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Investigation Study for Model Reference Fuzzy Control Scheme of Synchronous Generator Coupled with Wind Turbine

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Abstract

Windmills require continuous observing and command to attain the required output power when the wind velocity has fluctuated. Command a nonlinear physical windmill needs an efficient regulator that calibrates the environment's fluctuations and initial conditions. As the fluctuations in wind speed are continuous, the conventional type of control will not be active for most cases of wind variations. An efficient control technique has been suggested to damp the impacts of non-linearity property. The current research provides modeling, numerical verification, and analysis of model reference fuzzy control scheme for direct drive wind turbine coupled with a Permanent Magnet Synchronous Generator tied with the electrical network. The machine side control is designed to capture the most considerable energy to get better wind power production. The grid side control regulates the bus voltage that is transformed into regulated three-phase grid voltage and frequency. The main control objectives of Proportional Integral control and model reference fuzzy control have been simulated and then compared. Armature profiles are also verified for different cases of operation through simulation. This controller's behavior guarantees excellent dynamic performance with wind speed variation due to the control system's robustness.

Keywords: Permanent Magnet Synchronous Generator, Model Reference Fuzzy Control, Wind Energy Conversion System.

1. Introduction

The generation of wind power for various control schemes will enforce power system variables in rated limits. Wind power should be regulated entirely to maintain a suitable value of power delivered to the network. Nowadays, fixed or constant speed turbines are simple, cheaper, reliable, and rigid than other types of generators used in a variable speed windmill. Variable speed generators are more applicable in a stochastic variation of wind speed, especially when the variation within a short period.

In the last decades, a Permanent Magnet Synchronous Generator (PMSG) has been developed to satisfy the requirements of the electrical generation or grid-connected scheme due to high power delivered, high efficiency, and low mechanical maintenance compared to Double Fed Induction Generator (DFIG) [1-2]. Finally, PMSG has been utilized in wind power generation in stand-alone as well as on-grid operation.

The proposed model is a directly driven PMSG used with a wind turbine generator tied with the network to enhance the network as the infinite bus.

In the case of wind speed variation, the control scheme is required in case of a grid connection to maintain the voltage and frequency within rated limits.

Direct Torque Control (DTC) and Field-Oriented Control (FOC) are predominant in most of the application in AC drives command [3].

Direct Power Control (DPC) and Voltage Oriented Control (VOC) are the most famous schemes applied to control the grid side's output quantities. Furthermore, since the wind speed varies with time, the wind's power yield might be the best permissible level to satisfy the best efficiency for different wind velocity [4].

Nowadays, many regulators' schemes have been suggested and modified to push the wind power as other quantities to the grid to acquire several benefits, like losses reduction, and minimize the system's cost and size.

Model reference control is a generally applied control technique that exhibited robustness in dynamic response [5 - 6].

The current study shows the analysis and simulation of FOC on the machine side and VOC on the grid side to demonstrate a mathematical representation and estimate the signal's following situation in all sampling time [7].

This manuscript is organized as follows. Section 2 introduces electro-mechanical system modeling for variable speed direct drive wind turbine generator system**,** and section 3 presents conventional control system schemes. Section 4 deals with model reference fuzzy control; meanwhile, section 5 is focused on Simulation results and verifications. Finally, the conclusion and remarks have been drawn in section 6.

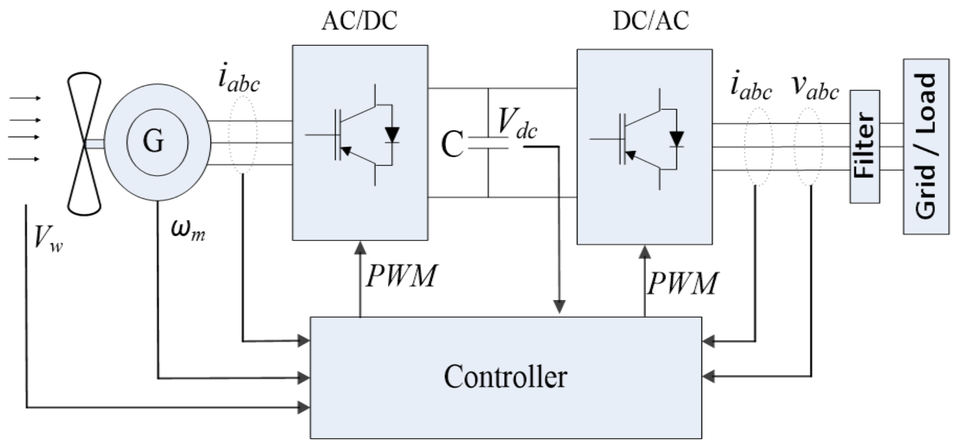


Fig. 1: Wind Energy Conversion System Diagram

2. Electro-mechanical system model

2.1. Model of wind turbine

According to the power conversion principle, wind energy can be translated to mechanical energy using windmill and finally to electric power using PMSG or DFIG.

The block diagram of the energy conversion system is presented in Fig. 1. According to Newton's Law, the power extracted by a windmill from an air stream scan an area *A* can be expressed in (1) [7]:

$$P_m = \frac{1}{2}\rho A v_w C_p(\lambda, \beta) \tag{1}$$

where P_m can be denoted to wind power measured by (W or Joule /second), the value of the air density ρ empirically measured from 1.1 to 1.3 ($kg.m^3$), and A is the area scanned by the blades (m^2), v_w is the speed of the wind (m/s). C_p defined as the power coefficient, and it is a function of the tip speed ratio. The Tip Speed Ratio (TSR) is denoted by λ can be expressed

$$\lambda = \frac{\omega_m . D/2}{v_w} \tag{2}$$

as in (2):

where ω_m is the windmill's speed measured in radian /second, and D is the diameter of the windmill swept area. The coefficient of power could be calculated as a function of TSR and pitch angle given in (3):

$$C_p(\lambda,\beta) = \mu_1\left(\frac{\mu_2}{\lambda_i} - \mu_3\beta - \mu_4\right)e^{\frac{-\mu_5}{\lambda_i}} + \mu_6\lambda \tag{3}$$

and

$$\lambda_i = \frac{1}{\left(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right)} \tag{4}$$

The extreme values of the power coefficient are bounded (40 -50)% based on Betz's limit to satisfy Maximum Power Point Tracking (MPPT) [8]. As a result, the power captured from the wind is usually < 50% to the above equation.

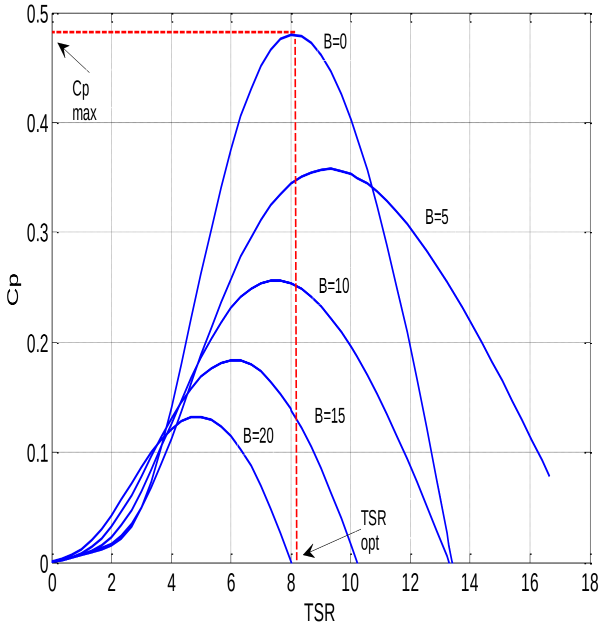


Fig. 2: Graph of power coefficient against TSR

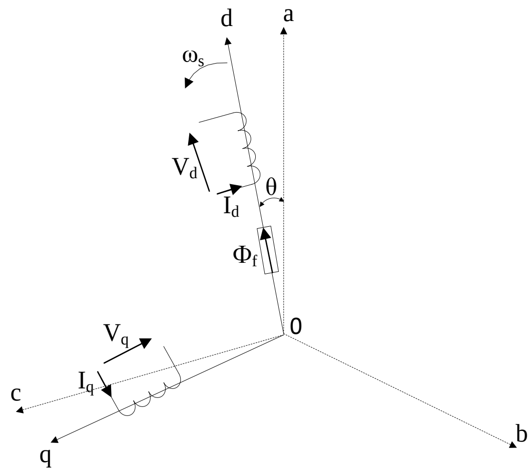


Fig. Fig. 3:Transformation from abc to dq

The value of the windmill power coefficient and the tip speed ratio presents the maximum Cp values can be obtained in all operational situations by adjusting the best TSR. By calibrating TSR during the command process, it can get MPPT for any fluctuation in wind speed [9 -10]. From synchronous machine characteristics, the mechanical power output changed by rotational speed ω_m .

The machine side controller's primary purpose is to acquire the best values of ω_m ; leads to obtain the highest value of the power from the wind. Therefore, useful Cp and TSR equations could be considered to acquire the maximum power used in the design, as given in Fig.2. The windmill equation can be expressed in (5) as in [11] :

$$J\frac{d\omega_m}{dt} = T_e - T_m - F\omega_m \quad (5)$$

J is the global moment of inertia, F is the coefficient of viscous friction, Te and Tm are the generator's electro-mechanical torque, and the windmill, respectively, develop the mechanical torque.

2.2 Modelling of a permanent magnet synchronous machine

The permanent magnet synchronous machine's voltages can be expressed in a dynamic rotating frame, which is perpendicular ahead of the direct axis w.r.t direction of rotation. The equations of the generator's stator voltages can be defined in *d*-axis and q –axis as in (6) and (7), respectively.

$$V_d^s = R_s i_d^s + L_d^s \frac{di_d^s}{dt} - \omega_e L_q^s i_q^s \quad (6)$$

$$V_q^s = R_s i_q^s + L_q^s \frac{di_q^s}{dt} + \omega_e (L_d^s i_d^s + \psi_f) \quad (7)$$

where R_s is the stationary part resistance, L_d^s and L_q^s are the self-inductances of the machine projected on the *d*, *q* axis, i_d^s, i_q^s are *dq* components of the stator currents, ψ_f is the permanent flux linkage and ω_e is the electrical speed of PMSG where represented in term of p_n number of pole pairs as given in (8):

$$\omega_e = p_n \omega_m \quad (8)$$

The electromagnetic torque equation could be calculated from the inner power as given in (9):

$$T_e = \frac{3}{2} p_n (\phi_d i_d^s + \phi_q i_q^s) \quad (9)$$

where

$$\phi_d = L_d^s i_d^s + \psi_f \quad (10)$$

and

$$\phi_q = L_q^s i_q^s \quad (11)$$

Electromagnetic torque can be regulated by adjusting, i_q^s. This torque will manage the mechanical torque. Finally, the mechanical power that fulfills the maximum power point seeking controller.

3. Conventional control system schemes

Since most of the physical parameters and variables should be maintained within rated levels, the output voltage and frequency should be kept as an infinite bus. To do that, the control system has been prepared to satisfy this target on both sides of the system [11].

Vector control is a widely deployed scheme used in field-oriented control to acquire a wide range of accuracy and velocity [12- 13].

This type of command scheme uses a Proportional Integral (PI) controller to fix the variable's tracking errors. The internal loop and external loop are the main loops noticed to perform this scheme in the MSC.

The internal loop aims to control the components of the current in direct and quadrature axes, while the external loop's responsibility is to command the rotational motion.

Due to the system equations' simplicity, the PI controller has experienced the good effect of using in operation [14]. K_P and K_I should be appropriately calibrated to obtain excellent operation and response [15].

The reference current *q*-axis component $i^s_{q\,ref}$ is adjusted by an outer loop which related to the speed controller, then the PI controller equation can be expressed in (12) and:

$$i^s_{d\,ref} = K_{p\omega} e_\omega + K_{I\omega} \int e_\omega dt \tag{12}$$

where $K_{p\omega}$ and $K_{I\omega}$ are the PI regulator parameters and can be adjusted carefully to ensure optimum operation, eω is the tracking error that controls the generator's speed.

Based on the reference quadrature component of current, then the regulated voltage in *d*irect and *q*uadrature axes can be specified by another PI regulator, as given in (13) and (14):

$$V_d^* = K_{pi} e_d + K_{Ii} \int e_d dt - \omega_e L_q^s i_q^s \tag{13}$$

$$V_q^* = K_{pi} e_q + K_{Ii} \int e_q dt + \omega_e (L_d^s i_d^s + \psi_f) \tag{14}$$

Where the pair (e_d, e_q) are the tracking errors in *dq* components of currents as given in (15) and (16) :

$$e_d = i^s_{d\,ref} - i^s_d \tag{15}$$

$$e_q = i^s_{q\,ref} - i^s_q \tag{16}$$

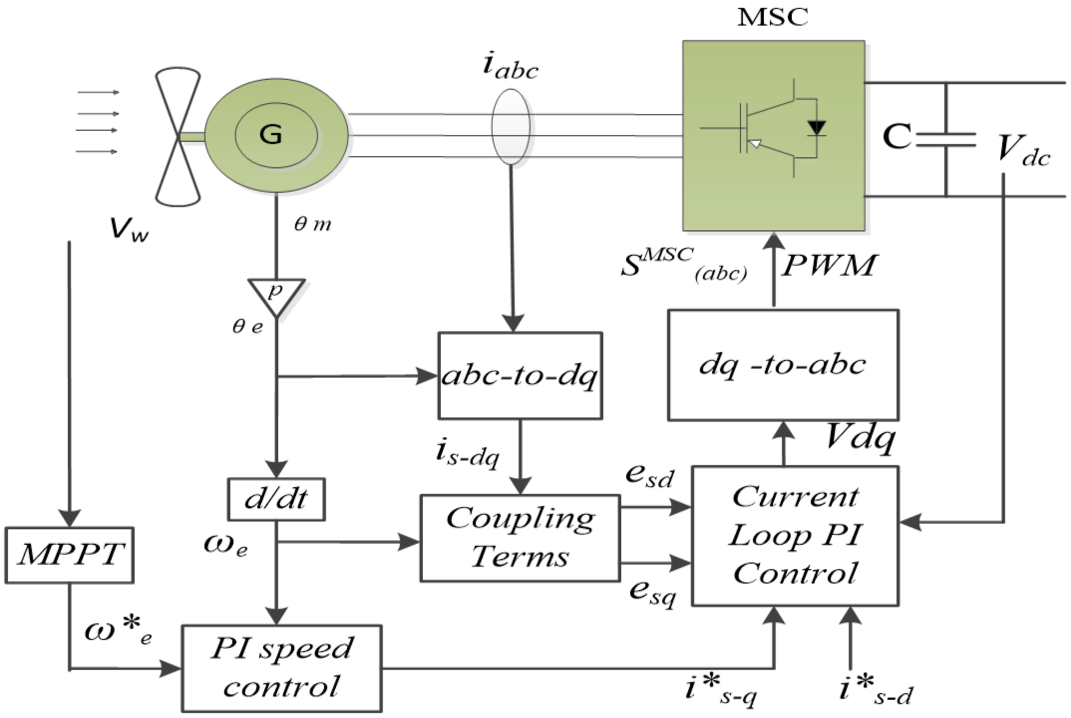


Fig. 4: The schematic diagram of the machine side PI control

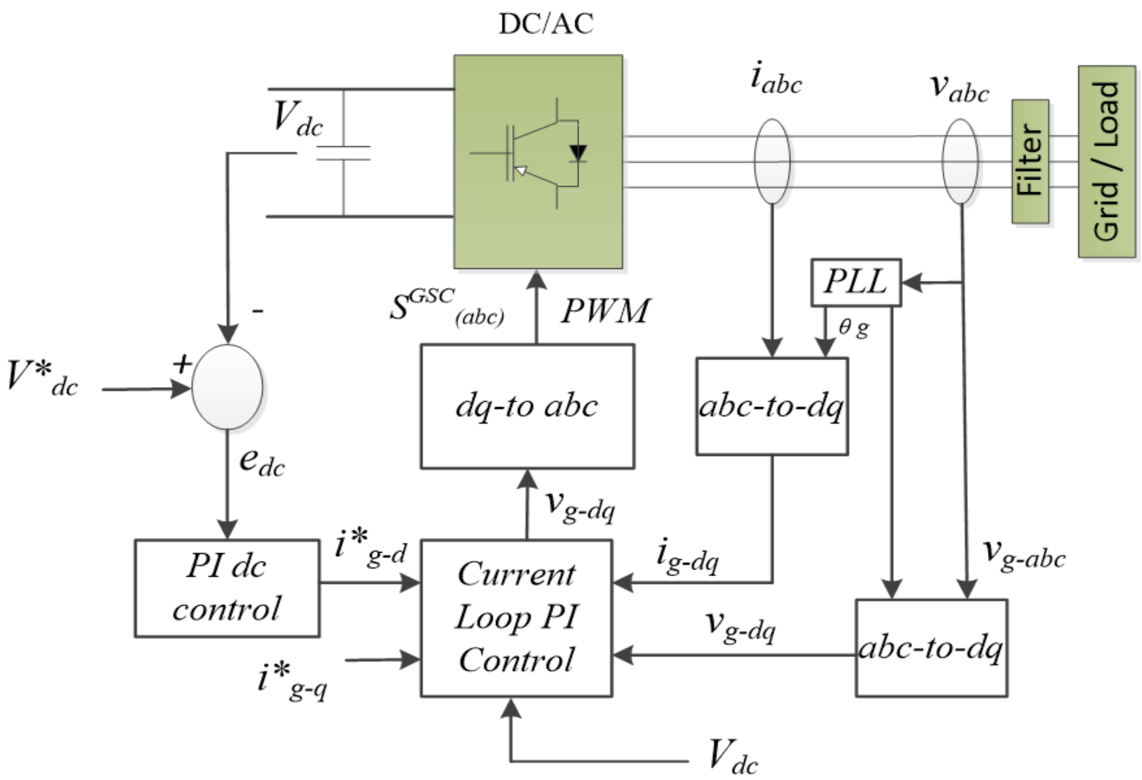


Fig. 5: The schematic diagram of the grid side PI control

The controlled output voltages are represented in *abc* voltages using inverse Park's transformer to obtain the controlled values of three-phase voltages, which are essential to adjust the pulses of PWM of the power electronic converter. The machine side schematic diagram of the current controller is presented in Fig. 4. The decoupling between the d and q axis is performed.

In grid side control, the PI controller's current loop is presented in Fig. 5, where the DC voltage is transformed to AC using trigged six pulses IGBT devices through a pulse generator.

Regulating the generated currents will fix the output voltage that will be GSC's input, while the capacitor will smooth the DC voltage. The active power component will be transmitted to the grid, then the setting value of i_q^s is zero. Phase-Locked Loop (PLL) will control the voltage to keep the phase shift of the voltages synchronized with the line during the command system.

4. Model reference fuzzy control

To avoid the mathematical model problem and boost the elasticity of setting the control scenario, a fuzzy logic control is used [16]. When the system representation is ambiguous, then the smart techniques investigate better responses. The FLC needs expert background about system operation to calibrate the physical parameters [17 - 19]. A regulator can be done for speed tracking error for managing a fuzzy control scenario to minimize system elements' impact. The model reference is a robust scheme to avoid the impact of the varying parameter. The command signal can be prepared to run the regulated system for monitoring the dynamic mechanism. The proposed scheme of the MSC is clarified in Fig. 6. The command loop can be classified into an inner loop for currents and an outer loop for motion control. The motion control could be regulated by classical PI techniques to set the machine motion [20 - 21].
The proposed system consists of the reference model, direct FLC. The FLC is used with the PI controller to provide a better response, and the membership function of input variables errors and output currents are shown in Figs. 7 and 8, respectively, while the fuzzy control rule bases are represented in Table 1.

The obtained signal provided by the adaptive FLC is used to produce the modified iq. Consequently, the modified term will be added to the controller's output to provide the reference currents. The maximum torque ratio to a minimum stator current can be achieved by setting the stator current in direct axis to an optimum value. The quadrature - axis current is calculated through the outer regulator. The dynamic current components effected by the supplied voltage components per sampling interval [22].

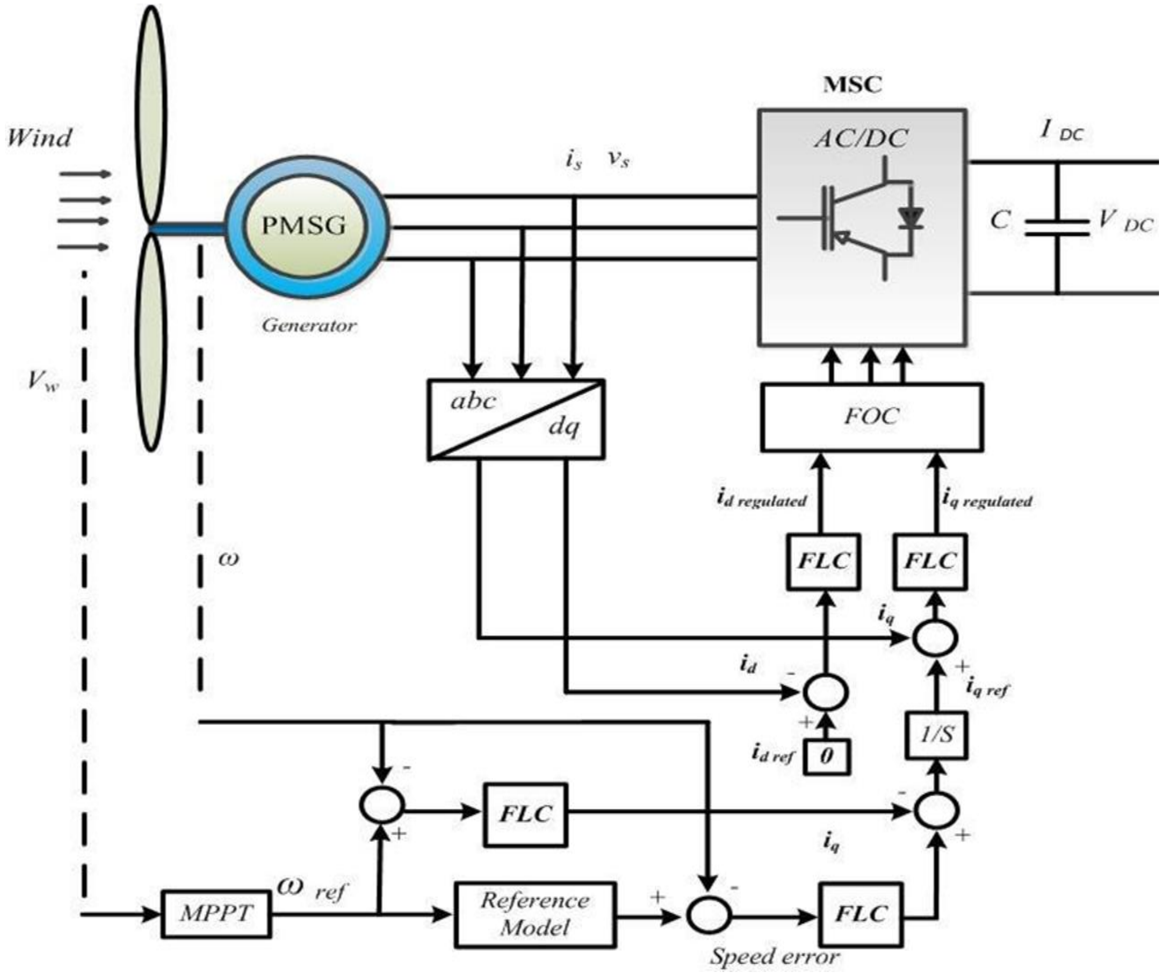


Fig. 6: MRFC - MSC Schematic Diagram

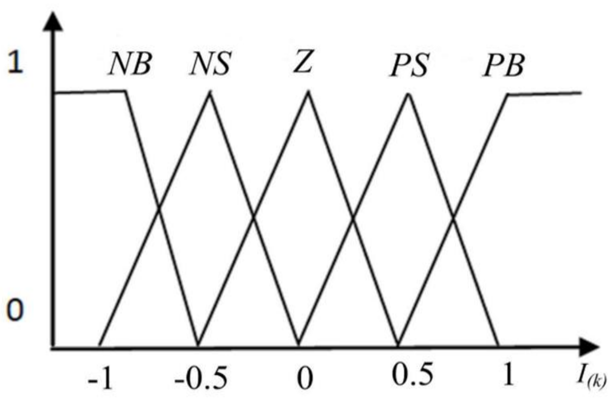


Fig. 7: Membership Function of input variables *e* and *de*

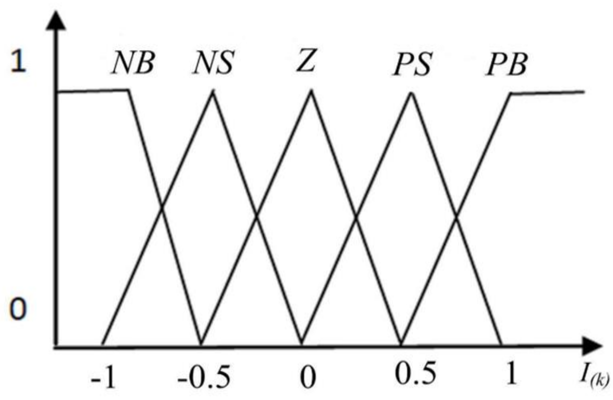


Fig. 8: Membership Function of output variables *iq*

Table 1: Fuzzy Control Rule Bases

e \ d	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

5. Simulation results and verifications

The MATLAB/Simulink R2018 has been used to demonstrate the proposed control MRFC in a grid-connected PMSG system. Assuming a step change in wind speed to test the system to acquire maximum power capturing and constant output voltage. Rotor speed and electromagnetic torque can be regulated for tracking the variation in wind speed.

For fast simulation, the proposed model of MRFC has been simulated in small scale generator and presented with regular steps of change of wind speed to prove the robustness of this type of control scheme compared to the traditional one.

The initial conditions have been adjusted to run the system in a stable state during the simulation. Achieving the most considerable torque at the smallest current by calibrating the set value of direct axis current to an optimum value in a machine side part.

Fig. (9) shows the variation of wind speed concerning with time. The mechanical power output of the windmill will be an input to the generator. Consequently, the rotor speed for both PI controller and MRFC will be varied when the wind speed changes, as given in Fig. (10).

The difference between mechanical and electro-mechanical torques is numerically negligible, while the generator current will vary with the variation of the wind, as shown in Fig. (11). The numerical verification shows the output currents will be simulated with evident distortion by using PI control compared with MRFC, which experienced low distortion in current signals, as shown in Figs. (12) and (13), respectively. The tracking speed error for MRFC is clarified in Fig.14. Compared to the PI controller, the system's test proposes an ideal case of rotational speed with low oscillation in the case of MRFC. The recent experience low overshoot, settling time, tracking error, and total harmonic distortion of flow current are shown in Table 2. The specifications of the system used in the simulation are shown in Table 3.

Table 2: Simple comparison between PI and MRFC current dynamic response

Windmill Features	windmill: blade radius	Ro = 2 m
	equivalent moment of inertia	Jeq = 10 kg.m2
	air density	ρ = 1.212 kg/m3
	rated wind speed	$Vw\_rated = 12\ m/s$
	cut-in speed, Vw	Vw, cut-in = 5 m/s
	critical speed	$Vw, cut - out$ = 24 m/s.
Parameters of PMSG	rated power	$Pg - rated$ = 6kW
	number of poles	p = 8
	stationary part resistance	Rs = 0.6 Ω
	direct - axis inductance	Ld = 1.4 mH
	quadrature - axis inductance	Lq = 2.8 mH
	magnetic flux	ψ = 0.12 V. s/rad
	rotational damping	D = 0
Power Converter	carrier frequency	fp = 5kHz
	bus voltage	$Vdc - rated$ = 300V
	bus condenser	C = 2,000μF

Table 3: Technical features for the windmill, PMSG, and power converter

	Overshoot %	Settling time (ms)	Error %	THD % of Currents
PI Control	3.31	2.5	0.75	2.73
MRFC	3.19	2.5	0.15	2.43

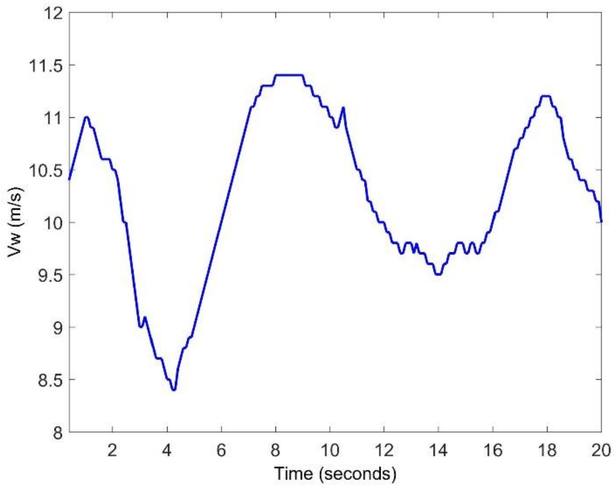


Fig. 9: Variation of wind speed measured by

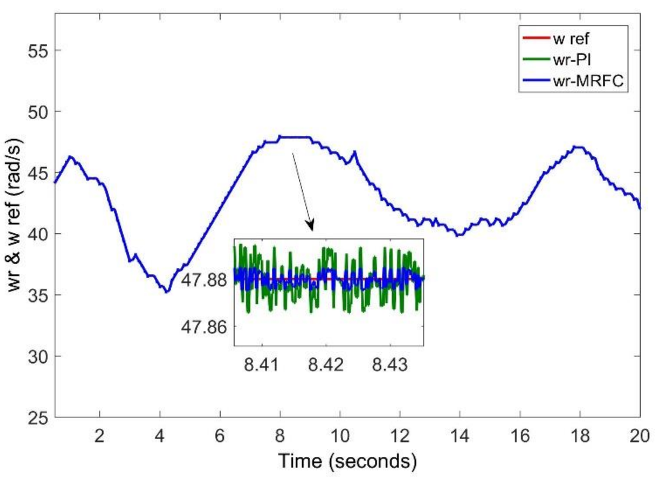
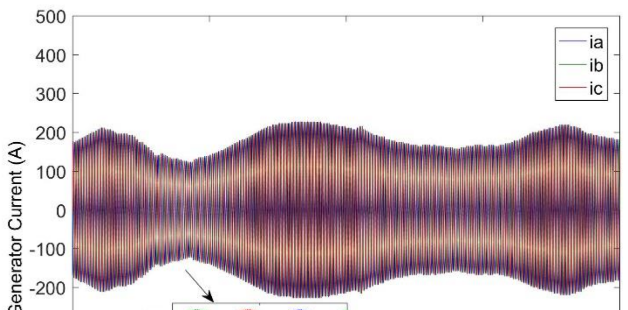
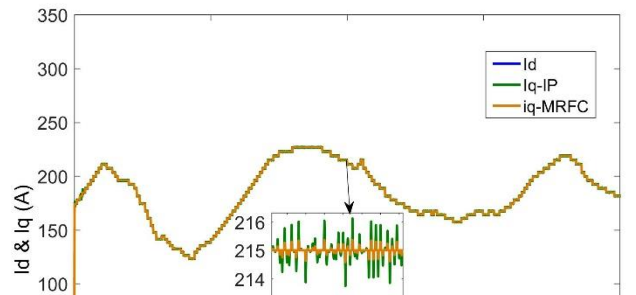


Fig.10: Tracking response of rotor with reference speeds for PI and MRFC





6. Conclusion and remarks

A new control strategy named model reference fuzzy control MRFC for a fully decoupled power electronic devices in a WECS has been proposed in this study. Firstly, the traditional control scheme has been investigated and then compared with the new efficient scenario to display the proposed scheme's benefits in a different environment and some cases. This control type has been utilized to provide a MRFC scheme using FLC with an electrical grid connection. Different wind speed values have been considered in case of a reasonable air viscosity condition and average temperature to analyze the system with these controllers. The scheme has two parts; MSC and GSC controllers. The first one calibrates the rotor speed to satisfy MPPT to get the best efficiency in power transformation, while another part is to adjust the - bus voltage and finally fix the output network voltage. The uncertainty of flow currents due to the fluctuation of wind speed causes high power energy losses, and it can be reduced using MRFC compared to the PI controller. The behavior of MRFC guarantees excellent dynamic performance with wind variation due to the robustness of the control system. It is also shown that MRFC presents a good percentage of tracking error and total harmonic current distortion compared with the classical PI controller, which leads to better system stability.

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