Enhancing power quality through the use of unified Power flow controllers based on fuzzy logic controllers

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ABSTRACT

Electrical power quality is crucial for industrial, commercial, and residential applications. Customers and utilities are increasingly concerned about power quality due to rising demand for high-quality electricity and an increase in distorted loads. Flexible alternating current transmission system (FACTs) controllers are widely used in power transmission systems and have numerous applications. The FACT system includes a unified power flow controller (UPFC) that regulates both active and reactive power flow in transmission lines. This study proposes a fuzzy logic controller (FLC)-based UPFC to improve power quality by controlling both active and reactive power flow, reducing total harmonic distortion (THD), correcting power factor, regulating line voltage, and improving transient stability. A research was conducted to compare the performance of the system with a standard PID controller and an FLC. Implementation of the system using the MATLAB/SIMULINK program validates the theoretical analysis.

Keywords: **FACTs, Power quality, SSSC, UPFCSTATCOM, Voltage stability**

1. NTRODUCTION

Electrical engineers are giving the term power quality (PQ) more thought these days. A crucial factor pertaining to the power system's voltage, current, and frequency is the power quality. Numerous circuits, including converters, magnetic circuits, non-linear loads, and flexible alternating current transmission system (FACTs) devices, are sources of harmonics and other issues that have a negative impact on power quality. The word "power quality" in electrical engineering can refer to various aspects, including supply dependability, voltage quality, current quality, service quality, and source quality. Numerous issues, such as voltage sag, voltage swell, harmonic distortion, absence or lack of VAR compensation devices, voltage interruptions, and transient situations, can affect the power system's power quality. Reactive power compensation is the process of effectively managing reactive power fluctuations in order to enhance a microgrid's performance.

The FACTs can mitigate electrical power problems in different conditions (steady-state, transient, and post transient steady-state) It can be classified into four types, the first type is shunt controllers such as static

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synchronous compensator (STATCOM), the second type is series controllers, for example, static synchronous series compensator (SSSC), the third type is a combination between the series and shunt controllers such as unified power flow controller (UPFC) and the final type is a combination between two series controllers such as interline power controller (IPFC) The SSSC is used to control power flow and to improve transient stability [10-12], while the STATCOM is used to regulate line voltage by injecting or absorbing the reactive power to the system [13-17]. The UPFC is one of the FACTS family members with very versatile uses [18-21], it has the ability to control the transmission line

parameters (voltage, impedance, and phase angle) at the same time. It consists of two converters: series converter and a shunt converter are connected by a common DC link capacitor, which can simultaneously control thetransmission line active and reactive power flow as well as to UPFC bus voltage [22-24]. This paper presents a simulation study of UPFC, connected with four busses (B1, B2, B3 and B4) system of 100-MVA, 500 KV and two of three-level 48-pulse GTO based converters in order to eliminate the harmonics and decrease the total harmonic distortion (THD). In order to increase the stability and to obtain optimum power flow, an optimum value of DC capacitor has been selected between the converters.

2. UNIFIED POWER FLOW CONTROLLER (UPFC)

The UPFC was developed for dynamic compensation and real-time control of ac transmission systems. It offers multifunctional versatility to address numerous issues confronting the power delivery sectors. All of the parameters (such as voltage, phase angle, and impedance) influencing power flow in the power system network can be controlled using UPFC simultaneously or separately. Thus, the adjective announces this special talent. “unified”. The main reason behind the wide spreads of UPFC is its ability to power flow

bi-directionally maintaining well regulated AC transmission line voltage. The UPFC is a generally synchronous voltage source (SVS), it is exchange both active and reactive power with the transmission system. The basic configuration of a UPFC with its main components is shown in Figure 1

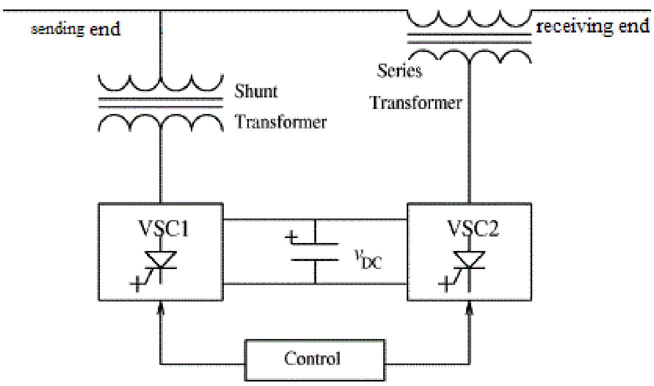

Figure 1. The schematic diagram of UPFC

3. THE MATHEMATICAL ANALYSIS OF UPFC SYSTEM

The installation of UPFC in the power grid requires intricate technical and economic research regarding its impact on power system performance. Even though the majority of recent research has concentrated on the

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potential applications of UPFC and its ability to act as a compensator in both dynamic and transient states of the power system to enhance power quality, the primary objective of UPFC application remains to introduce it as a FACT device to control both active and reactive power. The UPFC circuit diagram can be simplified into Figure 2, it is composed of two machines with the UPFC, the synchronous voltage source (Vpq) representing the UPFC has a controllable amplitude value |Vpq| with an angle ρ (0≤ρ≤2π)

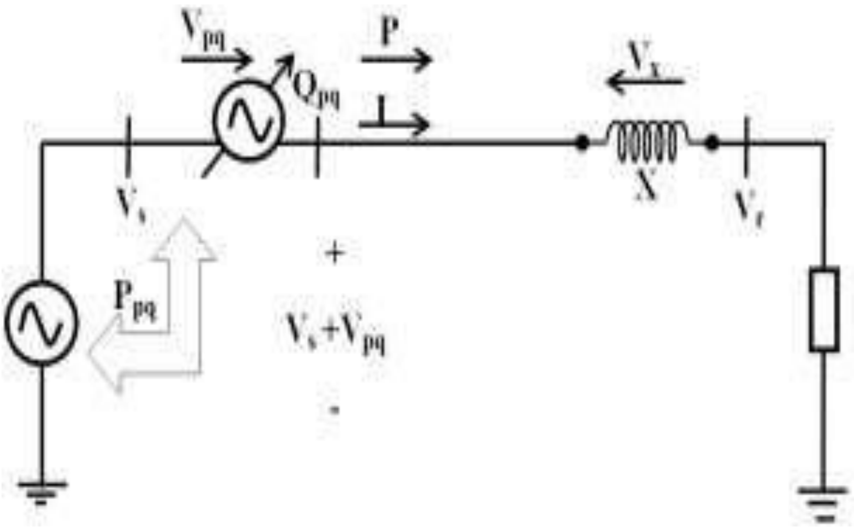

Figure 2. Simplified model of UPFC

Both active and reactive power flow can be controlled by injecting adjustable voltage via the seriesconvertor, and they can be expressed by (1).

$$P - jQ_r = V_r \left(\frac{V_s + V_{pq} - V_r}{jX}\right)^* \quad (1)$$

where (*) represents the conjugate value of the complex value, and the (V_{pq}) represents the injected compensating voltage. As shown in (1) can be rewritten as follows.

$$P - jQ_r = V_r \left[\frac{V_s - V_r}{jX}\right]^* + \frac{V_r V_{pq}^*}{jX} \quad (2)$$

V_s, V_r and V_{pq} can be calculated as below:

$$V_s = Ve^{\frac{j\delta}{2}} = V\left[\cos\frac{\delta}{2} + j\sin\frac{\delta}{2}\right] \quad (3)$$

$$V_r = Ve^{-\frac{j\delta}{2}} = V\left[\cos\frac{\delta}{2} - j\sin\frac{\delta}{2}\right] \quad (4)$$

$$V_{pq} = V_{pq}.e^{j\left(\frac{\delta}{2}+\rho\right)} = V_{pq}\left[\cos\left(\frac{\delta}{2}+\rho\right) + j\sin\left(\frac{\delta}{2}+\rho\right)\right] \quad (5)$$

By substituting (3), (4), (5) into (2), therefore P and Q_r can be determined as follow.

$$P(\delta,\rho) = P_o(\delta) + P_{pq}(\rho) = \frac{V^2}{X}\sin\delta - \frac{VV_{pq}}{X}\cos\left(\frac{\delta}{2}+\rho\right) \quad (6)$$

$$Q_r(\delta,\rho) = Q_{or}(\delta) + Q_{pq}(\rho) = \frac{V^2}{X}(1-\cos\delta) - \frac{VV_{pq}}{X}\sin\left(\frac{\delta}{2}+\rho\right) \quad (7)$$

δ is the system transfer angle.
$P_o(\delta)$, $Q_{or}(\delta)$ are active and reactive power of the system respectively.
V_s is the synchronous voltage.

4. THE VECTOR DIAGRAM OF OF THE CONTROLLER REGION

The vector diagram and controlling region of the UPFC were constructed for both active and reactive power flow controller modes. The active power (P) and reactive power (Q) are managed and boosted to approximately 80% of the UPFC's rated value. The active power is increased from (870 MW) to (950 MW), and the reactive power is increased from (-60MVAR) to (+20 MVAR), resulting in a control region shift from the beginning point (870-j60) MVA to (950+j20) MVA, as seen in Figure 3.

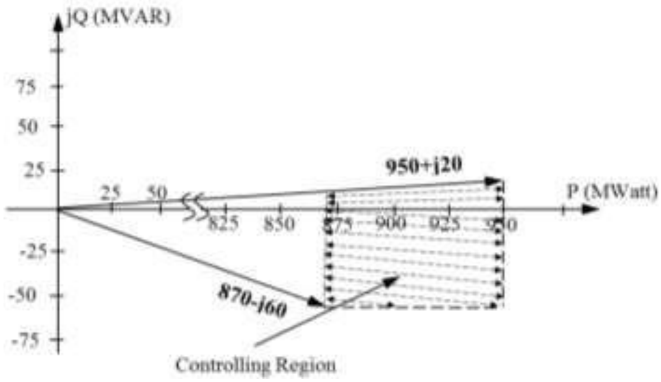

Figure 3. Vector diagram of the UPFC controller

5. THE FLOW CHART OF THE CONTROLLER CIRCUIT OF THE UPFC

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The proposed UPFC controller circuit has distinct controller circuits for both series and shunt converters, as indicated in the flow chart in Figure 4. The series converter is based on the series voltage (Vser) and series current (Iser), which are translated into their corresponding (dq-axis) components, Vser to (Vd-ser and Vq-ser) and Iser to (Id-ser and Iq-ser). Vd-ser and Id-ser determine the active power of the transmission line, whereas Vq-ser and Iq-ser determine the reactive power. The shunt converter is dependent on the shunt voltage (Vsh) and shunt current (Ish); these values are also converted into (Vd-sh and Vq-sh) and (Id-sh and Iq-sh), respectively.

depending on Iq-sh the reactive power of thetransmission line has been compensated, while Id-sh controls the active power between the two converters.

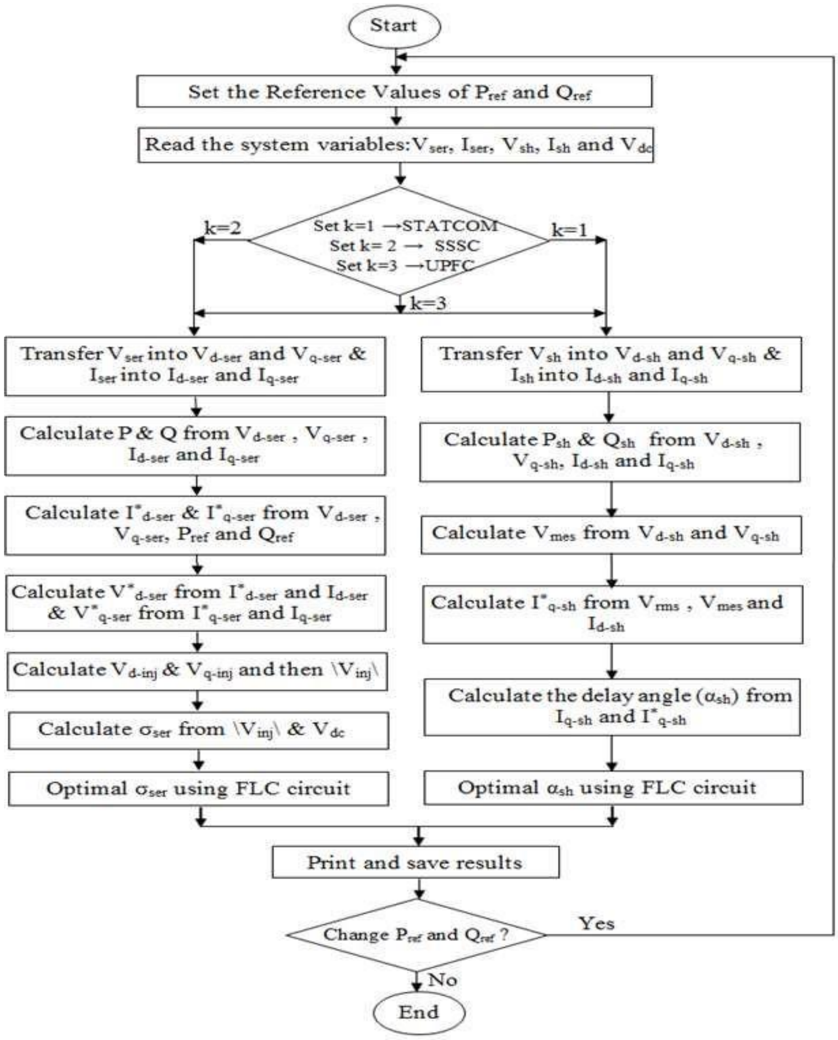


Figure 4. The flow chart of the proposed controller circuit of the UPFC

6. THE SIMULATION RESULTS

The proposed system (500kV and 100MVA) consists of four buses (B1, B2, B3, and B4), three transmission lines and two GTO-based converters of (100 MVA), each converter is 48-pulse four H-Bridge three-level cascaded connected converter. The circuit diagram with all system parameters is shown in Figure 5. The shunt converter is connected in shunt with the system at the left side of the (L_2=75 Km) through four shunt transformer, while the series converter is connected in series with the system at the same side of L_2 through four series transformers, this converter can inject a maximum voltage of 10% of nominal line voltage (50 kV) in series with the second line (L_2).

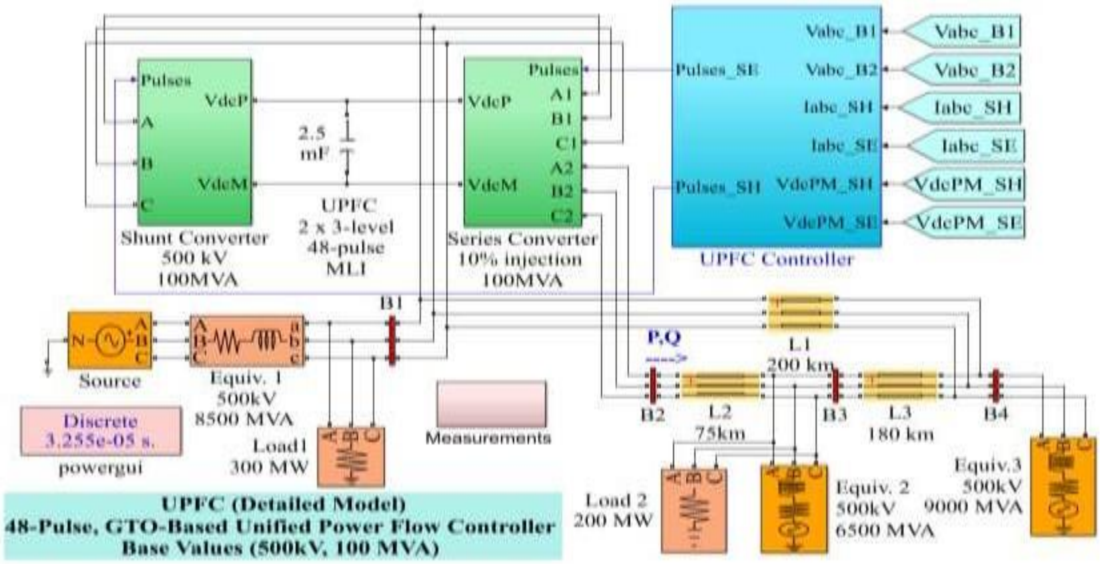
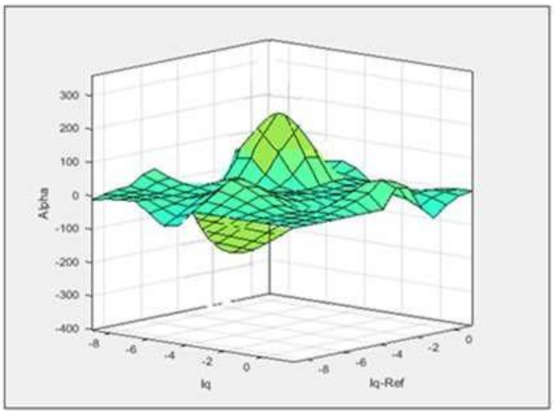


Figure 5. The simulink model of the proposed system

6.1 The simulation study of the fuzzy logic controller (FLC) circuits

The main controller circuit is made up of two parts: the shunt controller circuit and the series controller circuit. The fuzzy logic controller for the shunt controller circuit is based on two variables: the quadrature component of the shunt controller current (Iq) and the shunt current reference value (Iqref). The quadrature component of the shunt controller current (Iq), whereas the reference value of the shunt current (Iqref), is based on the measured value of the first bus voltage (Vmeas) and the reference value of the same bus voltage (Vref). The input signal of the shunt fuzzy controller circuit is either the error signal or the difference between Iq and Iqref (Error = Iq-Iqref).while the output signal is the delay angle of the shunt converter (α_{sh}) as shown in Figure 6. The fuzzy logic controller of the series controller circuit has been constructed depending on two variables which are the line active power (P) and reactive power (Q), while the output signal is the conduction angle of the series converter (σ_{ser}) as shown in Figure 7.



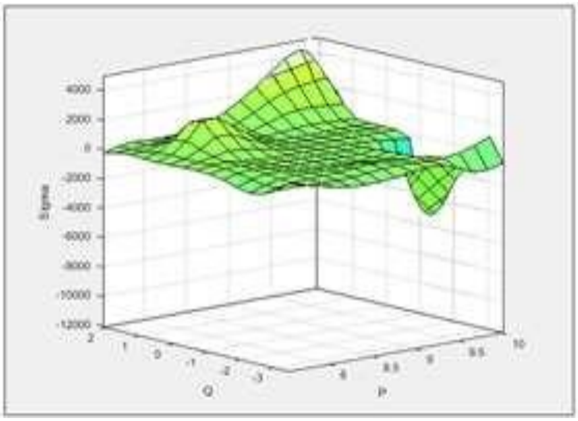


Figure 6. The relationship between I_q-I_{qref} against   Figure 7. The relationship between P, Q against σ_{ser}

6.2 The pulses pattern of the converters

The shunt converter of UPFC controller operates as STATCOM used to regulate B_1 voltage by absorbing or injecting the reactive power with the line by varying the DC bus voltage, and also it provides needed active power to the series converter through the DC bus. The conduction angle of the shunt converter switches is constant value (σ_{sh} =180-7.5=172˚). To regulate the reactive power of the system at the common point, the delay angle of the shunt converter (α_{sh}) is varied as clear from the pulse waveform of the first switch(S_{a1}) in Figure 8. The main purpose of the series converter is injecting a controlled series voltage in order to control the active and reactive power flow of the transmission line. The injected voltage is adjusted by varying σ_{ser} so this angle will be a different values as shown in Figure 9. It should be noticed that both angles α_{sh} and σ_{ser} are calculated instantaneously using the fuzzy logic controller.

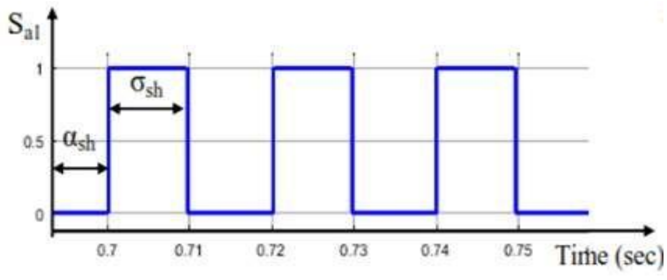


Figure 8. The pulses pattern of the first switch of the shunt converter

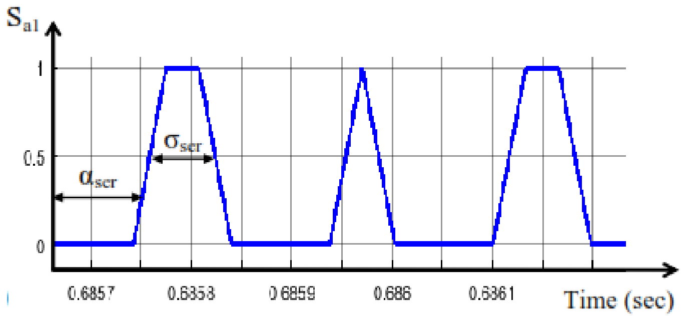
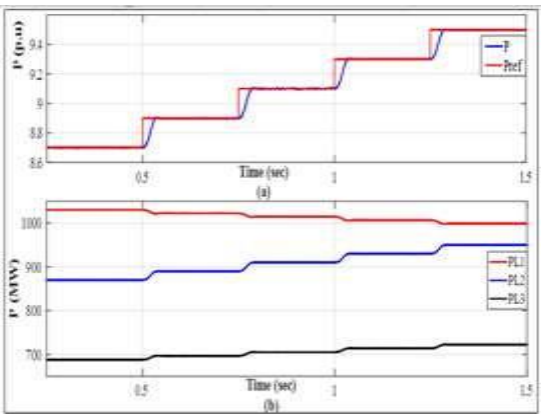


Figure 9. The pulses pattern of the first switch of the series converter

6.3 Power flow controlling

The initial values of the real and reactive powers are (P Initial= +870 MW) and (Q Initial =-60 MVAR). The series converter injects a controllable voltage (10%) of the rated voltage so this controller can control system power flow of (10%) of the rated value (80MW). Both active and reactive power have been controlled and changed in four steps. The active power is controlled and changed from the initial value to (950 MW) as shown in Figure 10, while reactive power is controlled and changed from rated value to 20 MVAR as shown in Figure 11.



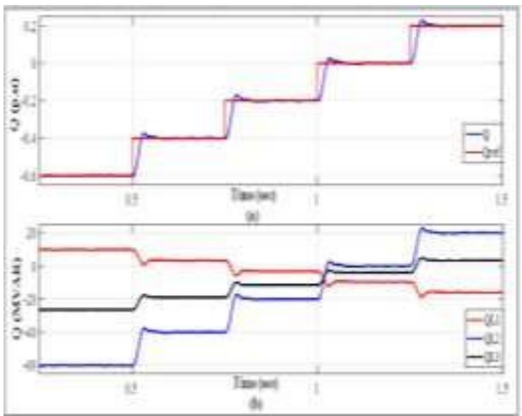


Figure 10. Active power (P) vs time of B2, where: (a) Per unit values, (b) Actual values

Figure 11. Reactive power (Q) vs time of B2, where: (a) Per unit values, (b) Actual values

6.4 Power factor

The power factor is one of the most important power quality issues. Since the UPFC is connected on the second bus (B2), the power factor of its voltage is checked and shown in Figure 12. From this figure it can concluded that the system is operating at unity power factor.

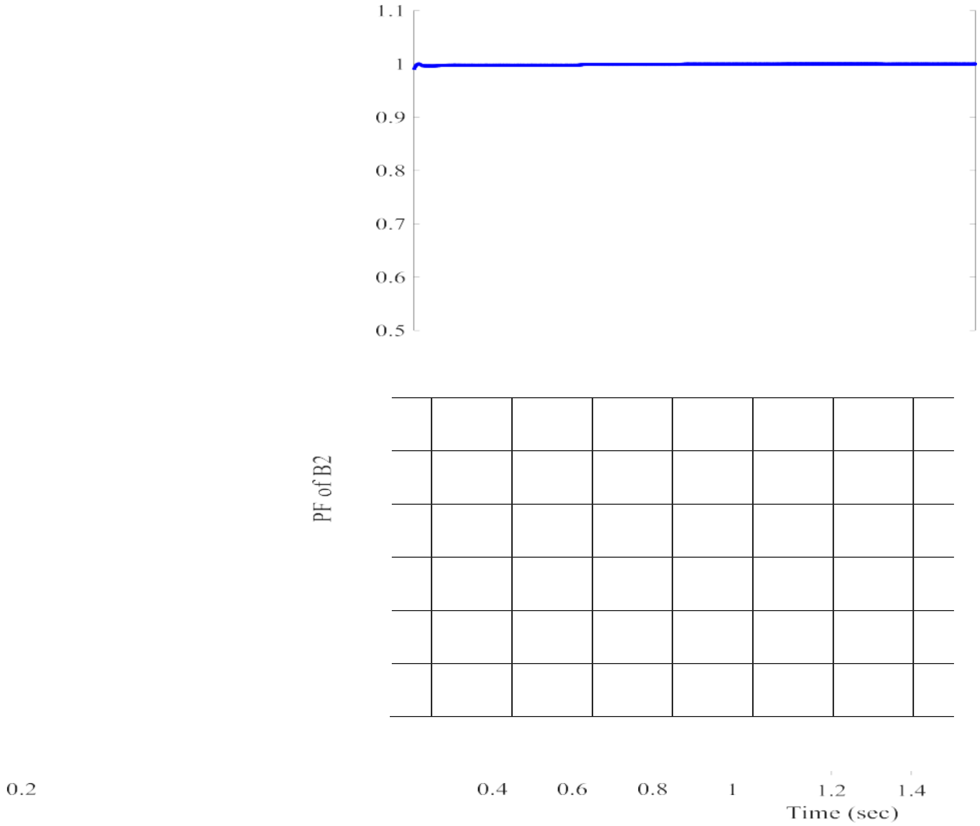
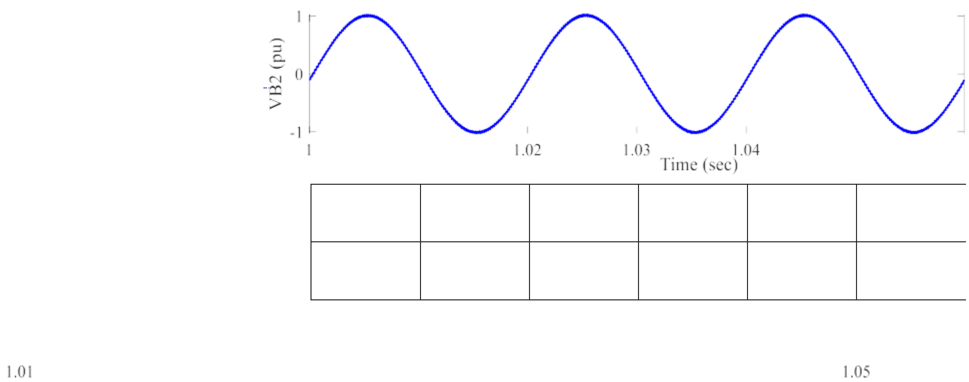


Figure 12. Power factor of the voltage across the second bus (B2)

6.5 The fast fourier transform (FFT) of the grid

The main purpose of using multilevel inverter is to obtain voltage and current waveforms nearly sinusoidal shape and to decreasing the Total Harmonic Distortion factor (THD) to a minimum value as possible. From the fast fourier transform (FFT) analysis of the voltage of second bus (B2) that shown in Figure 13, it can concluded that the system voltage is nearly sinusoidal waveform with low THD of (1.56%).



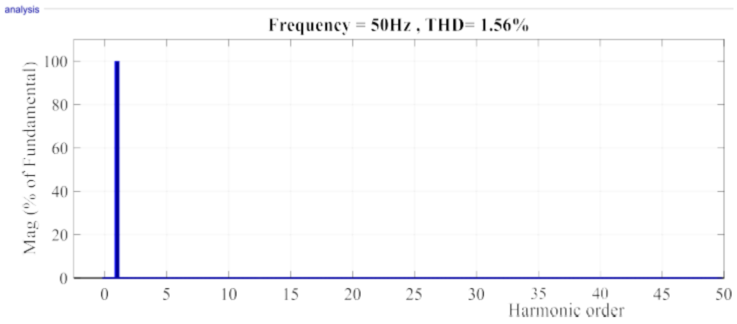


Figure 13. FFT and THD of the voltage across the second bus (B2)

6.6 A comparison between FLC controller and PID controller results

A comparison between controlled active power based FLC and PID controller is shown in Figure 14, from this comparison it can conclude that the system based FLC is faster response and more stable than the response of PID controller.

0.5 Time (sec) 1

Figure 14. Comparison between response of FLC and PID controller

6.7 The influence of DC link capacitor on the system performance

The main functions of the shunt converter are regulating line voltage by compensating sufficient reactive power to the transmission line as well as this converter used to provide (or absorb) the series converter by the needed active power through the DC link capacitor (C_{dc}). The C_{dc} plays a significant role for balancing the transmitted energy between the converters and its volume should withstand the high amount of this energy, thus it is very important to select a proper value of C_{dc} to improve the stability of the system.

The influence of C_{dc} for controlling active power from (870 MW) to (950 MW) and reactive power from (-60 MVAR) to (20 MVAR) has been studied clearly by analyzing the voltage across it (V_{dc}). The capacitance values are limited between ($C_{dc\text{-}min}<C_{dc}<C_{dc\text{-}sat}$), where ($C_{dc\text{-}min}$) represents the minimum value of C_{dc} required to operate in normal condition and ($C_{dc\text{-}sat}$) represents the maximum value of the capacitance required to operate in normal condition before it reaches the saturation region. For this work, the minimum value of C_{dc} is ($C_{dc\text{-}min}$ =1 mF), while the saturated value is ($C_{dc\text{-}sat}$ = 4 mF). One of the main functions of this work is improve system stability and one of the most important issues that realize this function is selecting optimum value of DC capacitor ($C_{dc\text{-}opt}$). By selecting the value of $C_{dc\text{-}opt}$ the transmitted DC power between the converters has been controlled in an efficient way. From the simulation study of the system it is observed that at ($C_{dc\text{-}opt}$ = 2.5 mF), the steady-state value of V_{dc} is stable to 20 kV, which means the transmitted DC power between the converters has been controlled efficiently.

7. CONCLUSION

This operation makes use of UPFC in conjunction with a four-bus system with a 100 MVA and 500 kV capacity. To minimize the harmonic content of the injected voltage, the UPFC is built with two three-level 48-pulse GTO multilevel inverters. Four important issues have been tested for both B1 and B2 because the controller circuit is located in the middle of them; the first issue is the active and reactive power flow of the system; the second issue is checking the harmonic contents and measuring the total harmonic distortion (THD) of the controlling buses (VB1 and VB2); the third issue is checking and measuring the buses power factor (PF); and the last issue is comparing the response of the fuzzy logic controller (FLC) with The two FLC played a very essential role in generating appropriate pulses for both converters, which leads to controlling active power and reactive power flow, regulating voltage and lowering voltage flicker, mitigating voltage imbalance problems, correcting power factor, Eliminating harmonics, boosting power quality, and improving performance. To improve stability and power flow, an optimum value of DC capacitor (2.5 mF) has been chosen between the two converters.

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