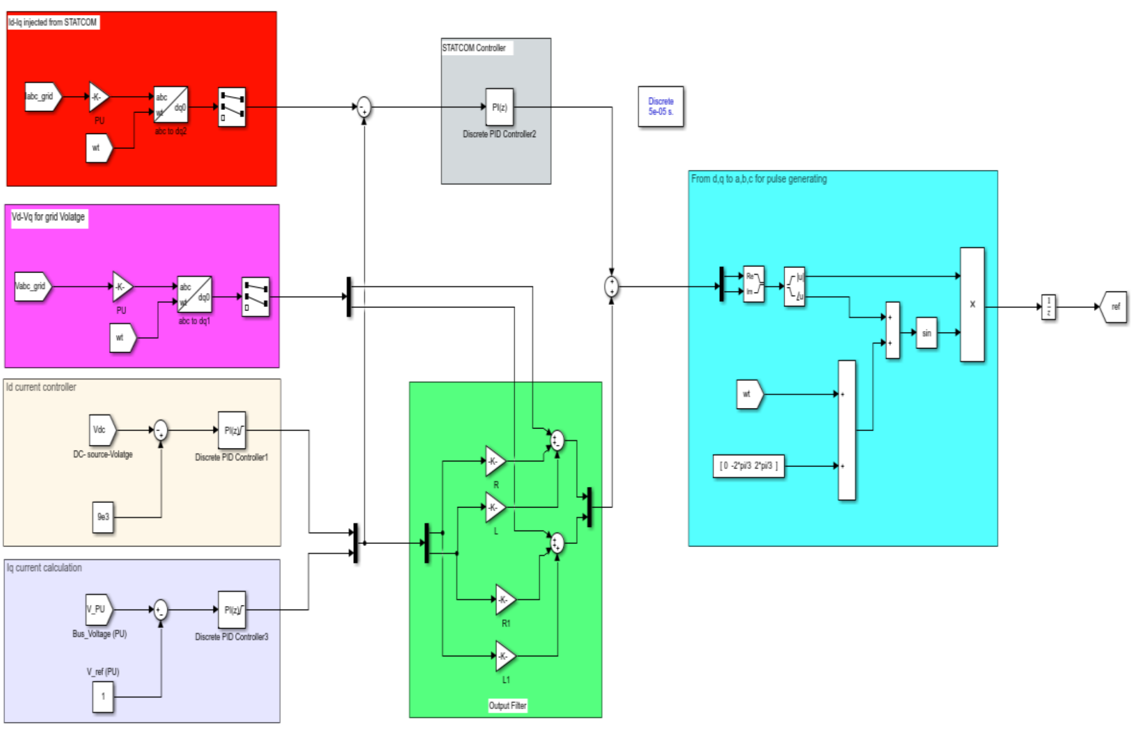

Figure 13. STATCOM overall controller simulation

Figure 13 shows the complete structure of the controller. In this controller, the d and q reference components are compared with the injected components, taking the output filter parameters into consideration. Subsequently, PI controllers will adjust the Vd and Vq components for the abc-modeled sine wave for PWM. After load flow calculations, it becomes evident that bus-5 (Ghamas) station has the lowest voltage under heavy loading and cut-off generation. To enhance the voltage stability profile, a STATCOM will be added to this substation. Figure 14 illustrates the connection with bus-5 substation.

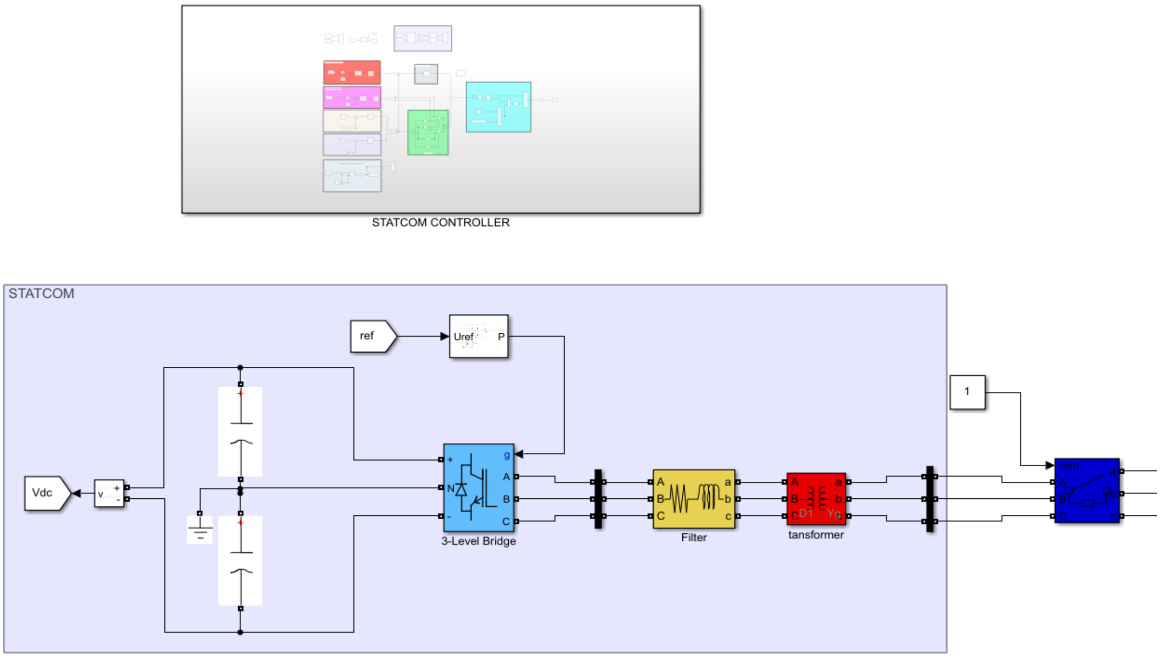

Figure 14. STATCOM connection with bus-5

3.3. Power system response with STATCOM

STATCOM is connected to bus-5 for voltage regulation. Through reactive power compensation, STATCOM can affect the load flow in the case study power system, that will change the voltage profile in the whole systems nodes. Figure 15 shows voltage profile for the power system under different loads and no genetion in bus-5.

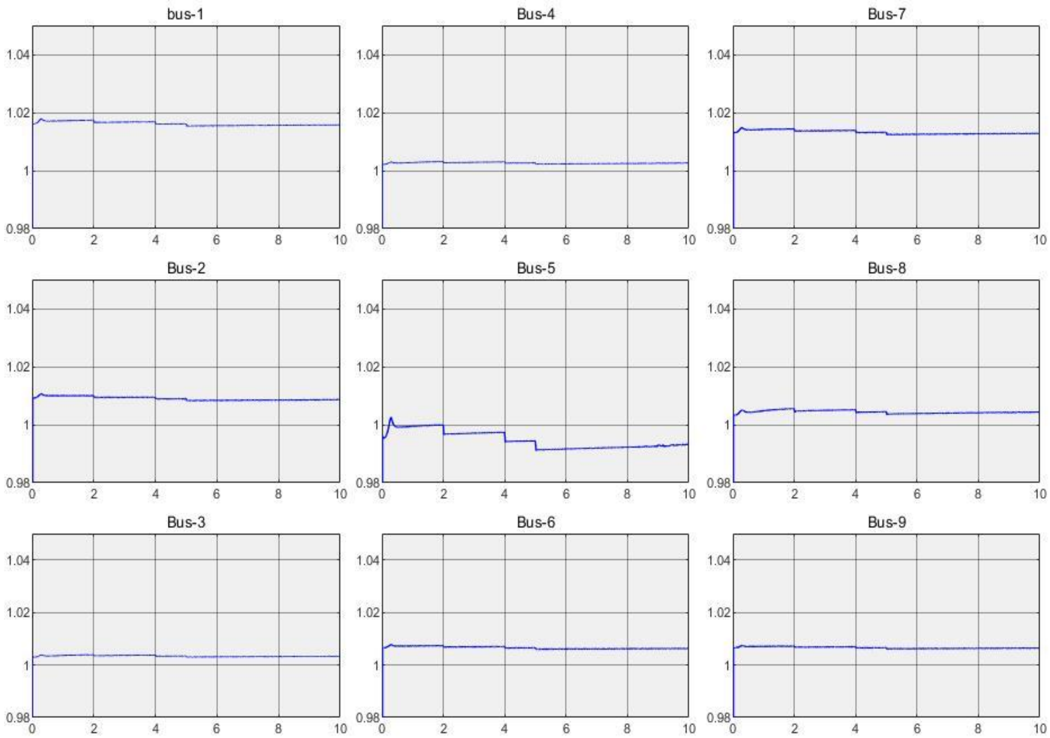

Figure 15. Voltage for each bus during simulation with STATCOM

Table 3 shows the voltage in PU for each bus after the loads were added, Figure 16 shows the voltage profile for buses on the final loading stage with STATCOM is connected to bus 5, and Figure 17 shows the voltage drop for bus-5 during the simulation. It's clear that there is an improvement in the voltage profile. From Figure 17, we can see that the voltage drop doesn't exceed 0.8% under heavy loading conditions. Table 4 shows a comparison of the voltage drop at bus-5 before and after.

Table 3. Bus voltage in the power system with the high load in bus 5 without generating with STATCOM

Bus number	Voltage (PU) MATLAB/Simulink
2	1.009
3	1.003
4	1.003
5	**0.993**
6	1.006
7	1.013
8	1.004
9	1.006
5	1.009

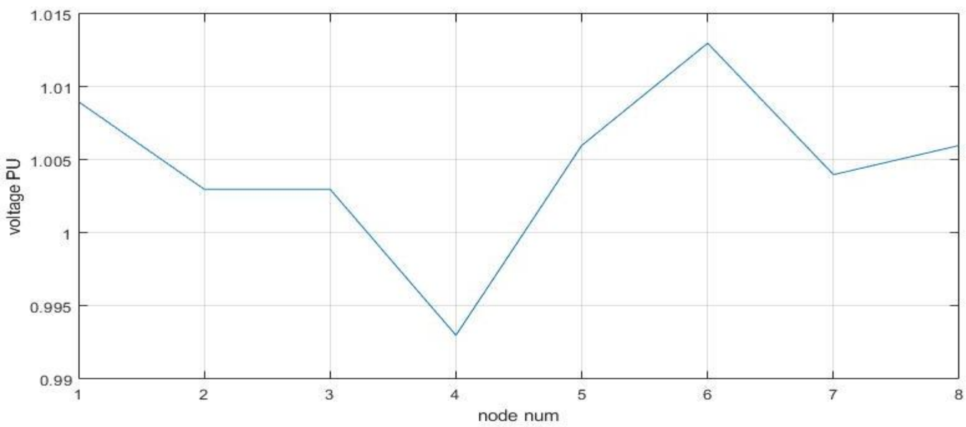

Figure 16. Voltage profile for the power system using MATLAB/Simulink with STATCOM

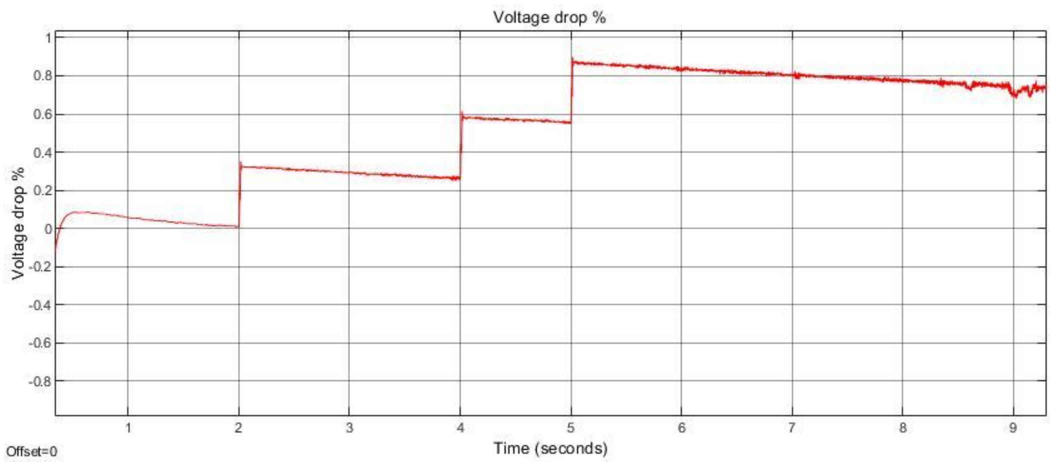

Figure 17. Voltage drop in bus 5 with STATCOM

Table 4. Voltage drop in power system with/without STATCOM

Operating condition	Voltage drop % (Without STATCOM)	Voltage drop % (With STATCOM)
No generating in bus -5	0.43	0.001
First loading	0.79	0.23
Second loading	1.18	0.57
Third loading	1.58	0.78

4. MODELING FC-TCR IN MATLAB/SIMULINK

FC-TCR is one of the SVC devices that use capacitors and inductance to regulate voltage by absorbing or compensating reactive power at the PCC. The capacitors in this device are fixed, similar to conventional capacitor banks, while the inductance is controlled by two thyristors to determine the operating condition. For this case study, a 7.5 MVAR capacitor bank and a 7.5 MVAR inductive load were used for voltage regulation. The equivalent circuit for FC-TCR is provided in Figure 18.

4.1. FC-TCR structure

FC-TCR consists of a capacitor XC connect in parallel with a fixed reactor of inductance XL and a bi-directional thyristor valve that is fired symmetrically in an angle control range of 90° to 180° [28]. The firing angle identifies operating pattern: at 90°, FC-TCR compensates reactive power, and at 180°, it absorbs reactive power. This regulation helps maintain voltage within an acceptable range. In this case study, FC-TCR will be connected to the bus-5 to improve voltage profile for the system. Figure 18 shows the equivalent circuit of FC-TCR [29]. Figure 19 shows the simulation for the power circuit of FC-TCR. Which we will use to compare the two flexible AC transmission system devices.

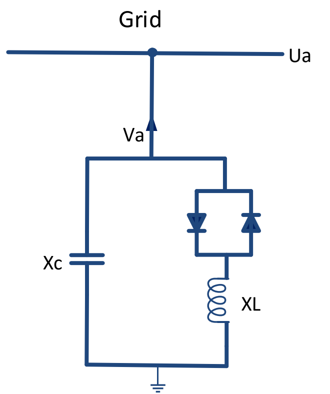

Figure 18. Equivalent FC-TCR circuit of SVC

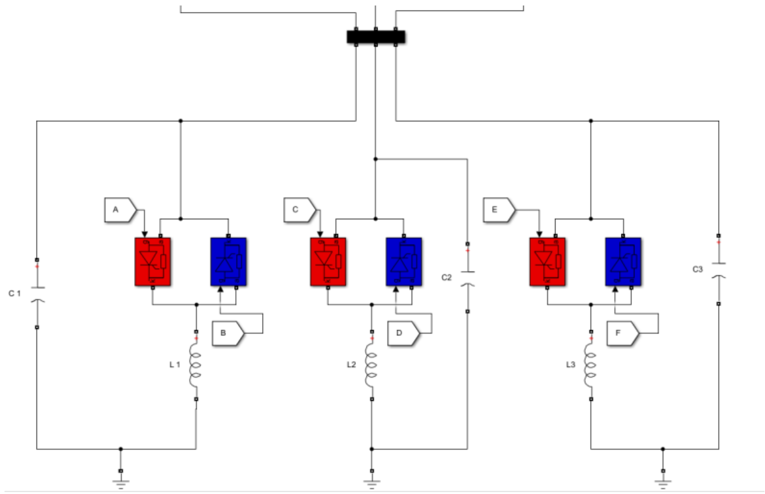

Figure 19. Power circuit simulation for FC-TCR

4.2. FC-TCR controller

The controller for FC-TCR has two stages. The first one calculates the amount of the reference reactive power based on the difference between the nominal voltage RMS in PU and the reference voltage for the bus [30]. The second stage controller is used to determine the firing angle α for the thyristors. Figure 20 shows the proposed structure for the controller. Figure 21 shows the full structure to illustrate the complete electrical circuit of the controller.

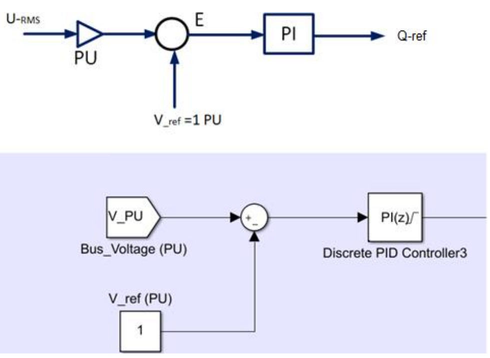

Figure 20. Reference reactive power calculations

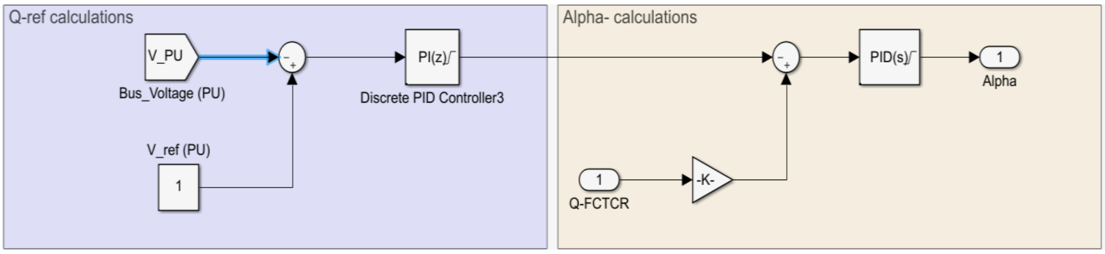

Figure 21. Simulation for the FC-TCR alpha controller

4.3. Improving power quality by FC-TCR

FC-TCR is connected to bus-5 for reactive power compensation during various operating scenarios. The firing angle controller adjusts the amount of reactive power injected into PCC based on the difference between actual voltage magnitude and the reference value [31]. Figure 22 shows voltage profile for the power system under different loads and no generation in bus-5.

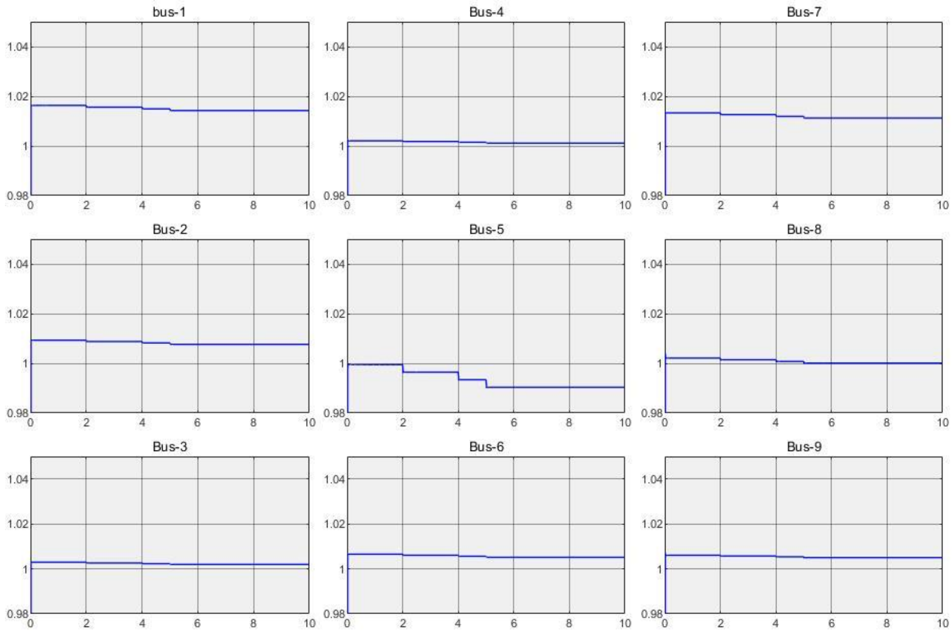

Figure 22. Voltage for each bus during simulation with FCTCR

Table 5 shows the voltage in PU for each bus after the loads were added to the studied network. Figure 23 shows the voltage profile for buses in the final loading stage using MATLAB/Simulink with FCTCR. Figure 24 shows voltage drop for bus-5 during the simulation. It is the critical node that was focused on in this study.

Table 5. Bus voltage in the power system with the high load in bus 5 without generating with FCTCR

Bus number	Voltage (PU) MATLAB/Simulink
2	1.008
3	1.002
4	1.001
5	**0.993**
6	1.011
7	1.005
8	1
9	1.005
5	1.008

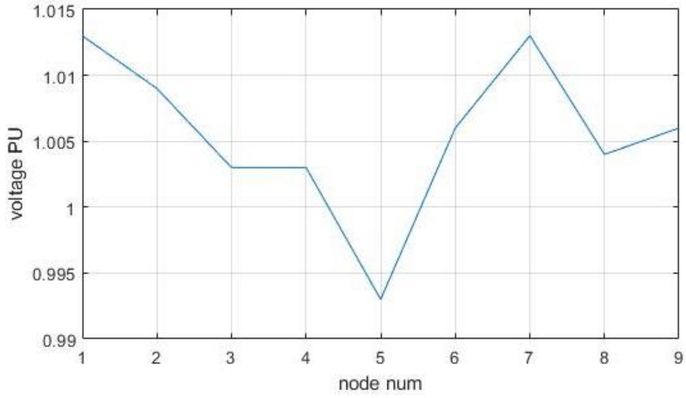

Figure 23. Voltage profile for the power system

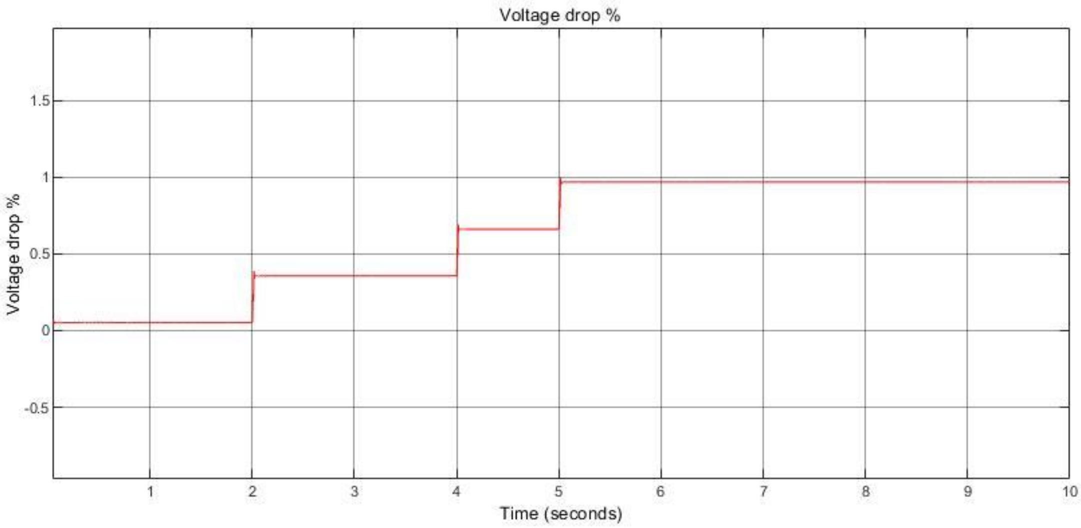

Figure 24. Voltage drop in bus 5 with FCTCR

From Figure 24, we can see that the voltage drop doesn't exceed 1% under heavy loading conditions. Which indicates the importance of using FACTS devices in high voltage transmission systems. Table 6 shows a comparison of the voltage drop at bus-5 before and after.

Table 6. Voltage drop in power system with/out FCTCR

Operating condition	Voltage drop % (without STATCOM)	Voltage drop % (with STATCOM)
No generating in bus-5	0.43	0.05
First loading	0.79	0.356
Second loading	1.18	0.661
Third loading	1.58	0.9688

5. RESULTS AND DISCUSSION

Using FACTS controllers can improve power quality parameters in a high-voltage utility grid. Both STATCOM and FCTCR offer high flexibility in injecting reactive power to support voltage at the PCC. Additionally, they address voltage swell/sag by compensating or consuming reactive power at the PCC. In a paper case study, the voltage profile improved for the critical bus (Ghamas) under heavy loading, even without generating units in the system. Table 7 summarizes the bus voltages under different operating conditions. Based on the data in Table 7, we can conclude that the use of STATCOM/FCTCR in the high-voltage utility grid reduces voltage drop in the PCC to an acceptable range. Additionally, it alters the power flow within the system, leading to an improved voltage profile across the entire grid.

Table 7. Bus voltage in the power system with/without STATCOM/FCTCR

Bus number	Voltage (PU) without FACTS	Voltage (PU) with STATCOM	Voltage (PU) with FCTCR
2	1.007	1.009	1.008
3	1.002	1.003	1.002
4	1.001	1.003	1.001
5	**0.984**	**0.993**	**0.990**
6	1.005	1.006	1.011
7	1.011	1.013	1.005
8	1.001	1.004	1
9	1.005	1.006	1.005
5	1.007	1.009	1.008

6. CONCLUSION

In this paper, FACTS controllers were employed to enhance power quality in the high-voltage power systems of Iraq's utility grid. Initially, load flow and bus voltage were calculated to identify the critical bus. Subsequently, we assumed heavy loading and no power generation conditions at the chosen bus to simulate faults occurring in Iraq's utility grid, which currently relies on conventional power devices. Two types of FACTS devices, namely STATCOM and FCTCR, were then applied. Both devices successfully supported voltage in the power system, with voltage drop not exceeding 0.8% using STATCOM and 1% using FCTCR. The outcomes of this study could encourage grid operators in Iraq to incorporate FACTS into their high-voltage power systems.

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