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Optimal Control and Analysis of Three Phase Electronic Power Transformers

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Abstract

The use of electrical energy has important place in modern society. In this regard, the studies were carried out on transformer which is one of the most important parts in transmission and distribution of the electric power. As a result of these studies, a new type of transformer based on power electronics has emerged. These new transformers are named as power electronic transformer (PET) or solid state transformer (SST). Interest in the electronic power transformer which used in many applications is increasing day by day. So, many researchers have focused on the control and design of these transformers. In this study, control strategy has been proposed for fuzzy logic controller (FLC) based PET system. Proposed PET system consists of input, isolation and output stages. In order to test dynamic performance of FLC based PET system, simulation study was carried out by MATLAB/Simulink. The results obtained from the FLC based PET are not only superior in the rise time, settling time and overshoot but can prevent from voltage sag-swell and has improved power quality.

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Keywords: Fuzzy Control, PWM converters, Transformers, Power quality

1. Introduction

Transformers which are used to provide galvanic isolation and to connect systems at different voltage levels are one of the most important equipment in modern electrical distribution and transmission systems. It is well-known that transformers are widely used in electrical power systems in order to perform many functions such as voltage-

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current transformation, galvanic isolation, energy transfer and noise decoupling, etc. Conventional transformers are one of the most bulky and expensive components in electrical power systems because of the composition consisting of iron cores and windings (McMurray, 1970; Liu et al., 2009; Wang et al., 2005). Moreover, conventional transformers have undesirable properties such as heavy weight and large size, low performance under load unbalance, sensitivity to harmonics, larger loss, etc (Rodriguez et al., 2012; Rahmat-Allah et al., 2012; Ronan et al., 2002).

By the rapid development of power electronics, microprocessors and semiconductor materials, power electronic technology has become inevitable for many sectors and applications. It ıs known that size of transformer is a function of the saturation flux density (Liu et al., 2009; Wang et al., 2005; Kang et al., 2009; Wang et al., 2007).The saturation flux density is inversely proportional to frequency and so, the weight and size of transformer can reduce by increasing the frequency of operation with power electronic converters. Recently, a new type of transformers, which is based on power electronics, has been introduced. These new transformers are named as PET or SST which realizes voltage-current transformation, galvanic isolation, power quality improvement, reactive power compensation, power flow regulation and power factor correction in one circuit. PETs have first proposed by McMurray in 1970 (McMurray, 1970). Then, studies on PETs have been done and many researchers have focused on the design and control of PET (Acikgoz et al., 2014; Lai et al., 2005; Subramanya e al., 2012). There are generally two approaches such as with dc link and without dc link for PET. PET system with dc link has three stages consisting input, isolation and output. Input stage is a three-phase PWM rectifier which is used to convert AC voltage into DC voltage. Because of fast dynamic response, unity power factor and constant DC bus voltage, three-phase PWM rectifier is used in PET systems. Isolation stage which realizes the galvanic isolation between the primer and secondary side consists of DC-DC converter and output stage consists of two level three-phase inverter which produces the desired output voltages and LC filter (Chen et al., 2012; Hanafi et al., 2009; Zixin et al., 2013; Acikgoz and Sekkeli, 2014). PWM based rectifier is used in input side of PET system in order to obtain unity power factor, fast response, and constant DC voltage. In the control of PWM based rectifier, DC bus voltage is generally controlled by using Proportional-Integral (PI) controllers designed with linear control methods. In the design of PI controllers, linear mathematical model of controlled system is required. Parameters of these controllers are tuned to obtain the best performance for a particular region of operation and conditions. Moreover, PI controllers have many disadvantages like slow response, large overshoots and oscillations. Intelligent controllers, based on Fuzzy Logic Controllers (FLC), Artificial Neural Network (ANN), Linear Quadratic Regulator (LQR) etc., have been used for many industrial applications in recently. FLC was first proposed by Lotfi A. Zadeh (Zadeh, 1965). The central idea behind FLC is to incorporate the expert experience of a human operator in the design of the controller. FLC is easily designed and don't need the mathematical model of system to be controlled. Because of this important feature, FLC is widely used in all fields. In this paper, we have been proposed a PET system with dc link. Unlike other studies, PWM based rectifier is controlled by FLC in order to improve dynamic performance of designed PET system. The rest of this paper is organized as follows. In Section II, it has given information about proposed PETs and design of proposed controller. The simulation results are given in Section III. Conclusions are presented in Section IV.

2. Mathematical Model of Proposed PET System

In this section, we present proposed PET system consisting three stages such as input, isolation and output stages as seen Fig.1. Three-phase grid voltages are first converted into DC voltage by using three-phase PWM rectifier. DC voltage obtained from PWM rectifier is transformed to high frequency square wave using single-phase inverter. High frequency square wave at secondary part of high frequency (HF) transformer is rectified with uncontrolled diode rectifier. Then, this DC voltage is transmitted to the inverter. According to Fig.1, the voltage variables are expressed as following:

$$u_{sa}(t) = \sqrt{2}U_s \sin \omega t \qquad (1)$$

$$u_{sb}(t) = \sqrt{2}U_s \sin(\omega t - 120) \qquad (2)$$

$$u_{sc}(t) = \sqrt{2}U_s \sin(\omega t + 120) \qquad (3)$$

$$u_{la}(t) = m_1 U_{dc} \sin(\omega t - \theta_1) \quad (4)$$

$$u_{lb}(t) = m_1 U_{dc} \sin(\omega t - \theta_1 - 120) \quad (5)$$

$$u_{lc}(t) = m_1 U_{dc} \sin(\omega t - \theta_1 + 120) \quad (6)$$

$$u_{0a}(t) = m_2 U_{dc} \sin(\omega t - \theta_2) \quad (7)$$

$$u_{0b}(t) = m_2 U_{dc} \sin(\omega t - \theta_2 - 120) \quad (8)$$

$$u_{0c}(t) = m_2 U_{dc} \sin(\omega t - \theta_2 + 120) \quad (9)$$

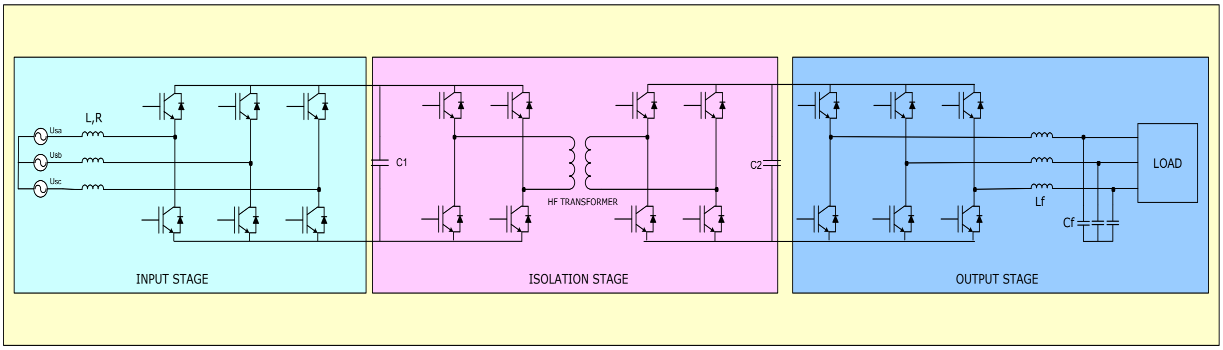


Fig 1. Block diagram of Proposed PET system

Where, m_1 *and* Θ_1 are amplitude modulation index and modulation angle for PWM converter used in the input stage. m_2 *and* Θ_2 are amplitude modulation index and modulation angle for PWM converter used in the output stage. u_{sa}, u_{sb} and u_{sc} are input voltages. $u_{La,}$ u_{Lb} and u_{Lc} are output voltages. U_{dc} is dc-link voltage of input stage. u_{0a}, u_{0b} and u_{0c} are AC voltages in the output stage. u_{la}, u_{lb} and u_{lc} are AC voltages in the input stage. Then, the following equations can be obtained by means of the physical circuit diagram (Liu et al., 2009; Wang et al., 2005).

$$L\frac{di_{la}(t)}{dt} = u_{sa}(t) - u_{la}(t) + Ri_{la}(t) \quad (10)$$

$$L\frac{di_{lb}(t)}{dt} = u_{sb}(t) - u_{lb}(t) + Ri_{lb}(t) \quad (11)$$

$$L\frac{di_{lc}(t)}{dt} = u_{sc}(t) - u_{lc}(t) + Ri_{lc}(t) \quad (12)$$

$$C_f\frac{du_{La}(t)}{dt} = i_{fa}(t) - i_{La}(t) \quad (13)$$

$$C_f\frac{du_{Lb}(t)}{dt} = i_{fb}(t) - i_{Lb}(t) \quad (14)$$

$$C_f\frac{du_{Lc}(t)}{dt} = i_{fc}(t) - i_{Lc}(t) \quad (15)$$

$$C_f\frac{du_{Lc}(t)}{dt} = i_{fc}(t) - i_{Lc}(t) \quad (16)$$

$$L_f\frac{di_{fa}(t)}{dt} = \frac{u_{0a}(t)}{k} - u_{La}(t) \quad (17)$$

$$L_f \frac{di_{fb}(t)}{dt} = \frac{u_{0b}(t)}{k} - u_{Lb}(t) \tag{18}$$

$$L_f \frac{di_{fc}(t)}{dt} = \frac{u_{0c}(t)}{k} - u_{Lc}(t) \tag{19}$$

$$\begin{aligned} \frac{d}{dt}\left(\frac{1}{2}Cu_{dc}^2\right) &= u_{la}(t)i_{la}(t) + u_{lb}(t)i_{lb}(t) + u_{lc}(t)i_{lc}(t) \\ &- \frac{u_{0a}(t)i_{fa}(t)}{k} - \frac{u_{0b}(t)i_{fb}(t)}{k} - \frac{u_{0c}(t)i_{fc}(t)}{k} \end{aligned} \tag{20}$$

$$\frac{di_{ld}(t)}{dt} = -\frac{R}{L}i_{ld} - \omega i_{lq} + \frac{m_1 \sin\theta_1}{L}u_{dc} \tag{21}$$

$$\frac{di_{lq}(t)}{dt} = -\frac{R}{L}i_{lq} - \omega i_{ld} + \frac{m_1 \cos\theta_1}{L}u_{dc} + \sqrt{2}\frac{u_s}{L} \tag{22}$$

$$\frac{du_{Ld}}{dt} = \frac{1}{C_f}i_{fd} - \frac{1}{C_f}i_{Ld} - \omega u_{Lq} \tag{23}$$

$$\frac{du_{Lq}}{dt} = \frac{1}{C_f}i_{fq} - \frac{1}{C_f}i_{Lq} - \omega u_{Ld} \tag{24}$$

$$\frac{di_{Ld}}{dt} = -\omega i_{fd} - \frac{m_2 \sin\theta_2}{kL_f}u_{dc} - \frac{1}{L_f}u_{Ld} \tag{25}$$

$$\frac{di_{Lq}}{dt} = \omega i_{fd} + \frac{m_2 \cos\theta_2}{kL_f}u_{dc} - \frac{1}{L_f}u_{Lq} \tag{26}$$

$$\begin{aligned} \frac{du_{dc}}{dt} &= -\frac{3m_1}{2C}i_{ld}\sin\theta_1 + \frac{3m_1}{2C}i_{lq}\cos\theta_1 \\ &+ \frac{3m_2}{2kC}i_{fd}\sin\theta_2 - \frac{3m_2}{2kC}i_{fq}\cos\theta_2 \end{aligned} \tag{27}$$

$$K = \frac{2}{3}\begin{bmatrix} \cos\omega t & \cos(\omega t - 120) & \cos(\omega t + 120) \\ \sin\omega t & \sin(\omega t - 120) & \sin(\omega t + 120) \\ \frac{3}{2} & \frac{3}{2} & \frac{3}{2} \end{bmatrix} \tag{28}$$

$$\left[i_{ld} i_{lq} i_{lo}\right]^T = K\left[i_{la} i_{lb} i_{lc}\right]^T,$$

$$\left[i_{Ld} i_{Lq} i_{Lo}\right]^T = K\left[i_{La} i_{Lb} i_{Lc}\right]^T,$$

$$\left[u_{Ld} u_{Lq} u_{Lo}\right]^T = K\left[u_{La} u_{Lb} u_{Lc}\right]^T \; \left[i_{fd} i_{fq} i_{lo}\right]^T = K\left[i_{fa} i_{fb} i_{fc}\right]^T$$

2.1. FLC Design For Input stage

The three-phase PWM rectifier is widely used in a wide diversity of applications in recent years. These rectifiers have many advantages such as bi-directional power flow, low harmonic distortion of line current, unity power factor, control of DC-link voltage. When considering all these features, the three-phase PWM rectifier is the most important part in PETs. In this study, three-phase voltage source PWM rectifier has used for PET system. The dc bus voltage in the three-phase PWM rectifier is generally controlled by a PI controller (Blasko and Kaura, 1997). But, it is difficult to find the parameters of the PI controller. So, many researchers are focused on this problem and they have been proposed many methods (Djerioui et al., 2012; Monfared et al., 2010; Acikgoz and Sekkeli, 2014). The three-phase PWM rectifier structure is as shown in Fig.2.

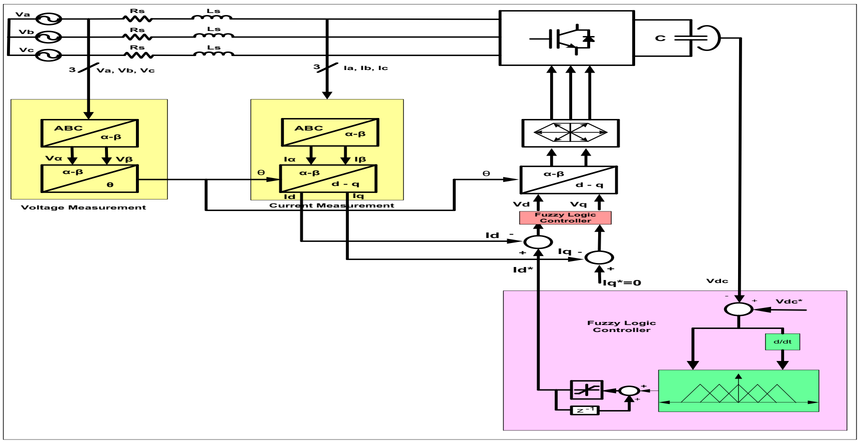


Fig. 2. Main circuit of three-phase PWM rectifier

In control of dc voltage, average value of dc-link voltages is compared with reference dc voltage. Error of dc voltage is applied to FLC controller. Reference value for d-axis current is obtained from output of FLC controller. Reference value for q-axis current is set to 0 in order to obtain unity power factor. Error of d and q-axis current and changes of these errors are given as input to PI controllers. Their differences are converted to Vq and Vd by FLC current controller. These voltages are sent to PWM block, which generates required signals for driving the semiconductor switching element ((Djerioui et al., 2012; Monfared et al., 2010). Moreover, an anti-wind up integrator is used to limit the output of FLC and compensate for steady state error. The block configuration required for PWM-based rectifier transformations is given in Fig. 2. FLC is used to control Vdc voltage in this study.

Table I. Rule Base

de e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

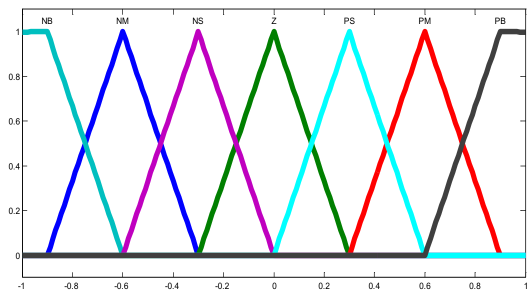


Fig. 3. Membership function of inputs and output

As known, FLC is preferred for many applications because of don't need the mathematical model of system to be controlled. Proposed FLC for PET system is given fig. 2. The inputs of FLC are error and change in error. These inputs are normalized to obtain error e(k) and its change Δe(k) in the range of -1 to +1. Normalized triangular membership functions are preferred for input variables and output variable (Zadeh, 1965; Gunes and Dogru, 2010). The fuzzy membership functions consist of seven fuzzy sets: NB, NM, NS, Z, PS, PM, PB as shown in Fig. 3. The total number of IF-THEN rules is 49 and the rule base of the FLC system is given in Table I.

2.2. Isolation stage

In fact, the isolation section is a DC-DC converter that includes single-phase inverter, high frequence transformer and diode rectifier. DC voltage obtained from the rectifier is first modulated into the high-frequency square wave by the single-phase inverter used in the isolation stage. According to the transformation ratio of the transformer, this square wave is obtained in the same manner as the secondary. Then, this wave is converted into DC voltage by using diode rectifier. HF transfomer provides the electical isolation and voltage transformation. The simplified model of the HF transformer is presented as:

$$V_2 = \frac{N_2}{N_1} V_1 \tag{29}$$

Where, V_1 and V_2 are the primary and secondary voltage of HF transformer. N points to turn ratio (Djerioui et al., 2012; Monfared et al., 2010; Acikgoz and Sekkeli, 2014).

2.3. Output Stage

Output stage consists of three phase inverter, LC filter and load. Three phase inverter used in the output stage has six directional switches which is converted DC voltage into three-phase voltages. We have proposed SVPWM technique for three-phase inverter. In the output stage, three-phase output voltages are first converted to voltages of d-q axis (Vd,Vq) in the synchronous rotating d-q reference frame. Then, these voltages are compared with the reference values of Vd and Vq. PI controller outputs are transformed to Uα-Uβ voltage which is used to generate inverter gate pulses (Chen et al., 2012; . Hanafi et al., 2009; Zixin et al., 2013; Acikgoz and Sekkeli, 2014).

3. Simulation Results

In this section, we have realized a number of simulation studies in order to test dynamic performance of proposed PET system. Proposed PET system is implemented in MATLAB/Simulink environment. MATLAB/Simulink model of proposed PET is given in Fig. 4. Proposed PET system consists of three parts such as input, isolation and output stages. The parameters of PET system used in the simulation are given in Table II.

Table II. Parameters of PET System

Parameters	Value
Input Grid Voltage	600 Vrms
Source Resistance and Inductance	0.1Ω, 3.5mH
Power Frequency	50 Hz
HF Transformer	4:1, 1000 Hz, 30 kVA
LC Filter	2 mH, 200 µF
PET Load	15 kW + j10 kVAR

As it can be seen in Fig. 4, DC voltage obtained from PWM rectifier is 2000 V. DC voltage is controlled by FLC and classic PI controller. Fig. 4 shows that FLC is advantageous compared with PI control in terms of rise time, settling time and overshoot. In Fig. 9, it is noticed that supply current in phase with grid voltage and so unity power factor is obtained.

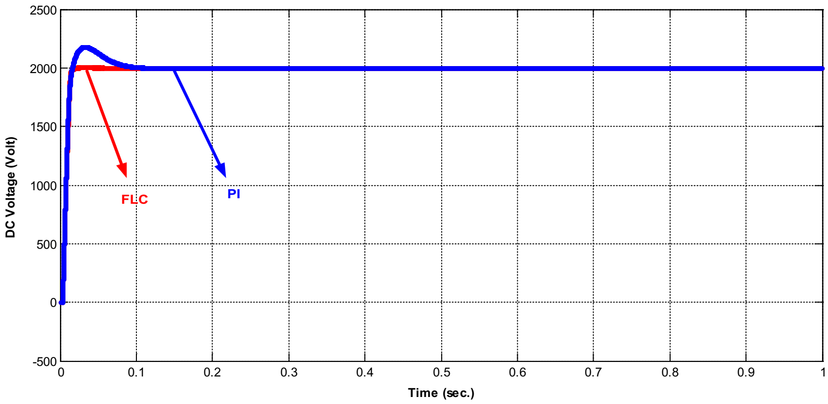
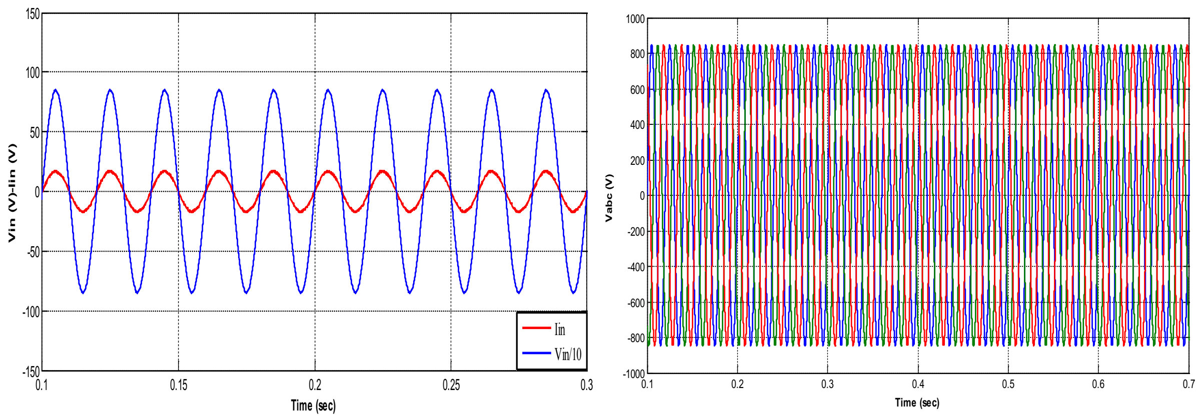


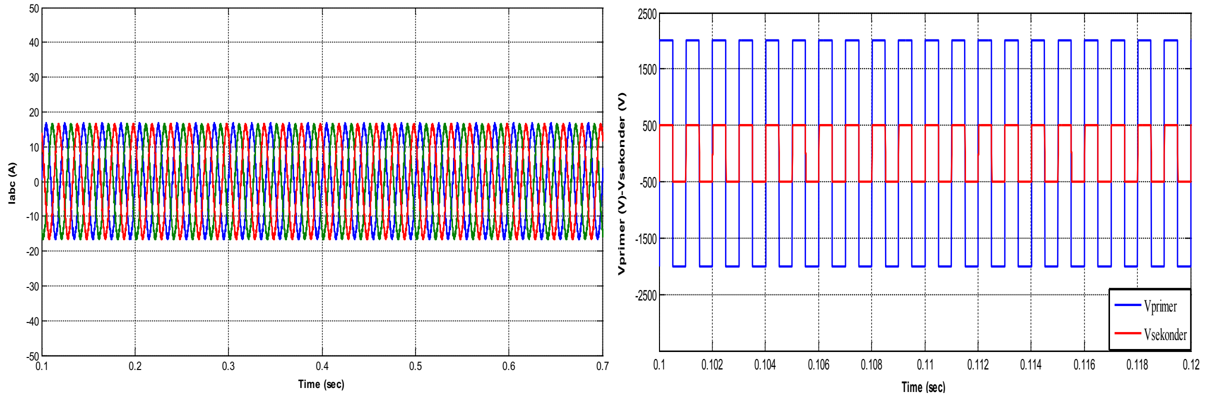
Fig. 4. Control of DC voltage with FLC and PI controller

Fig. 5 illustrates the waveforms of the input voltage and current. Grid voltage is first rectified by PWM the rectifier. The rectified DC voltage is converted into a high frequency square wave for transmission to the high-frequency transformer using single phase inverter as shown in Fig.6. High frequency square wave in the secondary side of transformer is shown in Fig. 6. Also, simulation studies were carried out to illustrate the performance of proposed PET system under voltage sag and swell conditions. Fig. 7 shows grid voltage when there is 20 % of three phase voltage sag from 0.3s to 0.4s in order to demonstrate the performance and capability of proposed controller and PI controller. Fig. 7 demonstrates the enlarged waveform of the rectified DC voltage. As shown in Fig. 7, when the voltage sag occurs, FLC follows reference DC voltage faster than PI controller. FLC reaches the reference DC voltage after approximately 0.02 second while PI controller reaches the reference DC voltage after approximately 0.1 second. The consequence of the fact that the FLC is characterized by a faster dynamic response. Fig. 8 shows grid voltage when there is 20 % of three phase voltage swell from 0.3s to 0.4s in order to demonstrate the performance of proposed controller and PI controller. According to the enlarged DC voltage given in Fig. 8, when the voltage swell occurs, It is shown that FLC has more efficient performance than PI controller and when voltage swell ends in 0.4 second, FLC reaches reference DC voltage more quickly



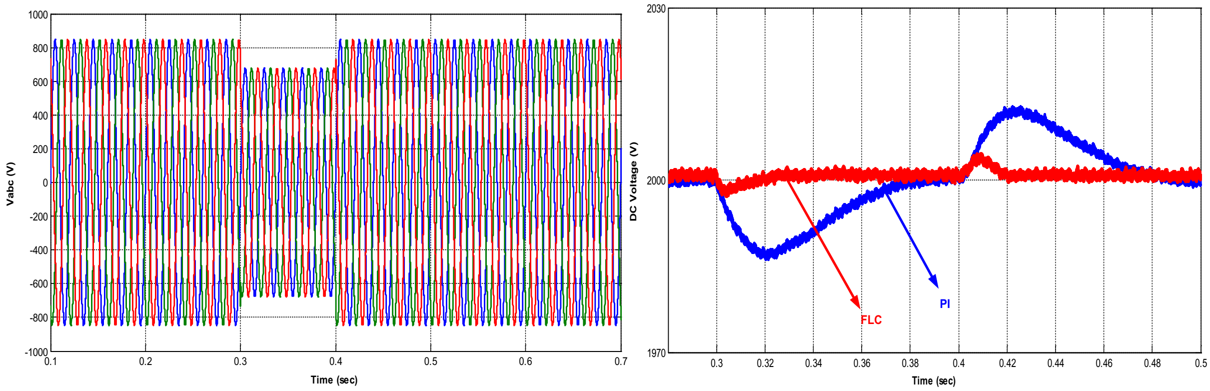
(a) (b)

Fig. 5. a) Voltage and current of one phase of grid b) Voltage and current of one phase of grid



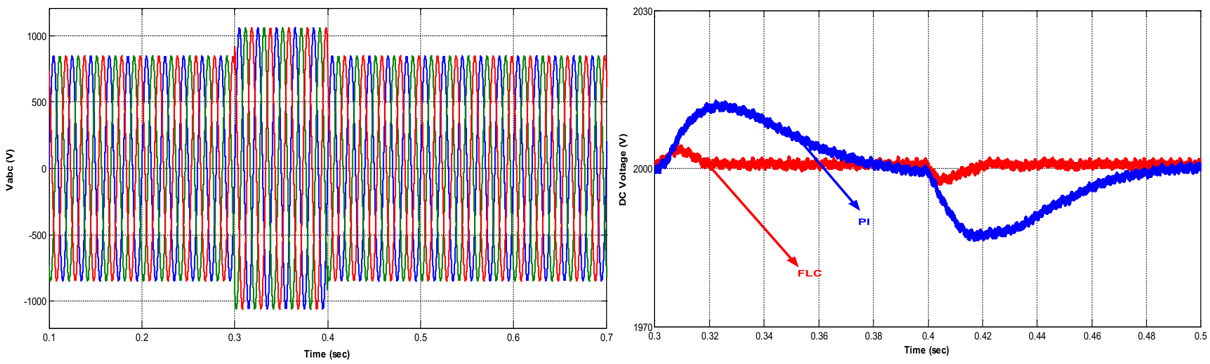
(a) (b)

Fig. 6. a) Voltage and current of one phase of grid b) High-frequency square wave in the primary side and secondary



(a) (b)

Fig. 7. a) Input voltage in voltage sag condition b) Enlarged waveform of the rectified DC voltage



(a) (b)

Fig. 8. a) Input voltage in voltage swell condition b) Enlarged waveform of the rectified DC voltage

4. Conclusion

In this paper, control and simulation of PET system with DC-link have been carried in Matlab/Simulink environment. FLC and PI controller have been designed for PET system. Both controllers are first used to control the DC voltage of PWM rectifier. FLC has superior performance when compared to PI controller in terms of rise time, settling time and overshoot. Then, In case of voltage sag and swell, performance analysis of both controllers was carried out via Matlab/Simulink. FLC has effective performance over PI controller in these conditions. Simulation results show that FLC gives a good response in all conditions over conventional PI controller. Moreover, unity power factor of the FLC is measured as 1 and the total harmonic distortions of three-phase output voltage of PET system, is controlled by FLC, are 1.04%, 0.97% and 0.98 %, respectively. As a result of this study, PET system has important features with regard to weight and size, efficiency, power quality, voltage regulation and losses. Moreover, It is observed that PET system has more dynamic performance using FLC.

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