A Comparative Study of Fuzzy Logic Controllers for Wind Turbine Based on PMSG

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Abstract- This paper gives a complete design and comparative study of vector control based on Proportional-Integral, fuzzy logic, and self-tuned PI by the fuzzy logic controllers for Permanent Magnet Synchronous Generator. The direct-quadrature currents components will be controlled by the proposed controllers in order to achieve the desired performance. A complete modeling of control strategies of the overall system is presented. In order to analyze the dynamic and transient performance, the simulations are done in Matlab-Simulink, the results are recorded and compared for a variety designed controllers. The controllers perforamance are analyzed according to the gains.

Keywords Permanent Magnet Synchronous Generator, PI controller, Fuzzy Logic Controller, Self-tuned PI controller, Vector control, Rectifier.

1. Introduction

In recent decades, a high concern was given to renewable energies, especially to Wind Energy Conversion System (WECS) due to the development of the power electronics technologies and drives [1],[2].

The variable-speed turbine presents several advantages including increased wind energy output, improved quality, and reduced mechanical stress [3]. But, it presents also drawbacks such as a high cost of manufacturing and power losses due to use of power converters, and a complexity of the system. However, the drawbacks can be compensated by the additional energy production. The converter system enables the control of the generator speed that is mechanically coupled with the wind turbine shaft through the gearbox system if needed as shown in Fig.1 [4].

The permanent magnet synchronous generator is characterized by their high power and torque density, which involve a better performance and efficiency in wind turbine application [5], [6],[7].

The conventional control strategy is based on a proper modeling of the system and analytic analysis of the transfer function which are not always available. An advanced control strategy such as fuzzy logic control is proposed to reply to the requirements of nonlinear systems.

The fuzzy logic controller is a based system of particular knowledge, using depth reasoning, in a chaining procedure before rules (rules activated by permissions). The control concept was presented for the first time by Lotfi Zadeh in the sixty in Berkley university. The fuzzy logic is used in several domains, the first application on control domain was proposed by Mamdani in 1974. Since 1987, The use of fuzzy logic techniques has increased in automatic and industry domains [8]. The using of fuzzy logic controller in power electronics applications provides the following advantages [9]:

- Fuzzy logic controllers are independent of the mathematical model comparable to other controllers [10]. Which makes him useful in power system applications that are difficult to model.
- Fuzzy logic controllers are desired for the applications that presents a non-linearities in the system.
- By imitating the linguistic logic of human thought, fuzzy logic controllers are designed based on control rules and membership functions, which are much less rigid than the calculation computers.

Also, compared to the nonlinear existing algorithms, the fuzzy logic controller does not present the chattering phenomenon as the sliding mode controller [11],[12].

In this paper a complete model of turbine and generator will be presented in the next section. In section 3, several control strategies are designed and presented. To validate the proposed controls, the simulation results are reported and discussed in section 4.

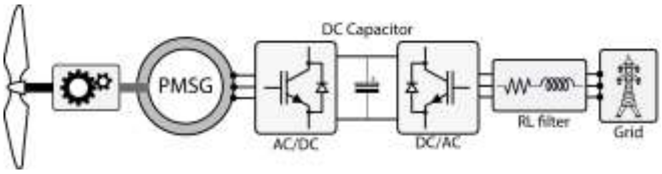

Fig. 1. Wind Energy Conversion System based on PMSG.

2. System Modeling

2.1. Wind turbine model

The turbine is composed of several components that converts the kinetic energy of wind to a mechanical energy which is characterized by the turbine power expressed as [13]:

$$P_t = \frac{1}{2}\rho\pi C_p R^2 v^3 \tag{1}$$

Where, P_t is the mechanical power extracted by the turbine, ρ the air density, C_p the power coefficient, R the turbine blade radius and v is the wind speed. Due to various losses in wind energy conversion system, the power extracted by the turbine is less than the aerodynamic power of wind [14], [15]. Therefore, the power coefficient comes as a ratio between the aerodynamic and turbine power. This coefficient depends mainly on the blade inclination angle (pitch angle: β) and the ratio between wind speed v and turbine speed w_t called tip speed ratio: λ as shown in Eq.(2) and Eq.(4).

$$C_p = 0.5\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right).\exp\left(\frac{-21}{\lambda_i}\right) + 0.0068\lambda \tag{2}$$

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

$$\lambda = \frac{R.w_t}{v} \tag{4}$$

2.2. Maximum Power Point Tracking control: MPPT

In order to produce the maximum power from wind, the tip speed ratio should be maintained at its optimal value λopt which is set at 8.1 in normal condition, that involve the power coefficient will be maximal C_{p-max} = 0.48 for a null pitch angle β = 0° as shown in Fig.2 and Fig.3.

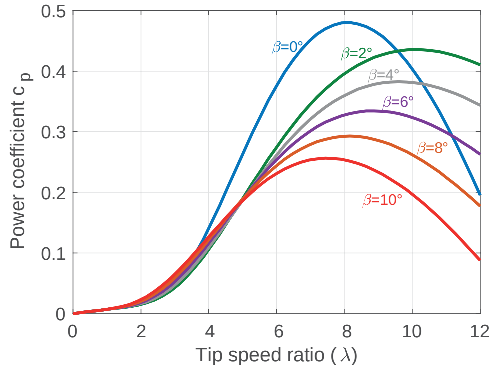

Fig. 2. Power coefficient curves according to the tip speed ratio for different values of pitch angle.

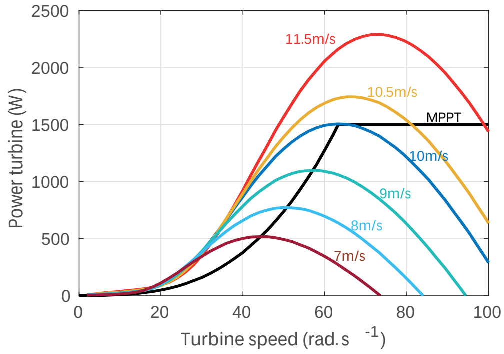

Fig. 3. The power turbine curves according to the rotational speed with focusing in the MPPT curve.

In this case, for a rated value of wind speed, the optimal turbine speed and maximal power are expressed as:

$$\begin{cases} w_{t-opt} = \dfrac{\lambda_{opt}.v}{R} \\ P_{t-max} = \dfrac{1}{2}\rho.\pi.R^2.C_{p-max}.v^3 \end{cases} \tag{5}$$

Then, the turbine is controlled in order to rotate with the reference speed that gives a maximum power condition [16], [17]. The fuzzy controller is implemented for the MPPT controller block as shown in Fig.4.

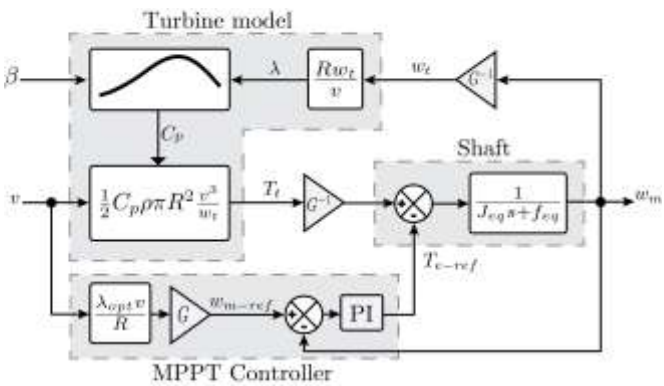

Fig. 4. Turbine system with fuzzy MPPT controller

With: $J_{eq} = J_m + \frac{J_t}{G^2}$, J_m and J_t are respectively the generator and turbine inertia, and G is the gear ratio.

2.3. PMSG Model

The PMSG model is characterized by the stator current-voltage equations Eq.(6) that describe the electric behaviors of the generator in synchronous rotary *dq*-plan, an equation of electromagnetic torque T_e Eq.(7) as a function of electrical parameters (L_{dq}, φ_f, i_{sdq}), and the mechanical behavior by Eq.(8) [18], [19].

$$\begin{cases} V_{sd} = -R_s.i_{sd} - L_d \frac{di_{sd}}{dt} + w_e L_q.i_{sq} \\ V_{sq} = -R_s.i_{sq} - L_q \frac{di_{sq}}{dt} - w_e L_d.i_{sd} + w_e \phi_f \end{cases} \quad (6)$$

$$T_e = \frac{3P}{2}\left(\phi_f.i_{sq} + (L_q - L_d) i_{sd}.i_{sq}\right) \quad (7)$$

$$J_{eq} \frac{dw_m}{dt} = \frac{T_t}{G} - T_e - f_{eq} w_m \quad (8)$$

Where, R_s is the stator resistance, L_{dq} are the stator-inductances in *dq*-frame, φ_f is the PM-flux, P is the pole pairs number, w_e and w_m are electrical and mechanical speed, V_{sdq}, i_{sdq} are the stator voltages and currents components in *dq*-reference, T_e and T_t are respectively the electromagnetic and turbine torques, J_{eq} and f_{eq} are respectively the equivalent system inertia and viscous damping.

3. Control Strategies of PMSG

The purpose of vector control is to simplify the control of PMSG as a DC motor, where there is a natural decoupling between the variable commands. This decoupling allows him to obtain a high-performance response system.

The conventional vector control is based on proportional-integral PI controller, which control the current loops. Where the q-axis current is controlled in such a way to guarantee a maximum active power generated with the reference power is P_{opt} and null value of the reactive power [20].

It should be noted that the reference target of direct-axis current will be set to zero $i_{sd-r} = 0$ according to Zero Direct Current ZDC control and the reference quadrature-axis current i_{sq-r} established by Eq.(9) with the reference of Electromagnetic torque T_e is given by the MPPT controller block as discussed previously and shown in Fig.9, the output controllers are the *dq*-axis voltages (V_{sd-r},V_{sq-r}) [21]. Depending on those voltages components, a switching pulse signal will be generated to control the rectifier in order to obtain the desired dynamic performance of PMSG.

$$T_e = \frac{3P}{2}\phi_f.i_{sq} = K_t.i_{sq} \quad (9)$$

3.1. Proportional-Integral Controller

In this section, the design of the PI controller for current loops is based on compensation of time constant of the controller with the time constant machine. The PI parameters are typically pre-set and remain unchanged during operation.

In that case, the electrical transfer function for the *dq*-currents of the PMSG is expressed by:

$$T(s) = \frac{1}{R_s + s.L_{dq}} = \frac{k}{1+\tau.s}$$

The mathematical formula of the PI controller is: $C(s) = k_p + \frac{k_i}{s}$, with k_p and k_i are successively the proportional and integral gains. According to Fig.5, the open loop transfer function is written as:

$$H_O(s) = T(s).C(s) = \frac{k.k_i}{s} \times \frac{1 + \frac{k_p}{k_i}.s}{1+\tau.s} \quad (10)$$

Conversion Systems, Wiley-IEEE Press, 2017, p. 352-.

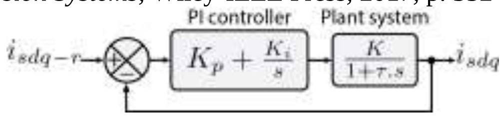

Fig. 5. PI controller diagram scheme for current loops in dq-plan.

By applying the compensation poles method, we obtain: $\tau = \frac{k_p}{k_i}$. Then the $H_O(s)$ is simplified to: $H_O(s) = \frac{k.k_i}{s}$. The closed loop transfer function is expressed as:

$$H_c(s) = \frac{H_O(s)}{1+H_O(s)} = \frac{1}{1 + \frac{1}{k.k_i}.s} = \frac{1}{1+\tau.s} \quad (11)$$

The system time response t_r is fixed in such a way to reach *95%* of the command signal: $t_r = 3\tau$. In that case the PI controller gains are:

$$\begin{cases} k_i = \frac{3}{k.t_r} = \frac{3.R_s}{t_r} \\ k_p = \frac{3.\tau}{k.t_r} = \frac{3.L_{dq}}{t_r} \end{cases} \quad (12)$$

As shown in Eq.(12) the controller gains depend mainly on the machine parameters which represents an inconvenient due to the uncertainties of the parameters during operation.

3.2. Fuzzy Logic Controller

Fuzzy logic allows the modeling of data imperfections and to a certain extent approaches the flexibility of human reasoning [22].

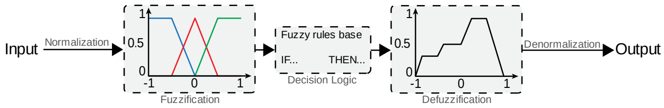

Fig. 6. Diagram block of fuzzy controller.

As shown in Fig.6, where the inputs are the error signals of current loops (e_d and e_q), and change rate of error (Δe_d, Δe_q), the outputs are the reference *dq*-axis voltages (V_{sd-r} and V_{sq-r}). The fuzzy logic controller is composed of three steps [23]:

- Fuzzification: after the normalization of variable input to defined interval which set in our case to [-1,1], the scale gains can improve the dynamic and transit performance of the controller as discussed later. The error e and change of error Δe is considered the variable inputs of the FL controller as shown in Fig.9. The triangular membership function type with overlap used for the inputs/output fuzzy sets from Fig.7 with the linguistic variables are BN (Big Negative), SN (Small Negative), Z (Zero), SP (Small Positive), and BP (Big Positive). By Adjusting the scale gains, all fuzzy controllers use the same structure in order to keep the simplicity of the system.

- Rule base or decision logic: the decision output is affected according to the input states as shown in table.1. The output is given by the "IF…THEN" block as an example: IF (e_d is BN and Δe_d is BN) THEN (V_{sd-r} is BN).
- Defuzzification: In this step, allows the return to the real output. By calculating the output depending on the membership degree, the calculation method is based on the max-min inference mechanism.

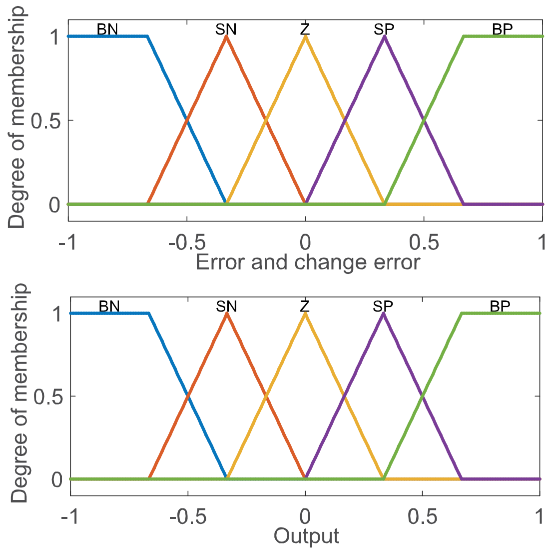

Fig. 7. Membership functions for the error e and change rate Δe (top), and the controller output (bottom).

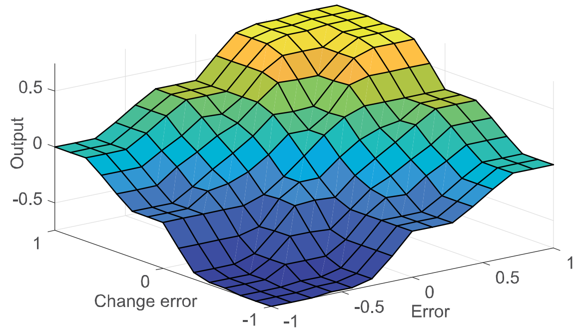

Fig. 8. The generated surface by the Fuzzy logic controller.

Table 1. Base rules table of fuzzy logic controller.

$\frac{du}{dt}$		*e* BN	SN	Z	SP	BP
$\frac{de}{dt}$	BN	BN	BN	SN	SN	Z
	SN	BN	SN	SN	Z	SP
	Z	SN	SN	Z	SP	SP
	SP	SN	Z	SP	SP	BP
	BP	Z	SP	SP	BP	BP

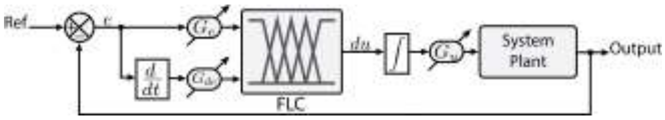

Fig. 9. Fuzzy logic controller diagram scheme

3.3. Fuzzy PI Controller

The main inconveniences of PI controller are the gains estimation and robustness, especially for nonlinear system such as the PMSG. Also, it becomes more difficult due to parameter uncertainties and external noises [24], [25]. In order to provide the controller system performance, it is possible to combine the fuzzy and PI Controller. Their work principle is similar to the previous controller as shown in Fig.10. Where the proportional and integral gains (k_p and k_i) are variables and self-tuned by the fuzzy logic controller. The fuzzy block outputs are the gains of PI controller [26], [27].

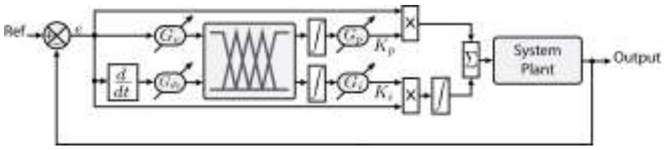

Fig. 10. Fuzzy-PI controller diagram scheme

4. Simulation Results and Discussion

The simulation results are presented to highlight the performances of the fuzzy logic and self-tuned fuzzy-PI. The proposed control diagram of the system is illustrated in Fig.11.

The *dq*-axis current loops are tested with PI, fuzzy logic and fuzzy-PI in order to establish a synthesis of the controllers performances.

Figure 12 shows the dynamic and transient performances of the controllers for a step changes current reference. By focusing on the transient state, The PI controller provides an overshoot before convergence to the target, while the fuzzy logic and fuzzy-PI controller converge directly and rapidly comparing to PI. Also, the only difference between the d and q-axis loop is the *dq*-inductances (L_d and L_q), but the controllers keep their dynamic performances, which involves that the proposed control strategies give a high robustness against parameters uncertainties.

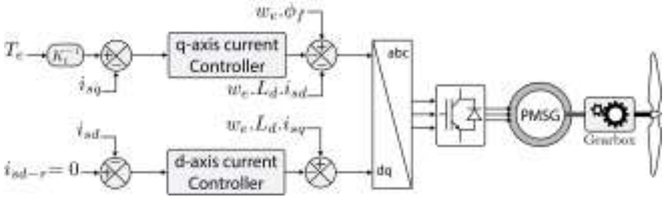

Fig. 11. Block diagram control system.

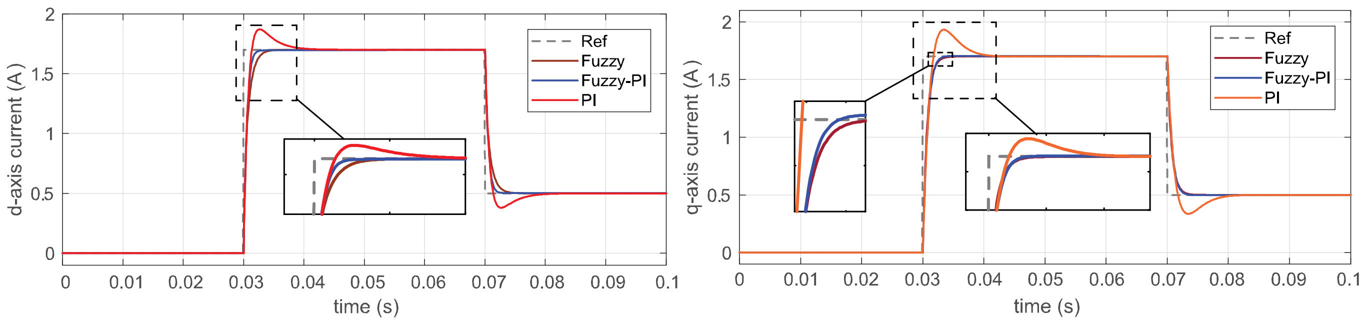

Fig. 12. Tracking performance comparison of dq-axis current loops with different proposed controllers.

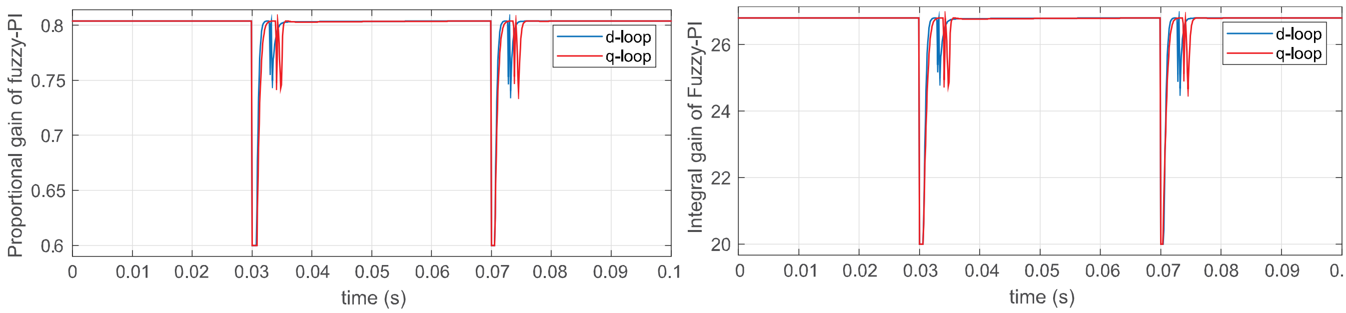

Fig. 13. Self-tuned proportional-integral gains by the fuzzy logic controller.

The fuzzy PI controller can control the dq-currents by adapting the PI gains through the fuzzy logic system. As shown in Fig.13, where the PI gains are adjustable according to the current targets. Also, it can be seen that the d-axis loop presents a small delay comparing to q-axis loop regarding the same performance.

The results plotted in Fig.14 shows q-axis current component under variable wind speed profile. The Fuzzy-PI gives a high tracking performance compared to the conventional PI, while the fuzzy control represents a slight delay to the target i_{sq-r}.

The optimal values are obtained by varying manually the gains of the controllers, the impact on the transient performance concerning current loops responses are observed and noted in Table.2 and Table.3. Where, the error gain G_e insure the convergence response, the derivative gain G_{de} acts on stability by controlling the damping of the system, and the output gain G_u affects on static error and precision if the gain less than the optimal or on the chattering phenomenon in the other case. Also, the proportional and integral Gk_{pi} gains in case of fuzzy-PI controller can affects on static error, damping, and chattering depending on the values of the gains.

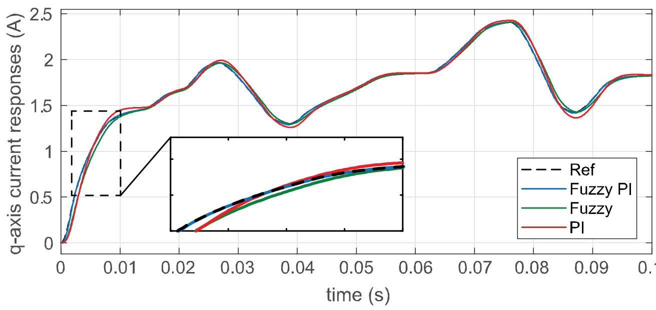

Fig. 14. q-axis current responses comparison performance of the proposed control strategies under variable wind speed profile.

Table 2. Gains evaluation of fuzzy logic controller.

Fuzzy Logic Control	G↓	Optimal value	G↑
Error gain: G_e	Over damped	0.016	High convergence
Derivative gain: G_{de}	Under damped	10^{-4}	Over damped with chattering
Output gain: G_u	Under damped	400	Undamped

Table 3. Gains evaluation of self tuned fuzzy-PI controller

Fuzzy PI Control	G↓	Optimal value	G↑
Error gain: G_e	Over damped	0.1	High convergence
Derivative gain: G_{de}	Critically damped	0.1	Critically damped
Proportional fuzzy gain:G_{kp}	Under damped	1.2	Convergence with static error
Integral fuzzy gain: G_{ki}	Static error with ripple in steady state	40	Under damped
Output gain: G_u	Over damped with static error	2.10^3	High convergence with chattering

5. Conclusion

A comparative study between the proposed controllers is presented in this paper. The controllers give an independent control of *dq*-current loops, where the fuzzy-logic and fuzzy-PI gives a high tracking performance compared to conventional PI. Also, the gains of fuzzy-PI are self-tuned that can allow a stability and robustness against parameters variations of the machine. Moreover, the controller gains are evaluated in order to identify the optimal operating point that gives the high tracking performance of the target.

Appendix

Table A1. PMSG Data

Parameter	Value
Nominal power P_n	1.5 KW
Stator resistance R_s	2.6Ω
dq-inductances [L_d,L_q]	[63.77mH, 94.32mH]
PM flux ϕ_f	0.4Wb
Equivalent system inertia J_{eq}	$0.0931 N.m.rad^{-1}.s^2$
Equivalent viscous damping f_{eq}	$0.0153 N.m.rad^{-1}.s$
Number of poles pairs P	2
Rated speed w_{nom}	$157 rad.s^{-1}$
Rated frequency f	50Hz

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