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A robust adaptive control of interleaved boost converter with power factor correction in wind energy systems

Fatih Karik[1], Ceyhun Yildiz[2], Fazil Kaytez*[3]

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Abstract: Power converters are generally utilized to convert the power from the wind sources to match the load demand and grid requirement to improve the dynamic and steady-state characteristics of wind generation systems and to integrate the energy storage system to solve the challenge of the discontinuous character of the renewable energy. In the low-voltage wind energy systems, interleaved boost converters (IBC) are often used to operate high currents in the system. IBCs are extremely sensitive to the constantly changing loading conditions. These situations require a robust control operation which can ensure a sufficient performance of the IBC over a large-scale changing load. Neural networks (NN) have emerged over the years and have found applications in many engineering fields, including control. In this paper, the adaptive control of interleaved boost converter with power factor correction (PFC) is investigated for grid-connected synchronous generator of wind energy system. For this purpose, a model reference adaptive control (MRAC) based on NN is proposed. Analysis results show that the proposed control strategy for the IBCs achieves near unity power factor (PF) and low total harmonic distortion (THD) in a wide operating range.

Keywords: *Model reference adaptive control, Wind energy systems, Boost converter, Power factor correction.*

1. Introduction

Wind energy has great potential to reduce energy dependence on traditional resources such as coal, oil and gas and to do it without as much damage to the environment. Wind energy systems have been the fastest growing source of electricity generation in the world since the 1990s. Today, wind energy systems that generate electricity are new and innovative. Developments in the field of aerodynamics, mechanical/electrical engineering, control technology, and electronics provide the technical basis for wind turbines commonly used today.

In wind energy conversion systems, power converters are widely used. In fixed-speed wind turbines, the converters are used to reduce inrush current (difference between the peak current value and the steady-state current value) and torque oscillations during the system start-up, while in variable-speed wind turbines they are employed to control the torque/speed of the generator and the reactive/active power to the network [1, 2]. Also, boost converters are often used for low and medium power wind systems of a few kilowatts to hundreds of kilowatts. As the power capacity of the wind turbines increases, regulating the voltage and the frequency in the power grid become more substantial. For this reason, it has become essential to use new power control systems as an intelligent interface between the wind turbine and the grid.

The problem of harmonic current pollution in electrical distribution systems has raised a significant interest over the recent years. Special attention has been dedicated to the improvement of line current harmonics and their negative effects due to the distortion of sinusoidal waveform characteristics [3]. The attention devoted to the quality of the currents absorbed from the utility line by electronic equipment is increasing due to several reasons. In fact, when a high THD of the line current causes electromagnetic interferences problems, a low PF reduces the power available from the utility grid [4].

Research on harmonic reduction and PFC has been intensified in the early nineties. Today's harmonic reduction and PFC techniques to improve distortion are still under development. With the introduction of compulsory technical standard such as IEC 1000-3-2, more researchers from both industries and universities are focusing in the area of harmonic reduction and PFC, resulting in numerous circuit topologies and control strategies. Hence, the PFC converters are an important research area in power electronics [3].

In AC power systems, harmonics occur when the regular electrical current waveform is distorted by nonlinear loads. PFC converters have been widely used in ac–dc power conversions to achieve high input PF and low THD. There are different basic topologies used in PFC converters (boost, buck, fly back, bridgeless etc.) [4, 5]. Also, there is an IBC which has some advantages. Extensive research work has been carried out on the IBCs and is available in the literature [6-12]. The IBC is considered as a good solution due to its merits, such as high efficiency, ripple reduction and small filter components. Hence, interleaving techniques provide high power capability, modularity and reliability [7-9].

The IBCs were used in various energy systems [10-12]. In recent years, many works have been focused on high efficiency or high voltage gain of IBCs and DC/DC boost converters [13-14]. In Ref [15] the authors used the maximum power point tracking (MPPT) to control an IBC in fuel cell electric vehicles. In Ref [16] the authors proposed a power switch failures tolerance and remedial strategy of a 4-leg floating IBC for photovoltaic/fuel cell applications.

[1] *Technology Faculty, Energy Systems Engineering Department, Gazi University, Ankara, Turkey*
[2] *Elbistan Vocational School, Kahramanmaras Sutcu Imam University, Kahramanmaras, Turkey*
[3] *General Directorate of Renewable Energy, Ankara, Turkey*
** Corresponding Author: Email: fkaytez@yegm.gov.tr*

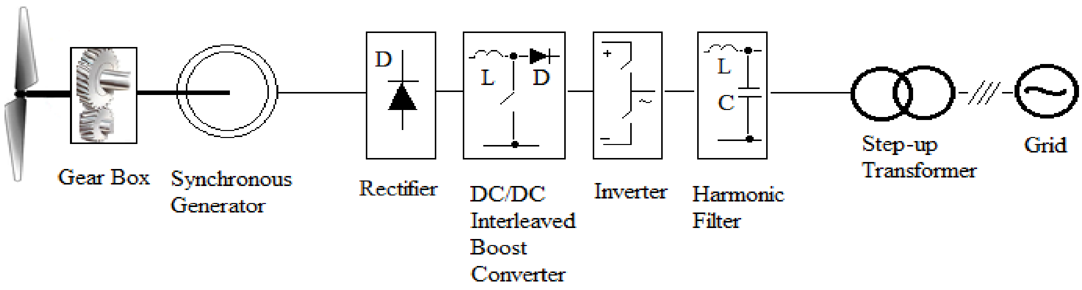

Fig. 1. A typical wind energy power system using IBC.

In Ref [17] the authors provided a comprehensive review of past and present converter topologies applicable to different generator-converter combinations in wind turbine systems.

PFC control strategy is typically done with two loops: an internal and fast current loop to improve THD and PF, and an external and slow voltage loop to stabilize the output voltage. The PI controller is generally used for the output voltage regulation. The current control is the most common control strategy which has different types since the primary objective of PFC is to force the input current to trace the shape of line voltage [3, 4]. As compared to well-known fixed gain controllers, the MRAC has ability to adapt itself to variations of process dynamics [18, 19]. MRAC has two parts, a reference model and the plant model that tracks reference model. The aim of the control strategy is to minimize the error between outputs of the plant and reference model [19]. During last decades lots of adaptation mechanisms (based on NN, fuzzy systems, PID etc.) have been proposed for MRAC [20-24]. The main contribution of this paper is the proposal of a new adaptive approach for current control of the IBC with PFC in wind power generation system. The output voltage of the proposed system is also regulated by PI controller.

The paper is organized as follows. In Section 2, the control system configuration of the IBC for wind energy systems are described and modeled. Section 3 is devoted to the modeling and control design of the IBC. The controller performances are illustrated through numerical simulations in Section 4. Section 5 provides the conclusion of the paper.

2. System configuration

Wind turbine systems capture the power from the wind by means of aerodynamically construction designed blades and convert mechanical energy to electrical energy. It is significant to be able to limit and control the converted mechanical power at higher wind speed. In wind energy conversion systems, a gear-box and a standard fixed speed generator are used to convert the low-speed, high-torque power to electrical power. It is necessary to step up the voltage using a DC/DC boost converter. A boost converter can be inserted between the synchronous generator and grid. Typically, A variable-speed wind energy power system with DC/DC boost converter is shown in Figure 1 [1]. According to the changing of the input direction of wind energy sources, the output voltage can be changed. To transfer the electrical power from wind energy sources to conventional 380V_{rms} AC electrical distribution systems, the converters are controlled by interleaved switching signals, which have the same phase shift and same switching frequency. Interleaving techniques have many features such as higher efficiency and reduced input and output ripple, are also realized in the boost topology. The interleaving technique consists in the parallel interconnection of a determined number of identical converter cells, whose control signals are strategically phase shifted in each switching time [1, 27]. In small wind turbines which are generally defined as producing no more than 100 kW of electricity, interleaved boost converters are mostly used to handle high currents in the system. The overall system is comprised of an uncontrolled diode rectifier followed by two boost cells and control blocks. Fig. 2 shows the system. According to the duty cycle status, in continuous conduction mode of the currents I_{L1} and I_{L2}, the converter has four possible stages of operation. A diagram indicating the conduction path of the IBC during stages is shown in Fig. 2.

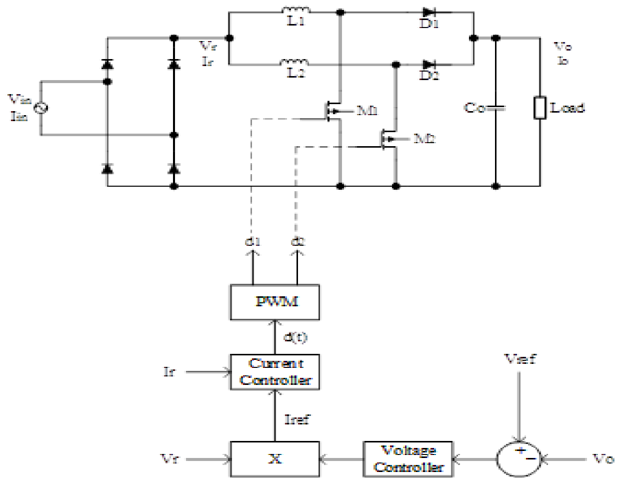

Fig. 2. Circuit diagram of diode rectifier, the IBC and control blocks model.

(a) The switches M_1 and M_2 are on and the currents of inductors increase. The output load current is supplied by the capacitor C_0.

(b) The switch M_1 is off and the switch M_2 is on. The inductor current I_{L1} has negative slope and the inductor current I_{L2} has a positive one.

(c) The switch M_1 is on and the switch M_2 is off. Therefore, the slopes of inductors' current dI_{L1}/dt and dI_{L2}/dt are positive and negative respectively.

(d) The switches M_1 and M_2 are off. As a result, the slopes of L_1 and L_2 inductors' currents are negative.

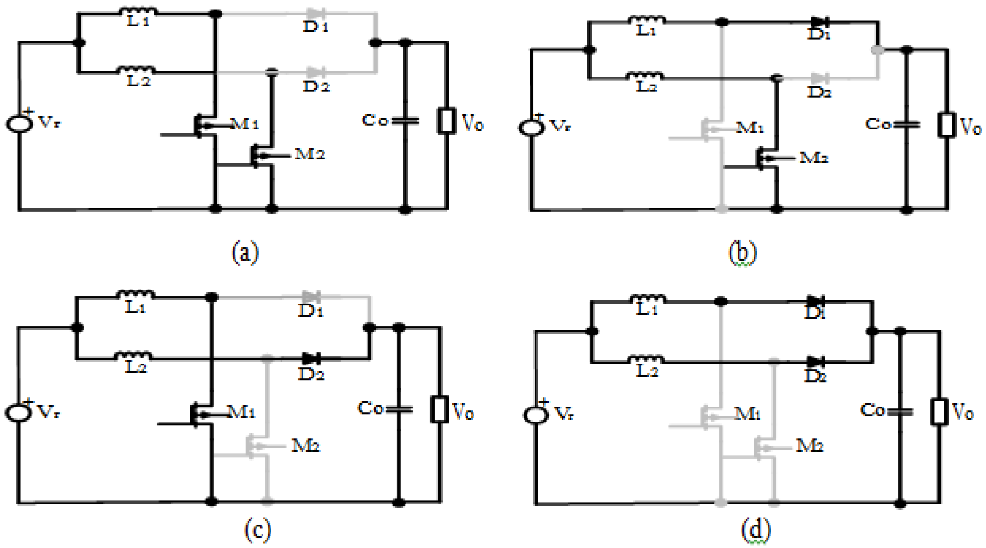

Fig. 3. Stages of the operation

The voltage, V_r is the rectified input voltage. Since the input line voltage (V_{in}) is sinusoidal, the duty cycle ratio is not constant. The time variation of the duty cycle for PFC circuits is expressed with Eq.(1) and can be represented as given in Fig. 3 for an input line voltage of 220 V_{rms}, 50 Hz line frequency (f_s) and an output voltage (V_o) 400 V. I_r is defined as below, also.

$$d(t) = 1\frac{V_r(t)}{V_o} \quad (1)$$

$$I_r = I_{L1} + I_{L2} \quad (2)$$

Two modes of operation can be characterized depending on relative amplitude of $V_r(t)$ and V_o. When $V_r(t)<V_o/2$ ($d(t)>0.5$), just the stages (a), (b) and (c) occur. When $V_r(t)>V_o/2$ ($d(t)<0.5$), just the stages (b), (c) and (d) occur.

The switching instants are sequentially phase shifted by equal fractions of a switching period. The second pulse width modulation (PWM) signal (d_2) is only phase shifted (Fig.4 and Fig. 5). This arrangement reduces the input current ripple amplitude and raises the effective ripple frequency of the overall converter without increasing switching losses or voltage and current stresses of any component [7,9].

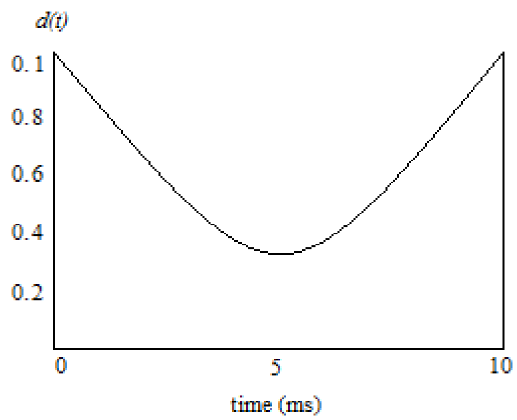

Fig. 4. Variation of the duty cycle for PFC circuits.

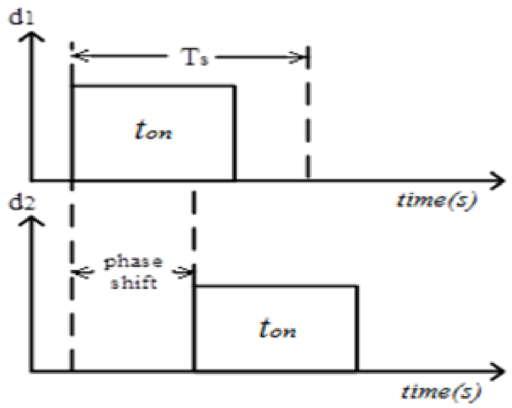

Fig. 5. Duty cycle signals of mosfets.

3. Modeling and control design of the interleaved boost converter

The proposed current controller is a MRAC based on NN. It has two main parts. There are a reference model part and NN part. Reference model is linear stable system to be imitated by NN and nonlinear converter system. NN part is radial bases function network (RBFN). RBFN supplies N_f signal to compensate error between reference model and nonlinear converter system. On the other hand N_f signal compensates nonlinearity of the plant. Sigma-modification-type updating law and RBFN used to implement nonlinear part of controller system [24,25]. So, it is a strong adaptive controller for nonlinear systems.

$y_m(t)$ and $y(t)$ and are the reference model and plant outputs respectively; $u(t)$ is control signal. k_m and a_m are appropriately selected coefficients during the preparation of the controller. The controller obtains best control signal, $u(t)$ by updating the RBFN parameters. Following equation represents.

$$u(t) = -a_m y(t) + k_m r(t) + N_f\left[y(t), w(t)\right] \quad (3)$$

N_f is output and w is the weight vector of the RBFN. Control strategy would compensate nonlinearities of the plant in the course of time thanks to the fast adaptation ability of RBFN. Studies [25,26] cover detailed explanation and stability analysis for this kind of controllers. Reference model is a very simple system. It has first order transfer function.

$$\frac{Y_m(s)}{R(s)} = \frac{k_m}{(s+a_m)} \tag{4}$$

In this study, the converter system is the IBC with PFC. *c(t)*, *r(t)* and *u(t)* stand for I_r, I_{ref} and *d(t)*, respectively.

4. Performance analysis

In this section, simulations are carried out to verify the theoretical analysis given in the previous section. Analysis studies are performed and presented by the Matlab®/Simulink. The topology of the proposed converter and the controllers are set up as shown in Fig. 6. To simplify the analysis, all the components are assumed ideal.

The performance of the proposed rectifier in Fig. 7 is evaluated on a 50 kHz, 1.5 kW prototype circuit that is designed to operate from a universal AC-line input (85–264 V_{rms}) with a 400 V output. A closed-loop control circuit is used to drive the two active switches and regulate the output voltage. Each duty cycle PWM signal is controlled through 1800 phase shift, and two-channel PWMs can be stably generated and operated. The performance of the proposed method is tested by observing the input current. Fig. 8 shows the waveforms of the input voltage, input current, and output voltage. The output voltage is 400 V, as expected. The input current is sinusoidal and in phase with the input voltage. The measured PF is 0.99, and THD is 3.2%. Model parameters and results at nominal power are showed in Table 1.

The waveforms of voltage and current of the shared active switches are shown in Fig. 8, 9. The result shows that input current of the converter is converged to the reference value. Fig. 10 shows the harmonic spectrum of the input line current. The harmonic current limits are met for all specified operating conditions.

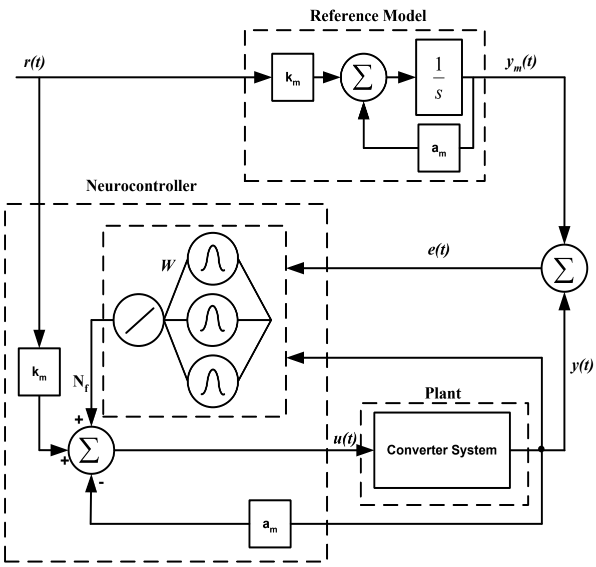

Fig. 6. Schematic model of the proposed control system

Table 1. Used parameters in the study.

Parameters	**Symbol**	**Value**
Output power	P_o	1.5 kW
Output voltage(D.C)	V_o	400 V
Input voltage(A.C)	V_{in}	220 V_{rms}
Input frequency	f_{in}	50 Hz
Switching frequency	f_s	50 kHz
Inductance values	L_1=L_2	1.5 mH
Output capacitor	C_o	1.5 mF
Simulation results at nominal values		
Input power factor	*PF*	0.99
Input THD (%)	*THD*	3.20
Output voltage fluctuation	ΔV_0	8 V

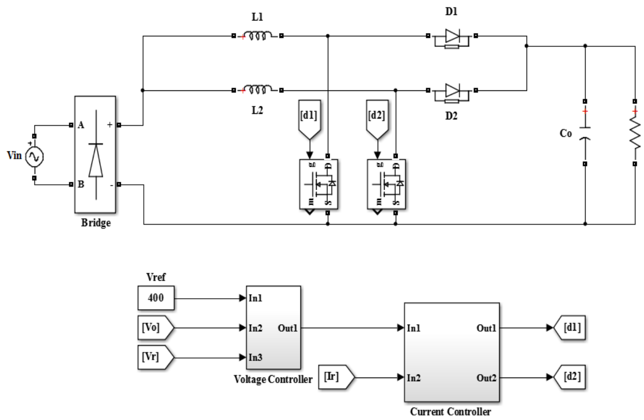

Fig. 7. The IBC and controller blocks.

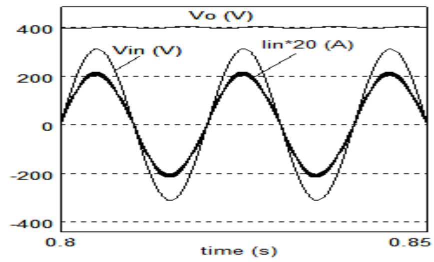

Fig. 8. Input current and voltage waveform at nominal values.

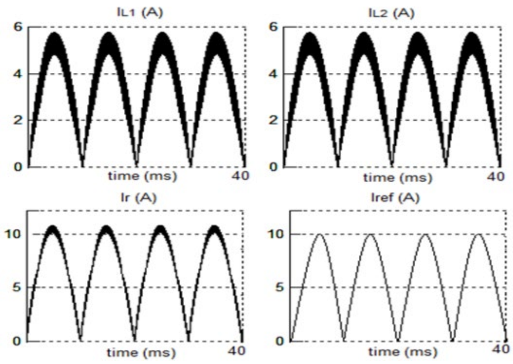

Fig .9. The current waveforms.

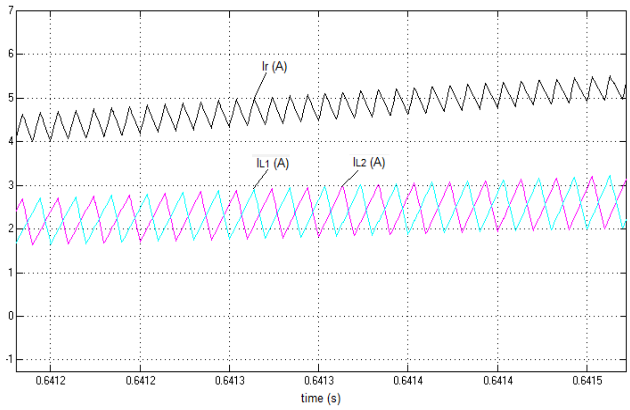

Fig. 10. Input current ripple cancelation by the interleaving technique.

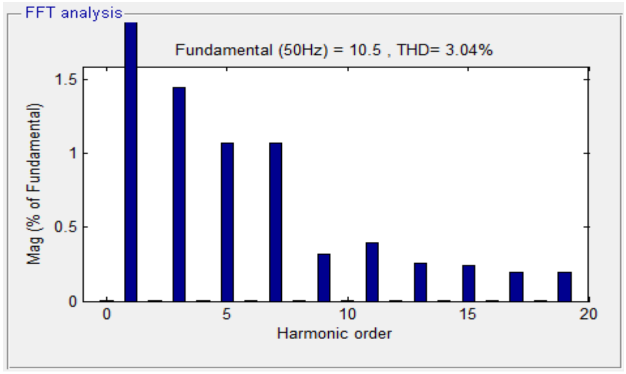

Fig. 11. Harmonic components of input current at nominal values.

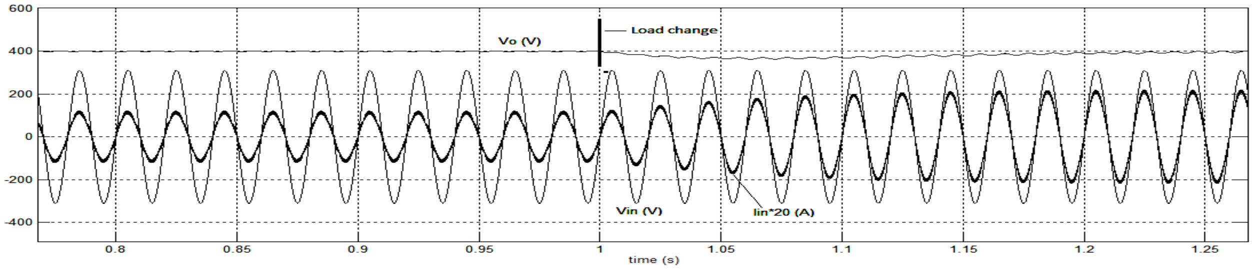

Fig. 12. Line current and output voltage for step load change (Half load to full load).

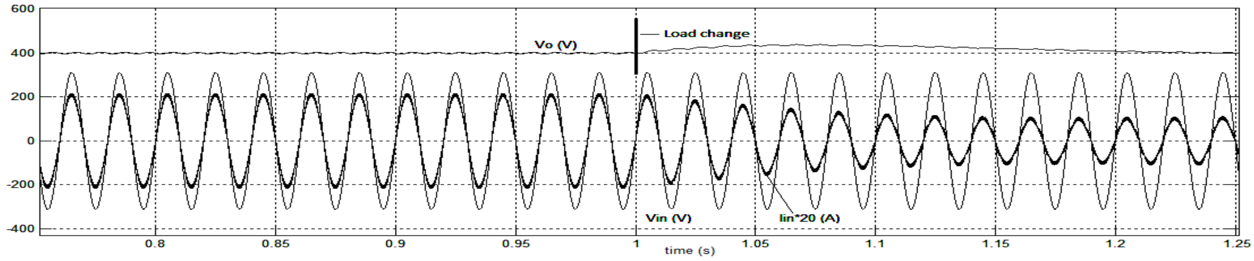

Fig. 13. Line current and output voltage for step load change (Full load to half load).

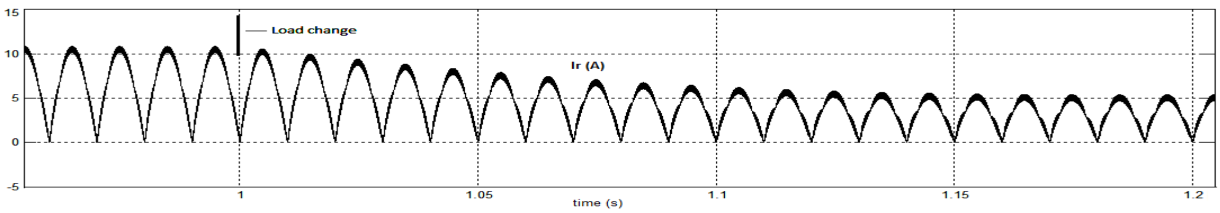

Fig. 14. Rectified line current for step load change (Full load to half load).

The output power of the converter is changed between full load and half load. For this case, the PF and THD of input current for output power values of 1.5 kW/0.75 kW are 0.99/0.99 and 3.2%/4.8%, respectively. Fig.11, 12 and 13 show the converter response to load variations. It can be seen from figures that the input current of the converter tracks the reference current via the proposed control technique when the voltage controller stabilize the output voltage. The effects of the input voltage changes on the converter performance for proposed method are analyzed and shown in Fig.14, 15 and 16. In this part of simulation the output power is kept constant at 1.5 kW and the input line voltage effective (rms) value changes from 220 to 180/85 V_{rms}, 220 to 264 V_{rms}. The input PF and THD of the input current for input voltage value of 85/180/220/264 V_{rms} are 1.00/1.00/0.99/0.99 and 1.3%/2.0%/3.2%/3.8%, respectively. It can be seen from figures and values that the input current of the converter tracks the reference current by the current control method.

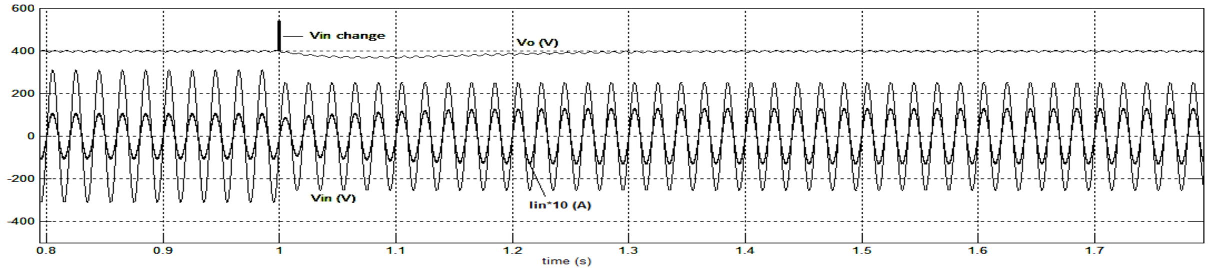

Fig. 15. Line current and output voltage for input voltage change (V_{in}: 220 V_{rms} to 180 V_{rms}).

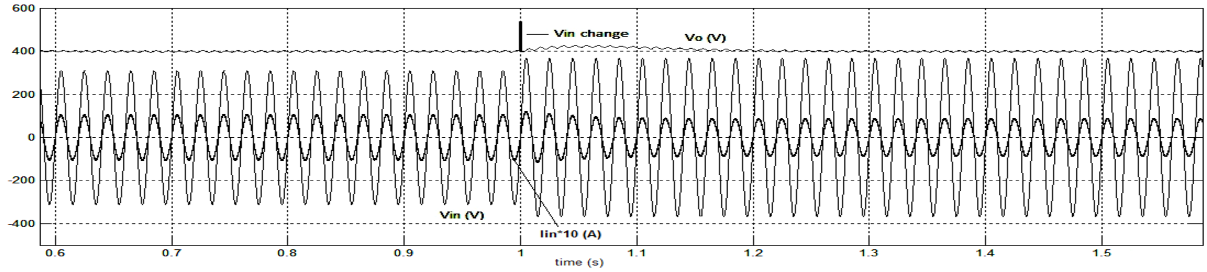

Fig. 16. Line current and output voltage for input voltage change (V_{in}: 220 V_{rms} to 264 V_{rms}).

5. Conclusion

The power of the wind generator describes the features of the converters used in the extraction of wind electric power. The designs of converters are based on the requirements of the generation source and the electric load.

In wind conversion systems, an optimal control may improve the efficiency of the generation system and extend the life of its elements. In this study, the MRAC based on NN current control for wind power systems has been proposed to improve the robustness, stability and dynamic characteristic of the IBC with PFC. For the specific purpose, a comprehensive analysis has been conducted. Basically, the controller inspects the state of the converter and generates the control variable that provides adaptive control. Analysis results show that the proposed method can achieve sinusoidal line current, unity PF with low THD and voltage stability under both the steady and transient states. Although the controller that proposed in our study is applied to a specific converter, this control technique can definitely be generalized to other power converters in wind conversion systems.

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