Performance Analysis and Design of Robust Controller for PWM Rectifier

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Abstract

In this paper, a new controller has been proposed for pulse width modulation (PWM) based rectifiers. Control scheme of proposed PWM rectifier is used two Neuro-Fuzzy Controllers (NFC) which has robust and nonlinear structure in order to control the reactive power and DC voltage of PWM rectifier. Thus, reactive power and DC voltage are controlled effectively. Moreover, simulation studies are carried out to test the performance of the proposed control scheme at Matlab/Simulink environment. The simulation results obtained from the proposed control scheme are not only superior in the rise time, settling time and overshoot but have high power factor, lower total harmonic distortion (THD) and good power quality.

1. Introduction

By the rapid development of power electronics, microprocessors and semiconductor materials, power electronic technology has become inevitable for many sectors and applications. Nowadays, AC-DC converters are used in adjustable speed drives, uninterruptible power supplies, photovoltaic systems, battery charging systems, welding units, DC motor drives and communication systems. Diode and thyristor rectifiers which have simple structure, robust and low cost are used in systems that requires AC-DC conversion[1,4-6]. These rectifiers which produces high harmonic currents are a harmonic source and bring harmonic problems [1].

Since the last 20 years, pulse width modulation (PWM) rectifiers are widely used for AC-DC conversion. It is well-known that PWM rectifiers have been used in many applications such as high performance AC motor applications and telecomination systems [1-7]. Also, PWM rectifiers have many advantages like constant DC voltage, fast dynamic response, unity power factor, low harmonic distortion and bidirectional power flow. Generally, Two control methods have been proposed for PWM rectifiers. Voltage orinted control (VOC) based on internal current control loops became very popular method. Another control method is called as direct power control (DPC) which has not internal current loops and PWM blocks. The main goal of these control techniques is to reduce the current harmonic and to regulate the DC bus voltage [7-11].

In the control of PWM based rectifier, DC bus voltage is generally controlled by 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 [12]. Moreover, PI controllers have many disadvantages like slow response, large overshoots and oscillations. To solve these problems, many academics and researchers have been proposed several control methods. Intelligent controllers, based on Fuzzy Logic Controllers (FLC), Artificial Neural Network (ANN), Linear Quadratic Regulator (LQR) and Sliding Mode control (SMC), have been used for many industrial applications and PWM rectifier in recently [12-16]. To obtain a good performance both in transient and steady-state from PWM rectifier, intelligent controllers which have nonlinear and robust structure can be used in control of PWM rectifier. Neuro-fuzzy controller that has nonlinear, robust structure and based on FLC whose functions are realized by ANN is one of these intelligent controllers [17-21].

In this paper, NFC controller is proposed for DC voltage and q-axis current control of PWM rectifier in order to achieve a good dynamic response. Designed NFC structures for DC voltage and q-axis current have two inputs, single output and six layers. This paper is organized as follows. Mathematical model of PWM rectifier is given in Section 2. The description of the NFC and its training algorithm are explained in Section 3. The simulation results related to proposed controller are given in Section 4. Section 5 provides conclusions of this study.

2. Mathematical Model of PWM Rectifier

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 [1-2, 12]. The dc bus voltage in the three-phase PWM rectifier is generally controlled by a PI controller [26]. 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 [10-12]. The three-phase PWM rectifier structure is as shown in Fig. 1. The source phase voltage is expressed as:

$$V_a = V_m \sin\theta \tag{1}$$

$$V_b = V_m\, sin(\theta - 2\pi/3) \tag{2}$$

$$V_c = V_m\, sin(\theta + 2\pi/3) \tag{3}$$

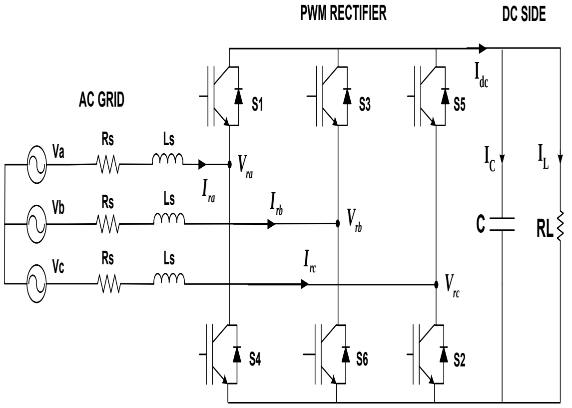


Fig. 1. Block diagram of three-phase PWM rectifier

The mathematical model of PWM rectifier in abc frame can be expressed as [12]:

$$\begin{bmatrix} L_s \dfrac{dI_{ra}}{dt} \\ L_s \dfrac{dI_{rb}}{dt} \\ L_s \dfrac{dI_{rc}}{dt} \\ C\dfrac{du_c}{dt} \end{bmatrix} = \begin{bmatrix} -R_s & 0 & 0 & 0 \\ 0 & -R_s & 0 & 0 \\ 0 & 0 & -R_s & 0 \\ S_a & S_b & S_c & -1 \end{bmatrix} \begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \\ I_L \end{bmatrix} + \begin{bmatrix} V_a - V_{ra} \\ V_b - V_{rb} \\ V_c - V_{rc} \\ 0 \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} V_{ra} \\ V_{ra} \\ V_{ra} \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ -1/3 & 2/3 & -1/3 \\ -1/3 & -1/3 & 2/3 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} V_{dc} \tag{5}$$

Where, L_s and R_s are grid inductance and resistance, respectively. I_a, I_b and I_c are grid phase currents; V_{ra}, V_{rb} and V_{rc} are the rectifier input voltages [12]. V_{ra}, V_{rb} and V_{rc} voltages can be found by opening and closing in accordance with the switching elements in the structure of rectifier to obtain the DC link voltage. Where, Sa,Sb and Sc show switching functions. These functions get 0, if the switch is off; if it is on, then they are 1. Clarke's matrix in α-β frame can be described as following [1,12]:

$$T = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{6}$$

According to Clake's transformation, the dynamic model of PWM rectifier can be defined as:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = L_s \begin{bmatrix} \dfrac{dI_\alpha}{dt} \\ \dfrac{dI_\beta}{dt} \end{bmatrix} + \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} + \begin{bmatrix} V_{r\alpha} \\ V_{r\beta} \end{bmatrix} \tag{7}$$

If Park's transformation is applied to rectifier system then following equation can be derived [12].

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = L_s \begin{bmatrix} \dfrac{dI_d}{dt} \\ \dfrac{dI_q}{dt} \end{bmatrix} + \begin{bmatrix} R_s & -\omega L_s \\ \omega L_s & R_s \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} V_{rd} \\ V_{rq} \end{bmatrix} \tag{8}$$

Angle value (θ) required for transformations can be found with PLL (phase locked loop) in Matlab/Simulink or it can be obtain by using abc–αβ transformation. In this study, the required angle values were found by using following equations without PLL block.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} cos\theta & cos\theta \\ -cos\theta & cos\theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{9}$$

$$sin\theta = \frac{V_\beta}{\sqrt{\left(V_\alpha{}^2 + V_\beta{}^2\right)}} \tag{10}$$

$$cos\theta = \frac{V_\alpha}{\sqrt{\left(V_\alpha{}^2 + V_\beta{}^2\right)}} \tag{11}$$

Where, V_{rd}, V_{rq}, I_d and I_q are dq-axes rectifier's input voltages and currents. V_d, V_q, V_α and V_β are the dq-αβ axes components of the grid voltage. ω is the voltage angular frequency.

In control of dc voltage, average value of dc-link voltage is compared with reference dc voltage. Error of dc voltage is applied to NFC. Reference value for d-axis current is obtained from output of NFC. Reference value for q-axis current is set to 0 in order to obtain unity power factor. Error of d-axis current is given as input to PI controllers and error of q-axis current is given as input to NFC. Their differences are converted to V_q and V_d by using PI current controller and NFC. These voltages are sent to PWM block, which generates required signals for driving the semiconductor switching element. Moreover, an anti-wind up integrator is used to limit the output of NFC and compensate for steady state error [1].

3. Design of Proposed Controller for PWM Rectifier

NFC is nonlinear and robust controller type. NFC has many features such as make deductions from an expert knowledge like fuzzy logic controller and has learning, generalizations and adaptation like artificial neural networks (ANN) [17-18]. The negative effects of parameter changes and disruptive entry in the system is eliminated since NFC has adaptable and durable structure. Other important advantage of this controller does not need to be a mathematical model of controlled system. NFC combines the fuzzy logic controller into the ANN. NFC controller as given in Fig. 2 is adopted for this study. Fuzzy if-then rules are the following [18-21]:

$$R^j : \text{If } x_1 \text{ is } A_1^j \text{ and } x_2 \text{ is } A_2^j\text{, then } y \text{ is } w_j \tag{12}$$

Where, x_i is the input variable, y is the output variable. A_i^j is linguistic terms of membership functions $\mu_{A_i^j}(x_i)$ and w_j is real number of consequent part. j-i= 1,2,3,…,n. NFC structure used for control of DC voltage is shown in Fig. 2. As shown in Fig. 2, NFC has a first-order Sugeno-type network and consists of two inputs, one output, and six layers. Input variables of NFC have been identified in input layer. Error and change of error are chosen as input variables.

$$e(k)=i_q^* - i_q \tag{13}$$

$$\Delta e(k)=e(k)-e(k-1) \tag{14}$$

$$e(k)=V_{dc}^* - V_{dc} \tag{15}$$

$$\Delta e(k)=e(k)-e(k-1) \tag{16}$$

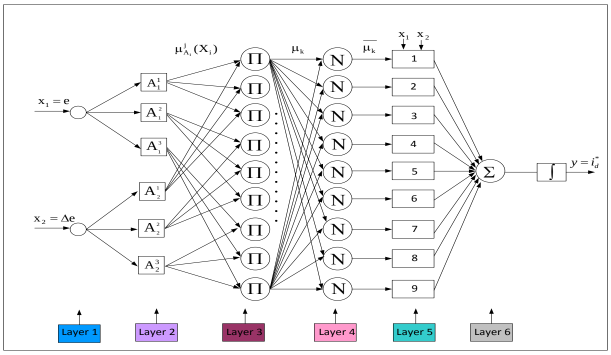


Fig. 2. Two-input sugeno type NFC structure

Layer 2 is layer of membership function. The degree of membership function for each input variable degree has been calculated in this layer. Three membership functions consisting of bell function and two sigmoid functions for each input are selected in this layer. The output of this layer is as following [17]:

$$net_j^2 = -\frac{(x_i - m_{ij})^2}{2(\sigma_{ij})^2}, \quad y_j^2 = exp(net_j^2) \tag{17}$$

Where, σ_{ij} and m_{ij} are the standard deviation and mean of Gaussian function in j-th term of i-th input node. Layer 3 of NFC includes rule base as fuzzy logic controller and fuzzy rules are determined in this layer.

$$net_k^3 = \prod_j w_{jk}^3 x_j^3, \quad y_k^3 = net_k^3 \tag{18}$$

Where, x_j^3 represents the j*th* input to the node of rule layer. The single node in this layer collects all incoming signals from the rule layer to obtain the final results. The output of the system using the central defuzzification for the Mamdani fuzzy model is given as [17];

$$net_0^4 = \sum_k w_{ko}^4 y_k^3, \quad y_0^4 = \frac{net_0^4}{\sum_k y_k^3} \tag{19}$$

Layer 4 is called normalization layer and calculates the degree of precision of the fuzzy rules. The fifth layer of NFC is called as the size of firing degree of a rule. The firing degree of normalized rules is multiplied by a linear function f in this layer.

This layer is output node of NFC and generates output current of d-axis for PWM rectifier. The parameters of the membership functions and the output weights of NFC are modified using the back-propagation algorithm to minimize the performance index (E) [17];

$$E = \frac{1}{2} e^2 \tag{20}$$

For PWM rectifier, the performance index for the parameters of membership functions can be derived as following:

$$\frac{\partial E}{\partial w_{k0}} = e.sgn(\frac{\Delta i_d}{\Delta y_0^4}) \frac{1}{\sum_k y_k^3} w_{k0}^4 \frac{x_i - m_{ij}}{(\sigma_{ij})^2} y_j^2 \tag{21}$$

$$\frac{\partial E}{\partial \sigma_{ij}} = e.sgn(\frac{\Delta i_d}{\Delta y_0^4}) \frac{1}{\sum_k y_k^3} w_{k0}^4 \frac{(x_i - m_{ij})^2}{(\sigma_{ij})^3} y_j^2 \tag{22}$$

4. Simulation Results

In this section, we realized a number of simulation studies in order to test the dynamic performance of proposed PWM rectifier system. Proposed PWM rectifier is implemented in MATLAB/Simulink environment. MATLAB/Simulink model of proposed PWM rectifier is given in Fig. 5.

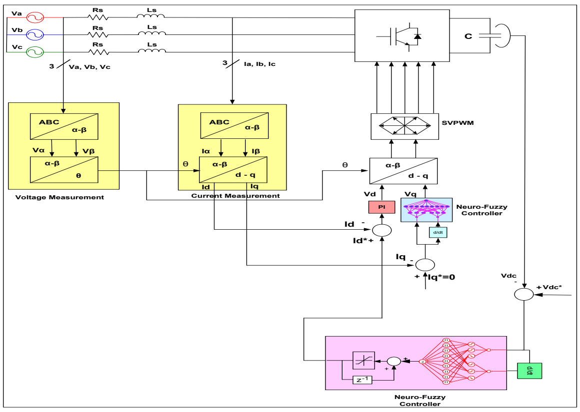


Fig. 3. Proposed control scheme for PWM rectifier

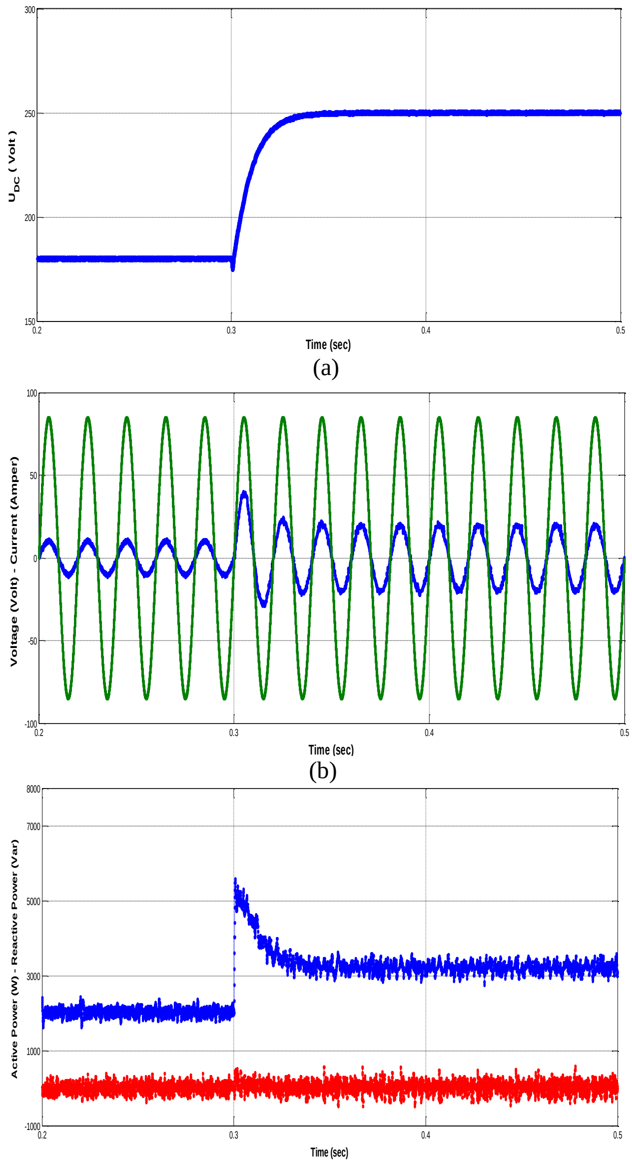
The electrical and control parameters of PWM rectifier used in the simulation study are given in Table I.

Table 1. Electrical parameters of PWM rectifier

Parameters	Value
Input Grid Voltage	70 V_{rms}
Source Resistance	100mΩ
Source Inductance	3.5mH
Load resistance	3.3mF
DC bus voltage	200 V
Sampling time	100µs
Switching time	5kHz

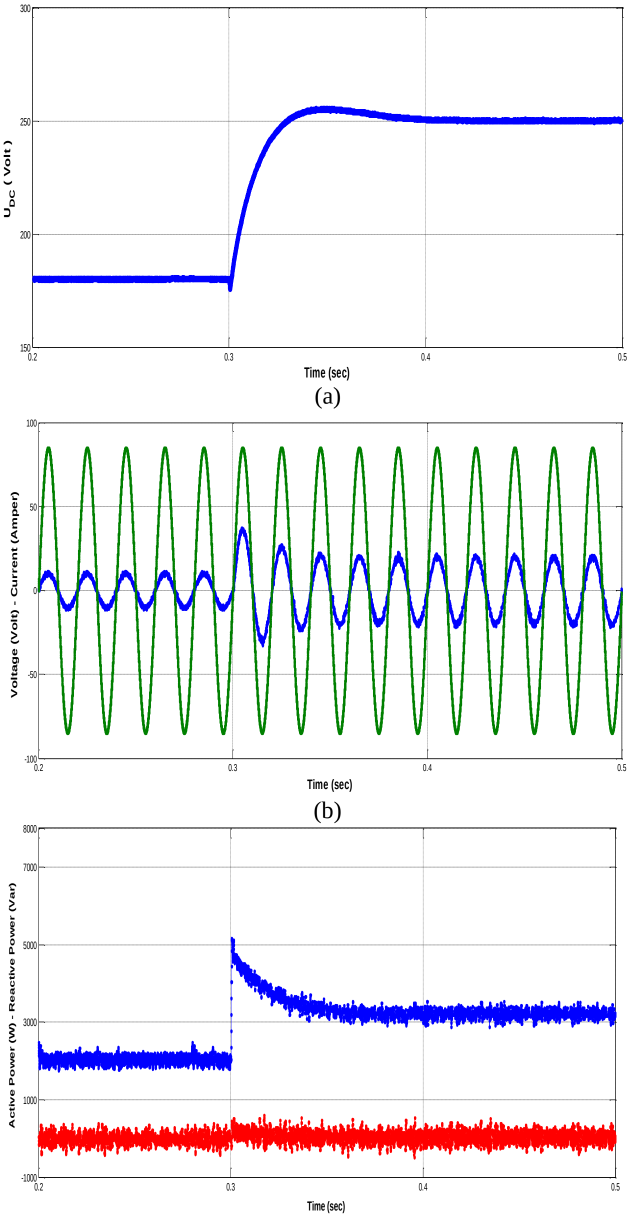
The fist test is realized in order to demonstrate the dynamic performance of proposed controller and PI controller. Figs. 4-5 show performance analysis, which was step of DC voltage from 200 V to 250 V at 0.3 sec, for the both controllers.

PWM rectifier starts to operate in steady state at 200 V. Then, a sudden step DC voltage command, from 200 V to 250 V, is performed. When the applied step DC voltage, PI controller response reaches the reference DC voltage after 399 ms with overshoot while the propesed controller follows the reference DC voltage without any overshoot and steady state error. The performance of the proposed controller is much better than the PI for all DC voltage change cases. The line currents given in Figs. 4(b)-5(b) have clearly sinusoidal waveforms and in phase with grid voltage. Moreover, active power is nearly 3kW and reactive power is zero because of good performance of proposed controller.



(c)

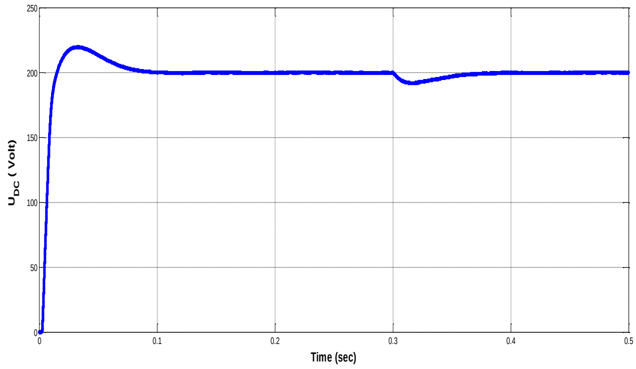
Fig. 4. Waveforms of PWM rectifier in transient state operation for NFC a) DC bus voltage b) Grid voltage and current c) Active and reactive power



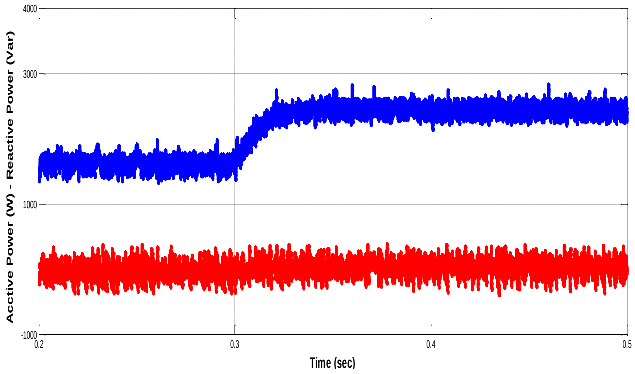
(c)

Fig. 5. Waveforms of PWM rectifier in transient state operation for PI controller a) DC bus voltage b) Grid voltage and current c) Active and reactive power

The second test is realized in order to indicate the performance of both controllers against the disturbance load. Constant DC voltage responses with load at 0.3 sec are given in Fig. 6-7. When the load is applied, there is sudden dip in DC voltage. The DC voltage response of proposed controller falls from 200 to 196.3 V and it takes 329 ms to reach the reference DC voltage and reactive power is 0 and reactive power is nearly 3kW while PI controller response dips from 200 V to 192 V and reaches after 399 ms. Moreover, reactive power responses of both controllers are shown in Figs. 6(b)-7(b). From these figures, reactive power is zero despite the disturbance load because reactive power is controlled by NFC which has robust structure.

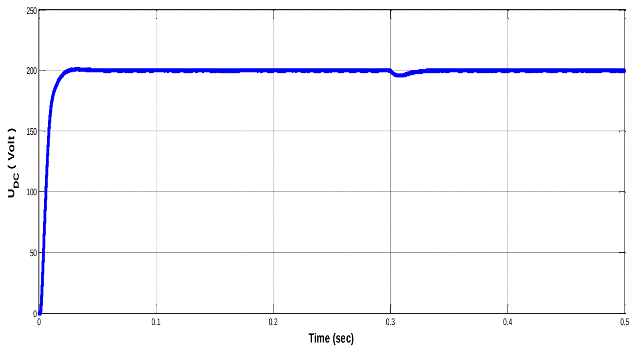


(a)

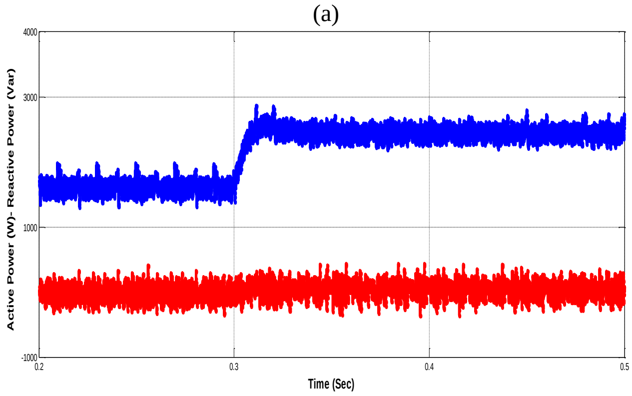


(b)

Fig. 6. Waveforms of PWM rectifier in disturbance load operation for NFC a) DC bus voltage b) Active and reactive power



(a)



(b)

Fig. 7. Waveforms of PWM rectifier in disturbance load operation for NFC a) DC bus voltage b) Active and reactive power

6. Conclusions

In this paper, control and simulation of PWM rectifier have been carried in Matlab/Simulink environment. NFC and PI controller have been designed for PWM rectifier. Both controllers are used to control the DC voltage and Iq current of PWM rectifier. According to IEEE 519-1992 harmonic current limits, proposed control scheme has a good THD value (5%< THD for both controller). Also, simulation results show that NFC controlled PWM rectifier can provide the desired reactive power exact and fast within own rated power limits even in the whole operating condition. In the proposed control scheme, reactive power is successfully achieved in whole conditions because of control of Iq current by using NFC. Moreover, NFC gives more superior performance than PI controller with respect to rise time, settling time, overshoot, THD and PF.

7. References

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