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Solar PV Integrated UPQC Modelling and Control using Modified Fuzzy Logic Controller

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Abstract— **This paper presents the designing and analysis of three-phase single-stage solar photovoltaic (PV) integrated unified power quality conditioner (PV-UPQC).The PV-UPQC comprises the series and shunt connected voltage compensators connected back to back via the DC link that is common to both. The shunt compensator performs dual functions of the extraction of PV array power and compensation of the harmonics caused due to load current. The Fuzzy logic controller is used and the PI controller has been used for the extraction of the maximum power from the photovoltaic PV panels to support the utility grid**

The load active current component is extracted using improved synchronous reference frame (SRF) control for improved performance of the PVUPQC. The series compensator helps in compensating power quality problems for the grid side such as grid voltage sags or swells. The compensator injects voltage in-phase during sag and out of phase during swell condition with common coupling point (PCC) voltage. The proposed system helps in combining the benefits of both, generation of clean energy and improving the quality of power. The Matlab-Simulink has been used to view the performance of UPQC during voltage sag and swell.

Keywords—UPQC; Series compensator; Shunt compensator; Synchronous reference frame theory; Photovoltaic system

I. INTRODUCTION

In this modern world, we are totally dependent on electrical power which is efficient and popular in nature. We cannot imagine our lives without electricity supply. However, if the quality and continual supply of the electric power is not achieved, the efficient functioning of the user tools becomes a challenge. The majority of the equipments used in commercial and industrial setup demand high power quality and also it must be uninterrupted. Hence the qualitative power is very important. With the advanced technology available today in power electronic devices, reducing these problems in power system is possible and also affordable. One such technology is FACTS, the flexible ac transmission system, makes it possible to improve the power quality and reliability. There are many semiconductor technologies that are used today in various loads that are built of power electronic components. They can be computer systems, speed drives that are adjustable, SMPS and so on. Another source of disturbance of power quality are the installation of various renewable energy systems which have gained a lot of momentum in the past years owing to greater environmental consciousness, improved technology and reliability. However, they can be major contributors of power quality problems pertaining to voltage like voltage sag, volage swll etc. This indirectly causes issues in other equipment functioning as well.

The main responsibility of a utility system is to supply sinusoidal form of electric power and the correct magnitude of current at right frequency at PCC (points of common coupling) to their customers. There are various Customised Power devices. Some of these devices are Active Power Filters (APF), Battery Energy Storage Systems (BESS), Distribution Series Capacitors (DSC), Distribution Static synchronous Compensators (DSTATCOM) Dynamic Voltage Restorer (DVR), Solid State Fault Current Limiter (SSFCL), Solid-State Transfer Switches (SSTS), Static Electronic Tap Changers (SETC), Static VAR Compensator (SVC), Superconducting Magnetic Energy Systems (SMES), Surge Arresters (SA), UPS Systems and UPQC. In this work, we focus on DSTATCOM, DVR and UPQC. Power quality includes all aspects including amplitude of voltage, voltage frequency and waveforms of current in the power circuits. Quality of power may be compromised due to transient conditions accumulate from the loads that are non-linear in the power circuit. The custom power concept **[6]**. The devices used for this purpose will correct the power quality at the point of delivery to customers. In **[5]** many examples of definitions of power quality level based on 3 categories: Quantum or level of voltage, continuous power supply and stable voltage have been presented. In **[10]** reviews on power engineering levels have been presented and described various power devices. These power conditioners are also known as DFACTS. He also compared the applications and operating modes of various FACTS devices. The most significant element for the utilities in achieving global benefits is the power supply reliability. Different types of custom power equipment to increase power quality as well as for maintaining the current and voltage profile were proposed. To enhance the power quality, custom power devices such as DSTATCOM, DVR and UPQC have been used. This paper is presenting a new configuration of the UPQC, known as a Multiconverter-UPQC (MC UPQC). By adding a VSC series into adjacent feeder, the system is enlarged.The topology proposed can compensate simultaneously the imperfections of current and voltage in two feeders with power sharing between two adjacent feeders that are not in connection. The system also compensates for interruptions without a battery storage system and therefore without limitations of storage capacity.

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II. CONFIGURATION OF PV-UPQC SYSTEM

The model of the PV-UPQC is as shown below, it is a three phase system. The integration of the photovoltaic system is done through the common DC link. The UPQC consists of the series compensator and the shunt compensator. It consists of a coupling inductor and the injection transformer. The designing of PV-UPQC begins with the PV array sizing, DC link capacitor sizing, voltage level sizing etc. The shunt compensator sizing is done in a way so to handle the PV array peak power output. It is also seen that it can perform the load power reactive power compensation and compensate the current harmonics. In this project, the DC link in the UPQC is integrated to the PV array directly. The PV array sizing is done such that the DC link voltage desired and the Maximum power point voltage is the same. The rating is chosen such that in the normal conditions in the Photovoltaic system, active load power supplied to the load and the grid as well. The specifications of the PV array has been given in the appendix A. The other component that has been designed in the project are the series injection transformer for the series compensator and the inductors that are used to interface the series and shunt compensator.

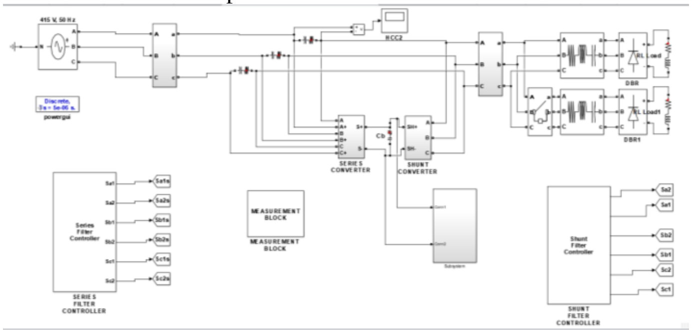

Fig. 1 PV UPQC Simulink Model

III. DESIGNING OF PV UPQC

The designing of PV-UPQC begins with the PV array sizing, DC link capacitor sizing, voltage level sizing etc. The shunt compensator sizing is done in a way so to handle the PV array peak power output. It is also seen that it can perform the load power reactive power compensation and compensate the current harmonics. In this project, the DC link in the UPQC is integrated to the PV array directly. The PV array sizing is done such that the DC link voltage desired and the Maximum power point voltage is the same. The rating is chosen such that in the normal conditions in the Photovoltaic system, active load power supplied to the load and the grid as well. The specifications of the PV array has been given in the appendix A. The other component that has been designed in the project are the series injection transformer for the series compensator and the inductors that are used to interface the series and shunt compensator.

1) DC Link Voltage Magnitude: The DC link voltage magnitude V_{dc} is calculated based of the system per phase voltage and the depth of modulation.[8] It has to be made sure that the voltage magnitude of the DC link must be more/ than twice the peak per-phase voltage of the three phase system, it is given by

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \quad (1)$$

Here, (m) depth of modulation is assumed to be 1 and grid line voltage is given by V_{LL} . After substituting the values of m and V_{LL} , weget the value of the magnitude of the DC bus as 677.7 V. This value can be approximated to 700 V(approx), it is seen theat the operating voltage of the Photovoltaic system is also the same as above at standard temperature conditions.

2) DC-Bus Capacitor Rating:: The sizing of the DC bus capacitor is done depending upon two major factors that is the powe required and the voltage level of DC bus which has been calculated above.The energy balance equation for the DC-bus capacitor is given as follows [8],

$$\begin{aligned} C_{dc} &= \frac{3kaV_{ph}I_{sh}t}{0.5\times(V_{dc}^2 - V_{dc1}^2)} \\ &= \frac{3\times 0.1\times 1.5\times 239.6\times 34.5\times 0.03}{0.5\times(700^2 - 677.79^2)} \\ &= 9.3mF \end{aligned} \quad (2)$$

Here, the average voltage of the DC bus is given by V_{dc} , the least DC bus voltage that is required is represented by V_{dc1} , overloading factor is given by a, per phase voltage is given by V_{ph} , the time necessary(min) inorder to attain the steady state value post disturbance is given by t, shunt compensator per phase current is given by $I_{sh}$and k is the constant factor for considerations in variation of energy during dynamics.

The value of least DC bus voltage is given by V_{dc1} : 677.69 V which has been calculated above, the values for V_{dc} , V_{ph}, I_{sh}, ,, t, a, dynamic energy change percentage and k are 700V, 239.6 V, 57.5A, 30ms, 1.2, 10%, 0.1. On substituting the above values we get the value of the DC bus capacitor rating as 9.3mF.

3)) Inductor interface used in the Shunt Compensator: The factors on which the rating of the inductor interfacing the shunt compensator depends on the voltage of the DC link, ripple current and switching frequency. The equation for calculating the inductor used for interfacing is given by :

$$\begin{aligned} L_f = \frac{\sqrt{3}mV_{dc}}{12af_{sh}I_{cr,pp}} &= \frac{\sqrt{3}\times 1\times 700}{12\times 1.2\times 10000\times 6.9} \\ &= 800\mu H \approx 1mH \end{aligned} \quad (3)$$

Here, the depth of modulation is represented by m, pu maximum overload value is given by a, switching frequency is given by f_{sh} , ripple current of the inductor is given by $I_{cr,pp}$. The values of m, a, f_{sh}, $I_{cr,pp}$ and V_{dc} is given by 1, 1.2, 10kHz, 0.2 of RMS phase current and 700 V respectively. On substituting the above values in the equation we get the value of inductor interfaced as 800 μH. Which can be approximately taken as to 1mH.

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4) Series Injection Transformer: The PV UPQC is designed in such a way such that the sag/swell compensation is done during 0.3 p.u or 71.88 V. Hence the injection voltage by the series transformer is 71.88 V, this causes the modulation index to be low for the series compensator because 700 V is the DC link voltage.

The modulation index for the series compensator is generally kept close to 1 or unity so as to ensure that the series compensator operates with minimal level of harmonics. The expression for the turns ratio can be given by :

$$K_{SE} = \frac{V_{VSC}}{V_{SE}} = 3.33 \approx 3 \tag{4}$$

From the above expression, we get the K_{SE}value as approximately 3, the exact value we get is 3.33. From the equation below we get, he rating of the series injection transformer as 10 kVA

$$S_{SE} = 3V_{SE}I_{SE_{sag}} = 3 \times 72 \times 46 = 10kVA \tag{5}$$

The current value of the VSC is taken as 46A because the value of grid current and the VSC value are the same. On substituting the the values of the voltage and current we obtain the value of the injection transformer voltage rating as 10kVA.

5) Inductor used to interface the Series Compensator:

Similar to inductor which is used for interfacing the shunt capacitor, for a series compensator also there is an inductor which is used for interfacing. The inductor used is based on factors like the ripple current, DC link voltage, switching frequency and voltage swell conditions.

It is given by the below equation:

$$L_r = \frac{\sqrt{3} \times mV_{dc}K_{SE}}{12af_{se}I_r} = \frac{\sqrt{3} \times 1 \times 700 \times 3}{12 \times 1.2 \times 10000 \times 7.1} = 3.6mH \tag{6}$$

In the above equation m stands for the depth of modulation, a is the representation of the maximum overload value in per unit, *fse* stands for switching frequency and *Ir* is the inductor ripple current. The value of m is 1, a = 1.5, *fse* =10 kHz and I_r = 0.2 A. of the grid current. On substitution of the above value in the equation, we get 3.6mH.

IV. CONTROLLING OF PV UPQC

The series compensator and shunt compensator are the main subsystems of the PV-UPQC. The shunt compensator compensates for load-related power quality problems such as load reactive power and load current harmonics. In this project in addition to doing the load reactive power compensation and load current harmonics, it is also used to supply the power from the solar PV array. This power extraction from the PV-array is done by using the Maximum power point tracking (MPPT) algorithm. The role of the series compensation is for the protection of the load from the power quality problems caused on the grid side like voltage swell and sag. This is done by the injection of required voltage which is in phase with the grid voltage.

A. Control Of Series Compensator

Pre sag compensation is done by the series compensator, along with compensation for energy optimization and in phase compensation. There are many strategies which are used for the compensation. Voltage of the same phase which is the same as the grid voltage is injected by the series compensator in this project, this leads to minimal voltage injection. The figure below shows the series compensator control structure. Extraction of the fundamental component of the point of common coupling voltage is done with the help of a phase locked loop which is mainly used for the generation of the reference axis in the dq-0 domain.
Using the information obtained regarding the frequency and phase of the point of common coupling voltage, the generation of the reference voltage is done. This task is performed with the help of the PLL. Conversion of the voltages at the PCC and load to d-q-0 domain is done. The load reference voltage d-axis component equals to the peak load reference voltage since the PCC voltage and the load reference voltage has to be in phase with each other. The component of the q-axis is kept zero. The series compensator reference voltage is obtained from the difference of the load reference and PCC voltage. Then the actual series compensator voltage is obtained by subtraction between the load and the PCC voltage. This value of the difference between the reference voltage signal and the series compensator voltage signal is used to generate the required reference signal from the difference sent to the PI controller. The gating signals that is needed for the series compensator is generated via the pulse width modulation voltage controller from the signals above after converting them to the abc domain.

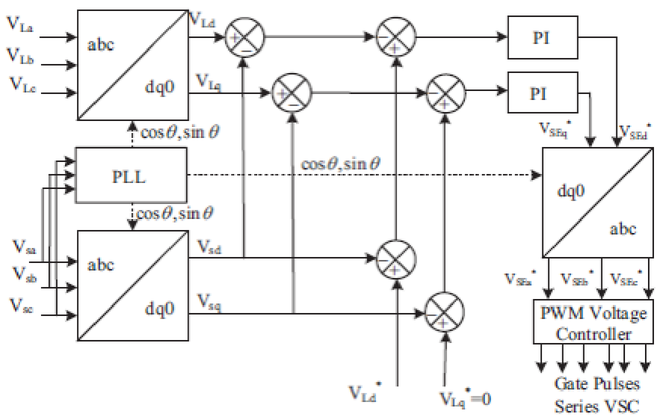

Fig. 2 Control Structure of Series Compensator

B. Control Of Shunt Compensator

Extraction of maximum power by the shunt compensator from the solar PV array is done using the Maximum power point tracking algorithm. This is done so that the PV array operates at Maximum power point. The Maximum power point tracking algorithm involves the generation of the reference voltage, this voltage is generated for the DC-link of

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the UPQC. There are many MPPT algorithms that are used[28], like Perturb and Observe (P&O), Incremental conductance algorithm etc. In this project the MPPT algorithm used is the Perturb and Observe technique .The PI controller is employed here to keep the DC link voltage constant at the generated voltage.

Inorder to do the compensation of the load current, the load current active fundamental component is extracted by the shunt compensator.The technique using which the extraction of the load current active fundamental component is done is the synchronous reference frame theory technique. The fig 2 illustrates the control structure of the shunt compensator. Using the Phase locked loop(PLL), we can obtain the information of the frequency and phase to convert the load current to the d-q-0 domain. The input to the PLL is PCC voltage. I_{Ld} is the load current d-component which on filtering is used for the extraction of the DC component I_{Ldf} . I_{Ldf} is used as a representation of the fundamental component in the abc frame/ of reference. For the extraction of the DC component without detoriation of the dynamic performance, the Moving average filter(MAF) can be used which is used for the extraction of the DC component.

The moving average filter transfer function is given by:

$$MAF(s) = \frac{1 - e^{-T_w s}}{T_w s} \tag{7}$$

Moving average filter window length is given by T_w , it's value is taken as half of the fundamental time period since the most lowest harmonics component present in the d- axis is double the harmonic component. It's time period is half that of the fundamental time period.

The moving average filter has a DG gain of unity and the the gain integer is zero of the window length.

The PV array equivalent current component is given by the equation below:

$$I_{pvg} = \frac{2}{3}\frac{P_{pv}}{V_s} \tag{8}$$

In the above equation, the PV array power is given by $P_{pv}$and the magnitude of the PCC voltage is given by Vs . The grid current reference of the d-axis is given by:

$$I_{sd}^{*} = I_{Ldf} + I_{loss} - I_{pvg} \tag{9}$$

Conversion of I^{*}_{sd} is done to the/ abc domain reference of the grid currents. After which a comparison is done with the grid current that is sensed by the hysteresis current controller for generating the pulses to control switches of shunt converter.

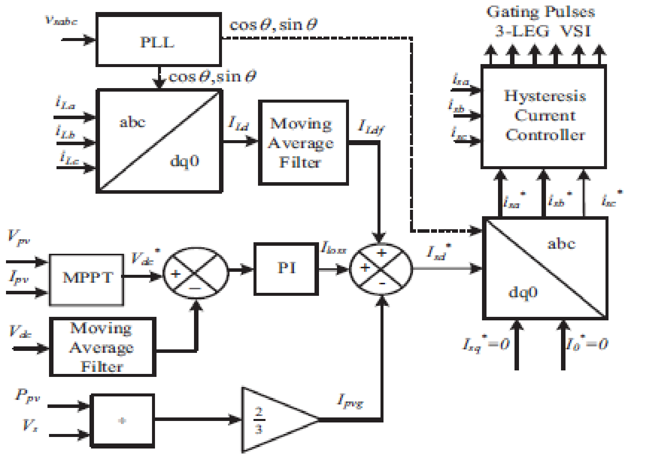

Fig.3. Control Structure of Shunt Compensator

C. Simulation Studies

The UPQC is simulated using Matlab/Simulink software and is comprises a supply of three-phase and critical load of three-phase three-wire, a series connected three-leg VSC, a shunt connected three-leg VSC and passive filters of small size to remove switching ripples. The models of supply system, linear loads, IGBTs using anti-parallel diodes, interfacing inductors, etc are used in modeling of VSC of DSTATCOM and DVR.

1. ***UPQC performance at critical load during voltage sag***

Figure 3(a) shows the UPQC system's transient performance under condition of voltage sag with a critical load. A sag in the supply voltage is created at 0.3s for 10 cycles and observed that load voltage is maintained with constant amplitude whereas supply current is incremented. During sag, DVR of UPQC injects voltage to control the load voltage. At 0.7s, the voltage distortions are applied and when observed, the supply currents are in phase with the supply voltage and are balanced under unbalanced supply loads. The load neutral current is provided by the third leg of DSTATCOM, thus under all operating conditions the supply neutral current is almost zero.

2. ***UPQC performance at critical load during voltage swell***

Figure 3 (b) shows the UPQC system's transient performance under condition of voltage swell with a critical load. A swell in the supply voltage is created at 0.3s for 10 cycles and observed that load voltage is maintained with constant amplitude whereas supply current is decremented. During swell, DVR of UPQC injects voltage to control the load voltage. At 0.7s, the voltage distortions are applied and when observed, the supply currents are in phase with the supply voltage and are balanced under unbalanced supply loads. The load neutral current is provided by the third led of DSTATCOM, thus under all operating conditions the supply neutral current is almost zero.

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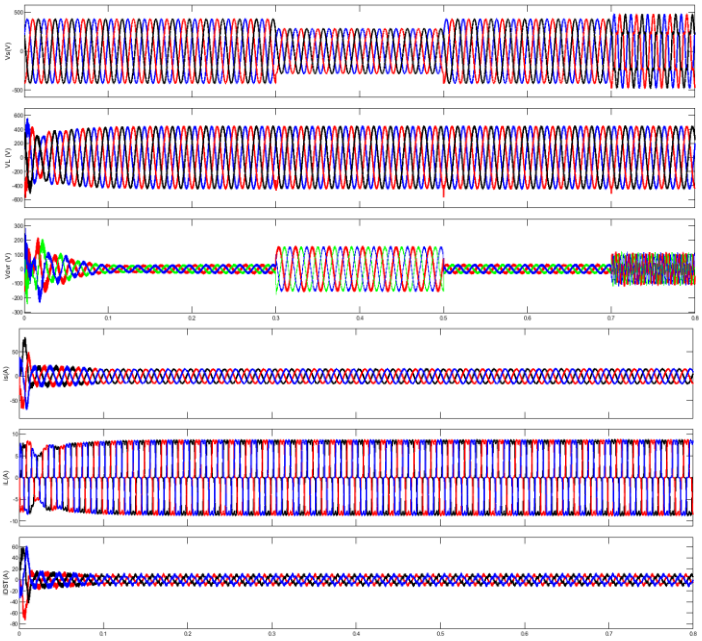


Fig.3(a).Performance of UPQC during Voltage Sag

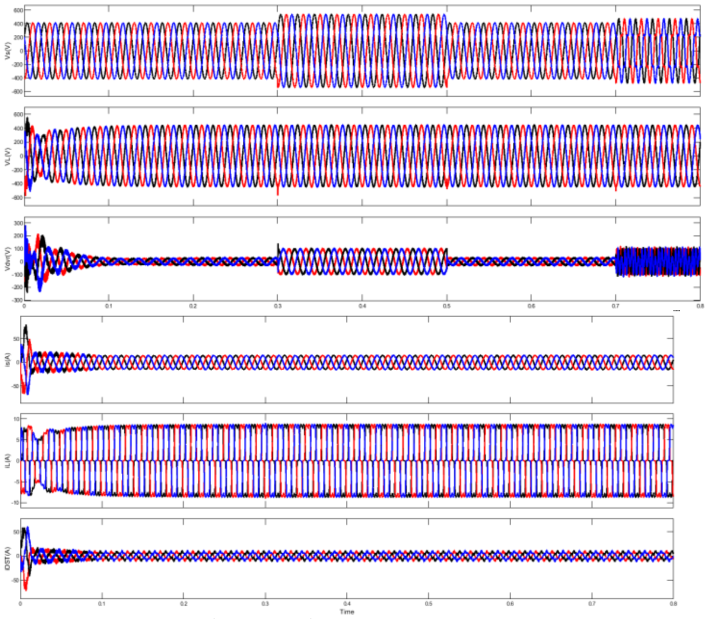


Fig.3(b).Performance of UPQC during Voltage Swell

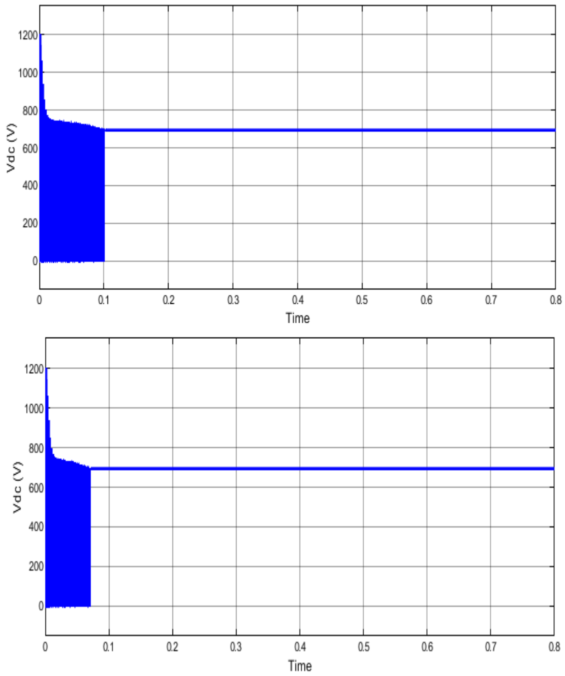
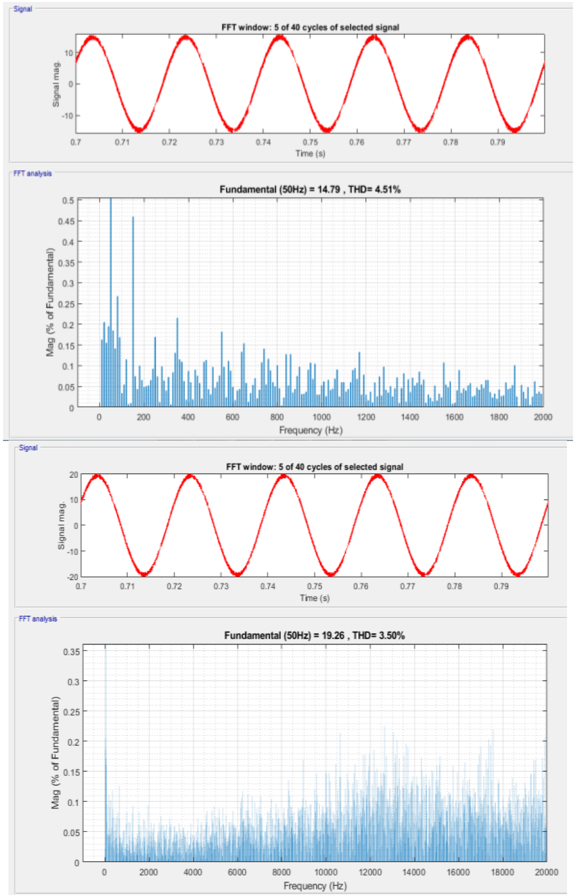


Figure 4 DC-link voltages with (a) PI controller and (b) FLC

From figure 4, it is shown that there is a clear difference between PI controller and Fuzzy controller in settling time. Thus FLC is more reliable and efficient than PI in improving step response.



(a)

Figure 5. Grid Current Harmonic Spectrum and THD using (a) PI controller and (b) Fuzzy controller

Figure 5 (a) and (b) shows the harmonic spectrum and Total Harmonic Distortion (THD) of grid current using PI and Fuzzy controller respectively. From figures, the THD of grid current using PI is4.51% and using FLC it is still reduced to below 3.50%, thus meeting IEEE standard requirements.

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