Enhancing of a wind power system control using intelligent artificial control and multilayer inverter

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ABSTRACT

The improvement of overall power quality and optimal control of reactive and active power are issues that have attracted many researchers. The harmonic is considered a main stressful source for energy quality. This paper proposed the ability of artificial intelligence at controlling the active and reactive power and to reduce torque ripple and current harmonics thus improve energy quality and the stability of system, that by using the artificial intelligence controller and a neural network based space vector modulation with two levels inverter (NSVM-2L). These inverter hold the offer improved efficiency and have on account of their capability of high voltage operation compared with traditional inverters as reducing the harmonic. These results showed that the fuzzy logic controller's dynamic performance is very superior to that of the PID controller of DFIG. The fuzzy controller works well for helping us to minimize the rate of harmonic distortion of absorbed currents and for correctly adjusting active and reactive power and its stability of wind turbine compared to PID controller.

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1. INTRODUCTION

In numerous regions around the world, variable renewable energy generated by sources such as wind and solar is expected to play a pivotal role in future zero-emissions electricity systems [1]. Lately, renewable energy sources have garnered increased attention as potential alternatives for meeting domestic energy demands [2], [3]. Due to its natural purity and abundant availability, wind power stands out as one of the most remarkable forms of renewable energy [4]. Currently, the most commonly employed wind turbine technology is the double-fed induction generator (DFIG) [5]. The fastest-growing renewable energy source is wind power, which has become economically viable and technologically advanced [6]. Large-scale wind production systems rely on double fed induction machines (DFIM) for their flexibility in reactive and active power management, as well as torque control. These machines are a vital component of variable-speed wind turbines [7]. This is a popular and dynamic research area, with a significant focus on controlling nonlinear systems [8]. Consequently, modern control systems are better equipped to address these challenges, offering robustness and reduced sensitivity, such as the artificial intelligence controller.

Modern megawatt-sized wind turbines consistently operate at variable speeds, a feat achieved through the use of converters [4]. These converters have a substantial impact on the cost of wind turbines and are often associated with individual generators [4]. The growing capacity and installation of wind farms necessitate the study and development of control mechanisms for the reactive and active power capabilities of wind farms. Wind power plants are now required to actively participate in the power supply system [9]. The primary objectives of these control capabilities are to automate wind turbine operation, impose safety limits, and maximize power generation [9]. Maximizing wind energy collection through power optimization helps reduce operating costs, minimize turbine loads for safe operation, and ensures consistent dynamic responses and enhanced product quality. Wind turbines, whether operating at constant or variable speeds, aim to capture as much wind energy as possible [9].

In this paper, we employ an artificial intelligence controller to optimize the reactive and active powers of the DFIG wind turbine. We replace the traditional pulse-width modulation (PWM) technique with a neural network-based space vector modulation with two levels (NSVM-2L) to reduce torque and flux ripples. Additionally, we utilize fuzzy logic controllers and PID controllers to control the reactive and active power on the stator-side. This approach significantly enhances power quality and offers outstanding performance even when DFIG parameter values change.

2. METHOD

The study is limited to proposing two strategies aimed at optimizing the active and reactive power of a wind turbine equipped with a doubly fed induction generator (DFIG). These strategies involve the use of a fuzzy logic controller and a PID controller. Key components of the methodology include the adoption of a neural network-based space vector modulation with two levels (NSVM-2L) in place of the traditional pulse-width modulation (PWM). This substitution serves to mitigate torque and flux variations within the DFIG. Additionally, the methodology employs both fuzzy logic and PID controllers to manage the regulation of reactive and active power on the stator side of the DFIG.

The performance of these control strategies is assessed through simulations conducted in MATLAB/Simulink. The results of these simulations reveal that the fuzzy logic controller yields a faster dynamic response and lower harmonic distortion when compared to the PID controller. To test the robustness of these control strategies, variations in DFIG parameters are introduced to assess how the controllers perform under changing operational conditions. In this regard, the fuzzy logic controller exhibits superior robustness, making it a favorable choice in scenarios with dynamic and variable operating conditions.

2.1. Modelling the chain of wind based on DFIM

Wind turbine modelling, the rotor power coefficient (Cp) is used to express the extractable power to available power ratio. Therefore, the extractable power may be expressed as [3], [10], [11].

$$\begin{cases} P_{aer} = C_P . P_{wind} \\ P_{aer} = 0.5 C_P(\lambda) . \rho . \pi . R^2 . V_1^3 \end{cases} \tag{1}$$

The tip speed ratio λ may be calculated using [12].

$$\lambda = \frac{\Omega_{turbine}}{V_1} . R \tag{2}$$

Where: $\Omega_{turbine}$ is represent turbine angular shaft speed, R is turbine radius in m, and V_1 is the wind speed in m/s.

$Cp(\lambda, \beta)$ for rapid rotation wind turbines presented in (3), is based on experimental data [13].

$$C_P = K_1 \left(\frac{K_2}{\lambda_1} - K_3 . \beta - K_4 \right) \exp\left(\frac{-K_5}{\lambda_1} \right) + K_6 . \lambda \tag{3}$$

With,

$$\frac{1}{\lambda_1} = -\frac{0.035}{\beta^3 + 1} + \frac{1}{\lambda + 0.08\beta} \tag{4}$$

or: $K_1 = 5176 * 10^{-4}$, $K_2 = 116$ $K_3 = 4 * 10^{-1}$ $K_4 = 0.5 * 10^{1}$; $K_5 = 0.21 * 10^{-2}$, $K_6 = 68 * 10^{-4}$. The aerodynamic torque exerted on the slow shaft of the turbine (in N.m) is given by [14], [15]:

$$T_{aer} = \frac{1}{2} C_P(\lambda) . \rho . \pi . R^2 . V_1^3 . \frac{1}{\Omega_{turbine}} \tag{5}$$

The following mathematical wind relation is used to represent the gear box, which modifies the turbine's speed in proportion to the generator's speed. Through a mechanical shaft system made up of a high-speed and low-speed shaft coupled by a gearbox, the induction generator is connected to the wind turbine [3], [16]:

$$\begin{cases} T_g = \frac{T_{aer}}{G} \\ \Omega_{turbine} = \frac{\Omega_{mec}}{G} \end{cases} \tag{6}$$

The total mechanical torque T_{mec} applied to the rotor [3], [15]:

$$T_{mec} = J\frac{d\Omega_{mec}}{dt} \tag{7}$$

$$T_{mec} = T_g - T_{em} - T_{vis} \tag{8}$$

where $J = \frac{J_{turbine}}{G^2} + J_g$: Total inertia appear on the shaft of the generator, Cem: Torque electromagnetic produced by DFIG-generator, Tvis: Torque of viscous friction, Tg :Torque from the Gear box, Ω_{mec}: Mechanical angular speed of the generator. G: gearbox ratio.

The resistance torque due to friction is modelled by a viscous friction coefficient f.

$$T_{vis} = f\,\Omega_{mec} \tag{9}$$

$$f = \frac{f_{turbine}}{G^2} + f_g \tag{10}$$

Where: f is the equivalent friction coefficient of the tree, $f_{turbine}$ is the coefficient of friction of the turbine, and f_g is the coefficient of the generator.

2.2. Modelling of DFIM

The equations of the DFIM vector control (d-q) with wound rotor are written as [17].

$$\begin{cases} \Phi_{ds} = \Phi_s \\ \Phi_{qs} = 0 \end{cases} \tag{11}$$

$$\begin{cases} \Phi_{dr} = (L_r - \frac{{L_m}^2}{L_S}).\,i_{dr} + \frac{L_m}{L_S}\Phi_s \\ \Phi_{qr} = (L_r - \frac{{L_m}^2}{L_S}).\,i_{qr} \end{cases} \tag{12}$$

$$\begin{cases} i_{ds} = \frac{\Phi_s}{L_s} - \frac{L_m}{Ls}.\,i_{dr} \\ i_{qs} = -\frac{L_m}{L_S}.\,i_{qr} \end{cases} \tag{13}$$

$$\begin{cases} V_{qs} = \omega_s\Phi_s = V_s \\ V_{dr} = (L_r - \frac{{L_m}^2}{L_S})\frac{di_{dr}}{dt} - g\omega_s(L_r - \frac{{L_m}^2}{L_S})i_{qr} + R_r.\,i_{dr} \\ V_{qr} = g\,V_s\frac{L_m}{L_S} + (L_r - \frac{{L_m}^2}{L_S})\frac{di_{qr}}{dt} + g\omega_s(L_r - \frac{{L_m}^2}{L_S}).\,i_{dr} + R_r.\,i_{qr} \end{cases} \tag{14}$$

$$\begin{cases} P_s = -V_s\frac{L_m}{L_S}i_{qr} \\ \Phi_s = -V_s\frac{L_m}{L_S}i_{dr} + \frac{{V_s}^2}{\omega_s L_S} \\ P_r = g(-V_s\frac{L_m}{L_S}i_{qr}) \\ \Phi_r = g(-V_s\frac{L_m}{L_S}i_{dr} + \frac{{V_s}^2}{\omega_s L_S}) \end{cases} \tag{15}$$

Torque electromagnetic equation in a generator is written in (16).

$$T_{em} = p.\frac{M_{sr}}{L_s}(-\Phi_s.i_{qr}) \quad (16)$$

With $M_{sr} = \frac{3}{2}Lm$.

2.3. Space vector modulation (SVM)

The fundamental idea behind the SVM method is to create Vref as precisely as feasible using the stationary vectors that are accessible to the inverter. Reference voltage Vr is generated by the inverter. The nearest three vectors (NTVs) for Vref are formed by the vertices of this triangle, and Vref is then synthesized using these three vectors, and repeating this process at each sample time (Ts). The SVM can best be explained based on a two-phase representation of Figure 1 [18], [19].

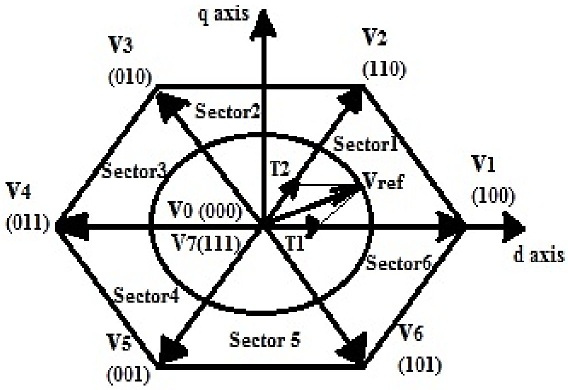


Figure 1. Principle drawing SVM for a three-phase two level-VSI

2.4. Level inverter

Multilayer inverters address standard VSI drawbacks with advantages like reduced harmonics, lower stress on power devices, decreased ratings, and a lower switching frequency [3], [20]-[22]. Using a two-level SVM method that calculates the maximum and minimum three-phase voltages (Va, Vb, Vc) detailed in Figure 2. Also, Figure 3 displays the NSVM technique for a 2-level inverter.

2.5. Fuzzy logic control scheme

Fuzzy logic controllers consist of three primary components: fuzzification, defuzzification, and inference rules. In the fuzzification phase, numerical values are transformed into fuzzy values or linguistic variables, which serve as inputs [23]. The defuzzification stage then converts these fuzzy values back into numeric outputs [23], [24]. Inference rules utilize linguistic control rules and a rule base to represent the desired control strategy and objective. In the case of this fuzzy logic controller, it uses error deviations and input errors from their references over each time interval as inputs, employing a Mamdani-type fuzzy logic control system [23], [25]. The controller interfaces with a neural network support vector machine (NSVM) system, with the fuzzy logic controller providing inputs to the NSVM. The diagrams of Figure 4 and Figure 5 illustrate how the FLC-NSVM and PID-NSVM systems are interconnected.

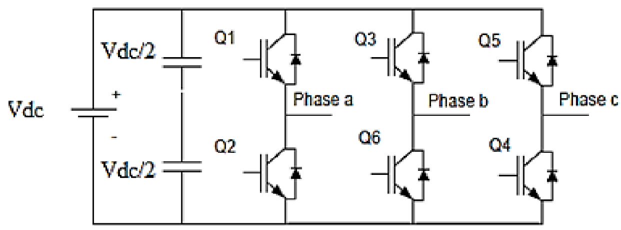


Figure 2. Schematic diagram of a two-level, three phases conventional voltage source inverter

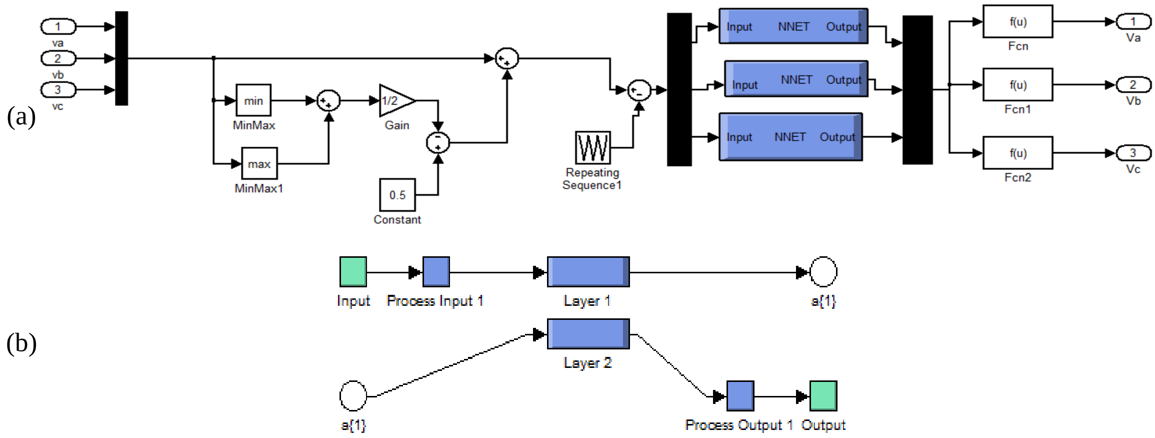


Figure 3. The NSVM technique by 2-level inverter (a) SVM strategy and (b) neural network layer

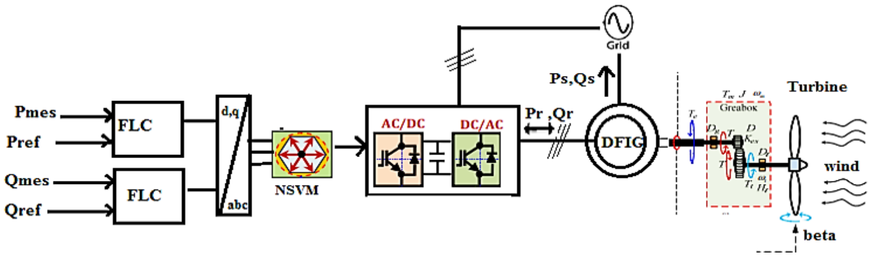


Figure 4. Diagram of fuzzy logic-NSVM controller for DFIG

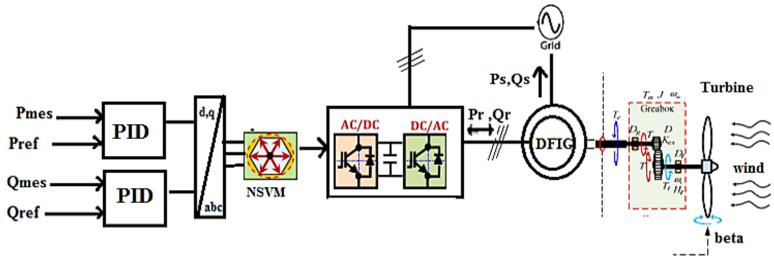


Figure 5. Diagram of PID-NSVM controller for DFIG

2 RESULTS AND DISCUSSION

In practice, it's necessary to conduct a simulation of the wind power conversion process to validate our theoretical research. The stator winding of the DFIG is directly connected to a 3-phase network (398/690 V/50 Hz), and the rotor winding is driven by a 3-phase converter controlled through neural network-based space vector modulation (NSVM). The parameters of the DFIG wind turbine are presented in Table 1.

Generally speaking, generators follow power control guidelines for active and reactive power. Fuzzy logic controllers react faster than PID controllers. It minimizes the overshoot of the active power, but the PID controller outperforms it in terms of reactive power (see Figure 6). Different control methods show differences in static error and response time. The stator power tracking is satisfactory for both control types and the response to disturbances is acceptable. Figure 7 shows the electromagnetic torque of the PID and fuzzy logic controller, and Figure 8 shows the three-phase stator current. Compared with PID control (see Figure 8(a)), fuzzy logic control (see Figure 8(b)) effectively reduces stator current and electromagnetic torque fluctuations. The frequency spectrum of source current harmonics' Total harmonic distortion (THD) levels is presented. Figure 9 display the frequency spectra for THD analysis in DFIG, with field-oriented control (FLC) and proportional-integral-derivative (PID) control methods, respectively. Table 2 provides a comparison of THD values in source current harmonics between DFIG systems controlled by FLC and PID. The results indicate that the THD rate is lower in the case of FLC compared to PID.

Table 1. DFIG wind turbine parameters

Symbol	Value	Description	Symbol	Value	Description
P	4	Number of poles	Rs	0.012 (Ω)	Stator winding resistance
J	1000 (kg.m^2)	Total inertia	Ls	0.0137 (H)	Stator inductance
fr	0.0024 (Htz)	Equivalent friction coefficient of the tree	Lr	0.0136 (H)	Rotor inductance
R	35.255 (m)	The turbine radius	M	0.0135 (H)	Mutual inductance
Rr	0.021 (Ω)	Rotor winding Resistance	g	0.03	Glissement

Table 2. The THD (%) of stator current

FLC-controller	PID-controller
0.42	0.98

Table 3. The THD (%) of stator current (robustness test)

FLC-controller	PID-controller
0.49	2.32

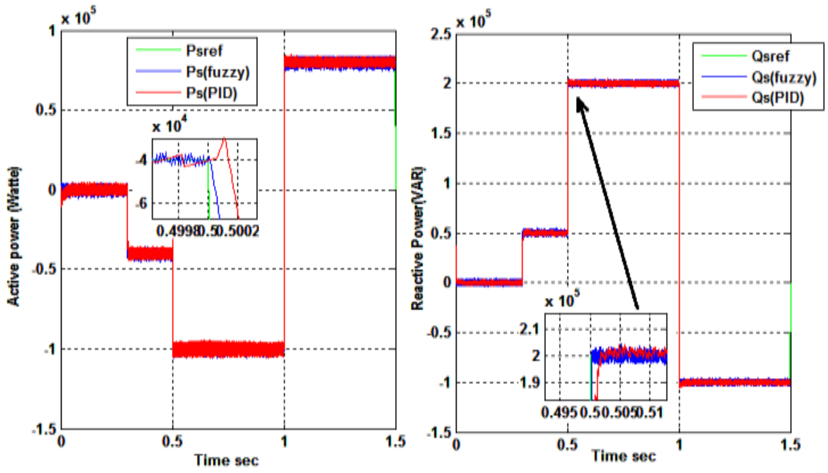


Figure 6. The reactions of the power of the DFIG with fuzzy controller and PID controller

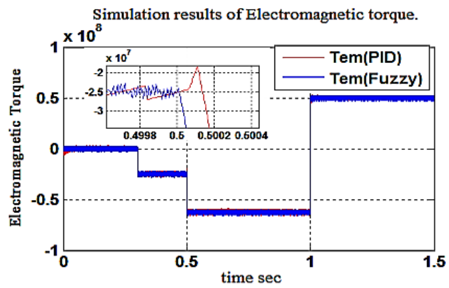
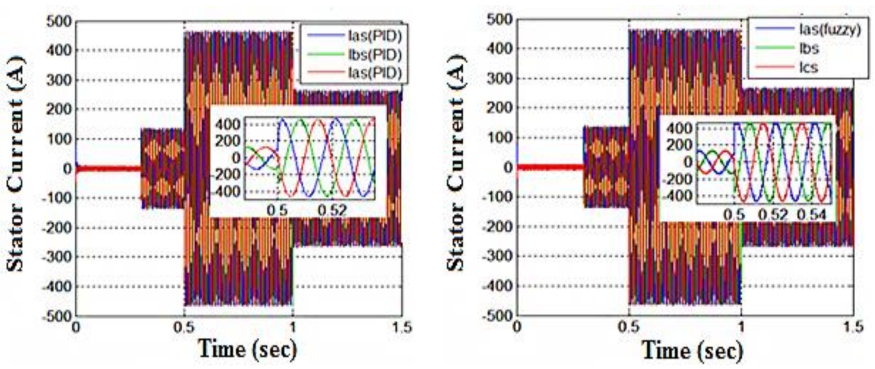


Figure 7. The electromagnetic torque of the PID and fuzzy logic controller



(a) (b)

Figure 8. The three-phase stator current by PID and fuzzy logic controller (a) PID controller and (b) fuzzy controller

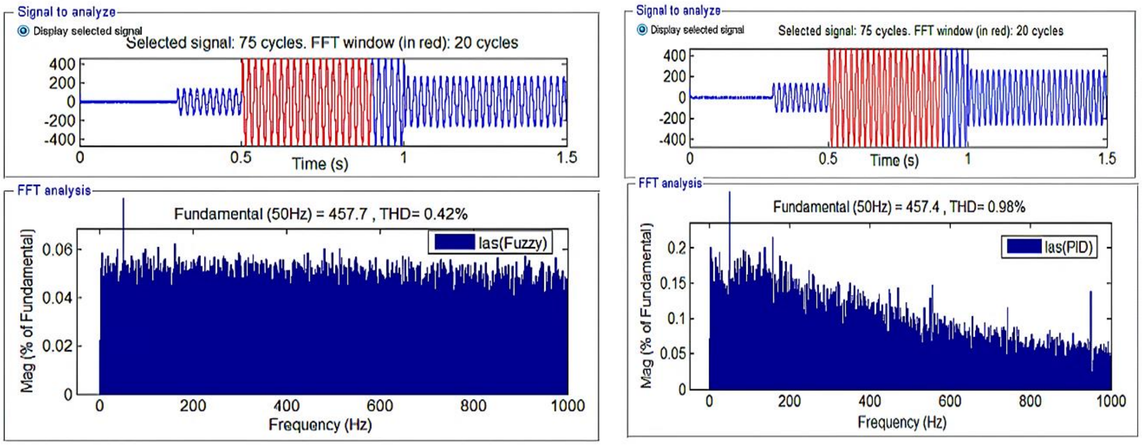


Figure 9. THD of stator current (FlC) and (PID) controller

In the context of durability testing, a robustness test was conducted by doubling the resistance values Rr and Rs, while halving the inductances Ls, Lr, and Lm. The results of this simulation are depicted in Figures 10, 11, and 12. These figures illustrate the impact of these modifications on the reactive power curve, active power curve, and electromagnetic torque curve, with PID control showing a more significant influence compared to fuzzy control (Figures 10 and 11). The results also reveal a substantial reduction in the total harmonic distortion (THD) value of the stator current when using fuzzy control (Figure 12). A comparative analysis of THD values is presented in Table 3, where it is evident that the THD rate achieved with fuzzy logic control (FLC) is lower than that with PID control (PIDC). Consequently, it can be concluded that the proposed fuzzy control method demonstrates superior robustness when compared to PID control.

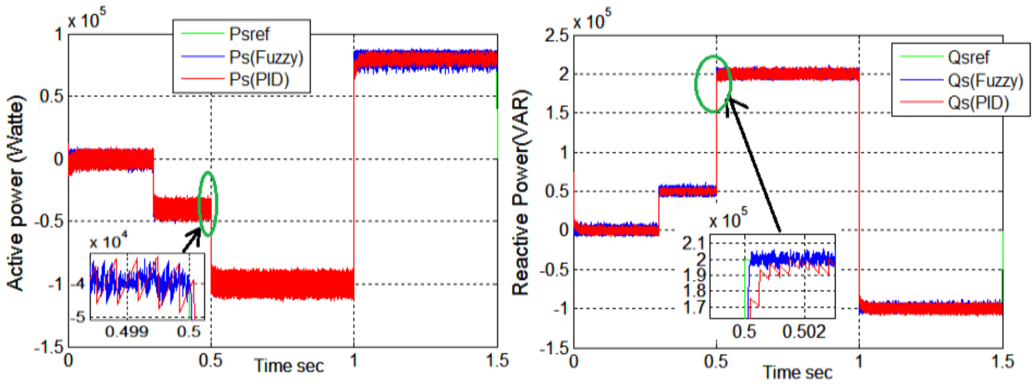


Figure 10. The Power of the chain of wind based on DFIG with fuzzy controller and PID controller (RT)

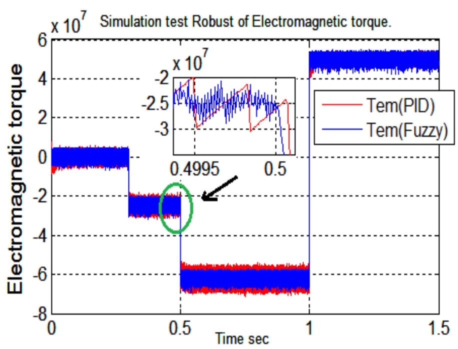


Figure 11. Electromagnetic torque (test robust)

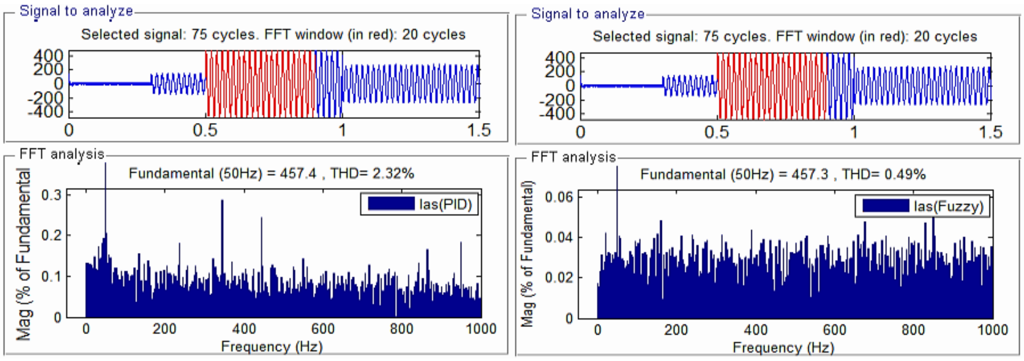


Figure 12. THD of stator current using fuzzy logic controller (RT) and PID controller (RT)

4. CONCLUSION

This paper discusses ways to enhance the efficiency of wind turbines equipped with a doubly fed induction generator (DFIG). The system is based on a DFIM with a 2-level space vector modulation using a neural network (NSVM-2L) inverter. Under identical operating conditions, DFIG's reactive and active control with fuzzy logic controller exhibits smaller overshoots, resulting in a faster response. This means that the fuzzy control technique contributes to improving power quality and optimizing reactive and active power better than PID control.

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