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Robust Tracking Control for DFIG in Wind Power Generation Systems Based Artificial Fuzzy Logic Technique

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***Abstract*—This paper deals with the Artificial Fuzzy Logic (AFL) power control strategy is introduced. This later is used to control the power flowing between the stator of the DFIG and the power network. The suggested AFL controller was tested and compared with one other suggested technique, Proportional-Integral (PI) controller. The simulation was carried out by means of computational simulations in Matlab/Simulink Software. The obtained results show that the suggested controller exhibits better behaviour in terms of settling time, overshoot, robustness with respect to machine parameters variation, and good tracking references.**

Keywords-Doubly Fed Induction Machine, Wind turbine, Vector Control, Artificial Fuzzy Logic, Proportional- Integral.

NOMENCLATURE

DFIG: Doubly fed induction generator,
WECS: Wind Energy Conversion Systems,
FL: Fuzzy Logic,
PI: Proportional-Integral,
θ_r ,θ_s: Mechanical rotor's position and stator's flux position,
Ω: Mechanical speed,
C_e , C_{mec}: Electromagnetic torque and prime mover,
R_r, R_s : The rotor and stator's resistances Per phase,
L_m: Magnetizing (Mutual) inductance,
L_r, L_s: Total cyclic inductances of the rotor and the stator,
g: generator slip,
f_r, J: Viscous friction and inertia,
P: Number of pole pairs,
f : Grid frequency,

I. INTRODUCTION

In addition to other renewable energy sources, the wind energy is proving to be one of the preferred choices to produce electricity. Unlike fossil fuels, wind energy is clean, pollution-free from greenhouse gases emissions (CO_2) and inexhaustible. However, it is not powerful enough to replace the existing sources, this fact has attracted a lot of interests on the methods of exploitation and development of the wind energy conversion systems (WECS) [1].

Nowadays, the Doubly fed induction generator (DFIG) is one of the most popular used variable speed wind turbines, because of its offers a lot of advantages, such as a slight rise in efficiency of wind energy extraction, the potential to control torque and reduce of inverter cost [2].

The control of induction machines and drives has been highly developed in recent years. Induction generators have been widely used for wind power generation, and the corresponding motors have been the workhorses in the industry for variable speed applications in a wide power range. In this context, there are a number of significant control methods available such as: scalar control, vector or field oriented control, direct torque and flux control [4][5].

In fact, many progress has been made for field oriented control strategy which is based on the proportional integral (PI) controller are traditionally used for controlling the active and reactive power of the DFIG [3]. PI controllers present appropriate performances in many applications. However, when parameters variations occurred, due principally to physical effects (temperature, saturation and skin effect). PI control performances may be critically deteriorated [4]. With the progress in power systems technology and increasing demand for quality energy, it is necessary to focus on the possibility of using modern control techniques [5][6].

So, in order to overcome such problems, some robust control techniques were proposed in the literature and were applied in several applications such as: sliding mode control, H_∞, adaptive control…etc; [5][6][7].

On the otherhand, artificial intelligence techniques in general such as: Takagi-Sugeno fuzzy method, fuzzy logic, genetic algorithms, neural networks and particle swarm optimization, were used and proves that they are too suitable to control systems that are characterised by variations of their parameters and ensured optimal performances [8][9][10].

Better solutions we can achieve by the use of a fuzzy logic controller, because of it uses the knowledge of the expert (human knowledge) and the implicit inaccuracy [10][11].

In fact, in several applications, the use of Artificial Fuzzy Logic (AFL) proved that such methods permit more robustness towards parameter's variations and external perturbations during the functioning of the process [10][11][12].

In this paper, the authors suggest to control active and reactive powers by using first in the process the Integral-Proportional (PI) controller then this latter is replaced by an AFL one respectively. After more, the two controllers are compared and results are discussed, the objective is to show that controllers can improve performances of doubly-fed induction generators in terms of reference tracking, sensibility to perturbations and parameters variations.

The paper is organized as follows. Section II presents a description and a detailed aerodynamic modelling of the variable speed wind turbine, the mechanical transmission system and the DFIG. The field-oriented control application of DFIG is discussed in section III. Section IV introduces the two types of controllers synthesis: Proportional-Integral (PI) controller and Artificial Fuzzy Logic (AFL) based controller. The simulation and results are presented in section V. Finally, section VI contains the conclusions of this study.

II. MODELLING OF SYSTEM UNDER STUDY

This section briefly describes the modelling of the studied system, as represented in Fig. 1.

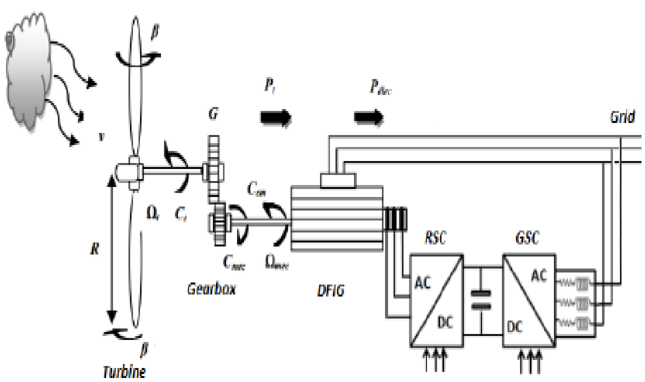

Fig. 1: Structure of a wind energy's conversion system by using the DFIG.

II.1. Modelling of Wind-Turbine

The aerodynamic power, which is converted by a wind turbine, P_t is dependent on the power coefficient C_p. It is given by:

$$P_t = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V^3 \tag{1}$$

Where ρ is the air density, R is the blade length and V is the wind velocity. The turbine torque is the ratio of the output power to the shaft speed Ω_t :

$$T_{aer} = \frac{P_t}{\Omega_t} \tag{2}$$

A wind turbine can only convert just a certain percentage of the captured wind power. This percentage is represented by Cp(λ,β) which is the function of the wind speed, the turbine speed and the pitch angle of specific wind turbine blades [11][12].

This ratio is called the tip speed ratio is given by:

$$\lambda = \frac{\Omega_t R}{V} \tag{3}$$

In this study, the mathematical representation of the power coefficient used for a wind turbine is given by:

$$C_p(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)\exp\left(\frac{-21}{\lambda_i}\right) + 0.0068\lambda \tag{4}$$

With : $$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{5}$$

II.2. Modelling of DFIG

The electrical equations of a DFIG are given by [1]:

$$\begin{cases} V_{ds} = R_s i_{ds} + \dfrac{d\phi_{ds}}{dt} - \omega_s \phi_{qs} \\ V_{qs} = R_s i_{qs} + \dfrac{d\phi_{qs}}{dt} + \omega_s \phi_{ds} \\ V_{dr} = R_r i_{dr} + \dfrac{d\phi_{dr}}{dt} - \omega_r \phi_{qr} \\ V_{qr} = R_r i_{qr} + \dfrac{d\phi_{qr}}{dt} + \omega_r \phi_{dr} \end{cases} \tag{6}$$

With;

$$\begin{cases} \phi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \phi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \phi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \phi_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \tag{7}$$

The rotor and stator angular velocities are expressed by the following relationship:

$$\omega_r = \omega_s - P\,\Omega_{mec} \tag{8}$$

The electromagnetic torque can be obtained using the power budget. There are several expressions of electromagnetic torque all equal:

$$C_{em} = \frac{3}{2} p \frac{L_m}{L_s} (\Phi_{qs} i_{dr} - \Phi_{ds} i_{qr}) \tag{9}$$

III. FIELD ORIENTED CONTROL OF DFIG

Induction generators can be controlled using various approaches such as: Direct Torque Control (DTC) and Field Oriented Control (FOC) [8]. Among the above control techniques, the FOC is widely employed in the industrial field due to its simplicity of conception and its good performances.

We use asynchronous reference with the q axis aligned to the computed stator flux (Fig. 2). Assuming that the resistance of the stator windings (R_s) is neglected, the voltage and the flux equations of the stator winding can be simplified as follow:

$$V_{ds} = 0,\ V_{qs} = V_s = \omega_s \Phi_{ds},\ \Phi_{ds} = \Phi_s,\ \Phi_{qs} = 0 \tag{10}$$

The active and reactive power equations at the stator side of a DFIG can be expressed as:

$$\begin{cases} P_s = -\dfrac{L_m V_s}{L_s} i_{qr} \\ Q_s = \dfrac{V_s^2}{\omega_s L_s} - \dfrac{V_s L_m}{L_s} i_{dr} \end{cases} \tag{11}$$

As can be seen from Eq. (11), P_s and Q_s are proportional to the rotor currents, I_{dr} and I_{qr}, respectively. The quadrature (q) current of the RSC (I_{qr}) is used for controlling the real power output while the direct (d) current (I_{dr}) is used for controlling the reactive power output.

By exploiting Eqs. (6), (7), (10) and (11), we can get the rotor voltages coordinate as:

$$\begin{cases} V_{dr} = R_r I_{dr} + \sigma L_r \dfrac{\mathrm{d} I_{dr}}{\mathrm{d}t} - g\,\omega_s \sigma L_r I_{qr} \\ V_{qr} = R_r I_{qr} + \sigma L_r \dfrac{\mathrm{d} I_{qr}}{\mathrm{d}t} + g\,\omega_s \sigma L_r I_{dr} - g \dfrac{L_m V_s}{L_s} \end{cases} \tag{12}$$

where: $\sigma = 1 - \dfrac{L_m}{L_r L_s}$ (leakage coefficient),

$g = \dfrac{\omega_s - \omega_r}{\omega_s}$ (slip) and V_s (stator voltage).

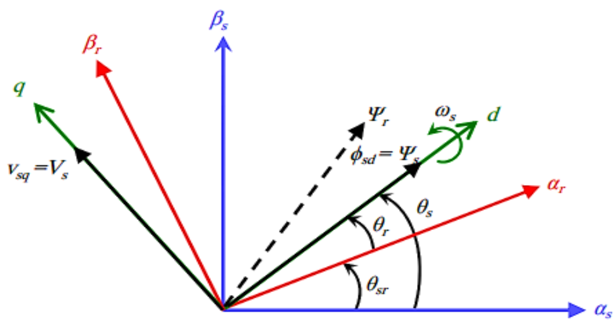

Fig. 2: Orientation of the stator flux.

From the above equations, we can develop a block diagram of the DFIG to regulate Fig. 3, the DFIG model become approximately decomposed in two decoupled subsystems.

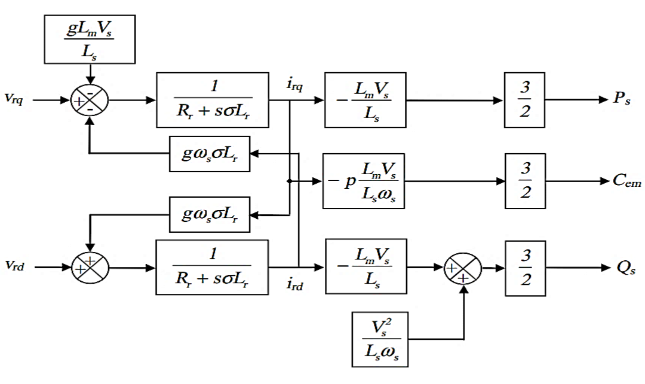

Fig. 3: Block diagram of the simplified model of the DFIG.

III. CONTROLLER SYNTHESIS

A. PI controller :

This type of regulator remains the most commonly used for controlling the DFIG as a generator, as well as in many industrial control systems [9]. For axes d and q, the open loop transfer function integrating the presence of the regulators is:

$$OLTF = \frac{p + \dfrac{k_i}{k_p}}{\dfrac{p}{k_p}} \cdot \frac{\dfrac{3L_mV_s}{2L_s\left(L_r - \dfrac{L_m^2}{L_s}\right)}}{p + \dfrac{L_sR_r}{L_s\left(L_r - \dfrac{L_m^2}{L_s}\right)}} \tag{13}$$

In order to eliminate the zero present on the transfer function, we choose the method of compensation of the poles for the synthesis of the regulator, which results in the following equality:

$$\frac{k_i}{k_p} = \frac{L_sR_r}{L_s\left(L_r - \dfrac{L_m^2}{L_s}\right)} \tag{14}$$

If the poles are perfectly compensated, the open loop transfer function becomes:

$$OLTF = \frac{k_p \dfrac{3}{2} \dfrac{L_mV_s}{L_s\left(L_r - \dfrac{L_m^2}{L_s}\right)}}{p} \tag{15}$$

The closed-loop transfer function can be expressed as:

$$CLTF = \frac{1}{1 + p\tau_r} \quad With: \quad \tau_r = \frac{1}{k_p}\frac{2}{3}\frac{L_s\left(L_r - \dfrac{L_m^2}{L_s}\right)}{L_mV_s}$$

Finally, we get:

$$k_p = \frac{1}{\tau_r}\frac{2L_sL_r - L_m^2}{3L_mV_s} \tag{16}$$

$$k_i = \frac{1}{\tau_r}\frac{2L_sR_r}{3L_mV_s} \tag{17}$$

The simplified schematic of the control is shown in fig. 4.

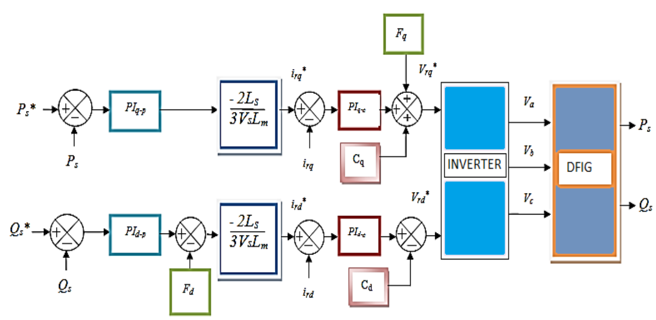

Fig. 4: Block diagram of the indirect control of DFIG by PI.

B. Design of fuzzy feedback controller

Fuzzy controllers have been popular especially in the industrial processes. Because of its effectiveness techniques when the mathematical model of the system is nonlinear or when there is no mathematical model [11].

The structure of the fuzzy control system consists of: Fuzzification, Knowledgebase, Inference engine, Defuzzification.
The schematic diagram of a complete fuzzy control system is given in Fig. 5. The plant control dI_{qr} is inferred from the two state variables, error E_p and change in error dE_p [12][13].

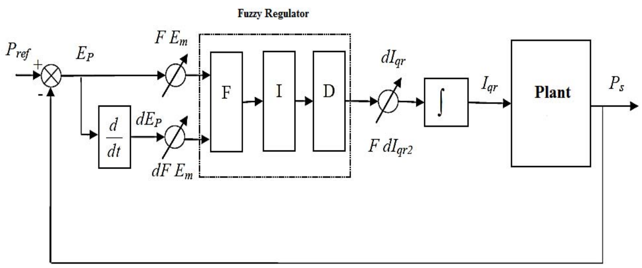

Fig. 5: Basic structure of the fuzzy control system.

We can calculate the two input variables $E_P(k)$ and $dE_P(k)$ at every sampling time as:

$$E_p(k) = P_{ref}(k) - P_s(k) \tag{18}$$

$$dE_p(k) = E_p(k) - E_p(k-1) \tag{19}$$

The control signal I_{rq}^{ref} is obtained after integrating the output of the fuzzy logic regulator.

$$I_{rq}^{ref}(k) = I_{rq}^{ref}(k-1) + dI_{rq}^{ref}(k) \tag{20}$$

To synthesize the fuzzy controller of two variables (active and reactive powers), the Fuzzy control uses a set of rules to represent how to control the plant. The complete control rules used in our system are shown in Table I.

TABLE I. RULE BASE FOR FUZZY CONTROLLER

CE \ E	NB	NS	ZE	PS	PB
NB	*ZE*	*ZE*	*PB*	*PB*	*PB*
NS	*ZE*	*ZE*	*PS*	*PS*	*PS*
ZE	*PS*	*ZE*	*ZE*	*ZE*	*NS*
PS	*NS*	*NS*	*NS*	*ZE*	*ZE*
PB	*NB*	*NB*	*NB*	*ZE*	*ZE*

Here: PB is positive big, PS is positive small, ZE is zero, NS is negative small, and NB is negative big, are labels of fuzzy sets.

In this paper, the triangular membership function, the max-min reasoning method, and the centre of gravity defuzzification method are used, as those methods are most frequently used in many works of literature [12][13][14].

IV. REGULATORS PERFORMANCES

In this section, the simulation of the dynamic's of the indirect vector control process with DFIG associated in wind system are developed by using the Matlab/Simulink software (Fig. 6), to access the effectiveness of the proposed AFL control strategy, the simulation results are shown for different scenarios.

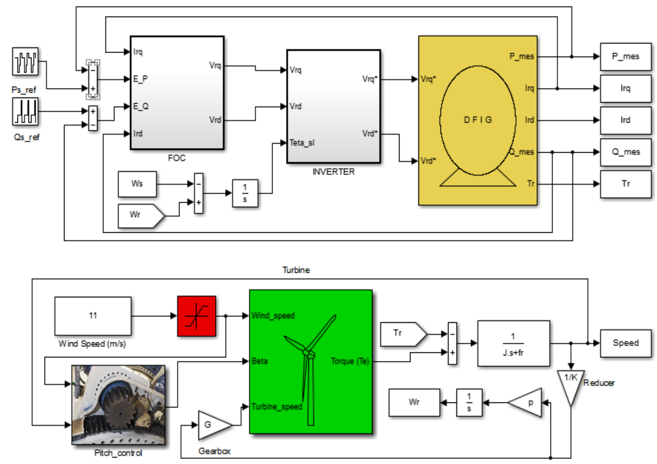

Fig. 6: Block diagram of the indirect control of the DFIG associated with wind system.

The regulators will be tested and compared taking in consideration parameters variations, in two different scenarios: reference tracking and robustness.

A. *Reference tracking*

As a first test, we considered that the machine operates in ideal conditions by considering different steps for an active and a reactive power. The corresponding results are represented in figs 7 and 8. Note that the obtained waveforms are obtained first in the case of PI controller (Fig.7), then with AFL controller ones (Fig. 8); respectively.

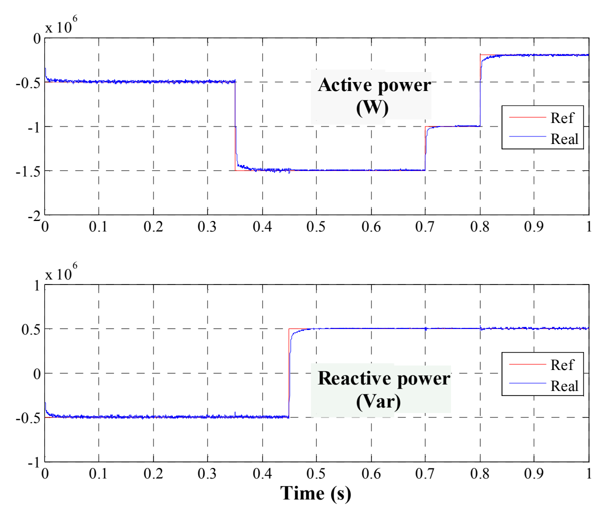

Fig. 7: Simulation results to the active and a reactive power impact (PI controller).

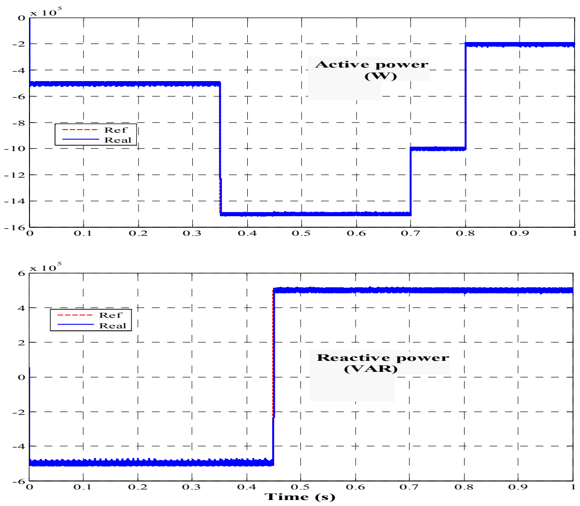

Fig. 8: Simulation results to the active and a reactive power impact (FL controller).

Figs 7–8 show the obtained simulation results. As shown in Fig. 8, the Artificial Fuzzy Logic regulator offers perfectly track their references (active & reactive powers values) compared to the PI regulator.

B. *Robustness*

In order to test the robustness of the two controllers, the value of mutual inductance L_m is decreased by 10%and 30% of its nominal value. Figs 9 and 10 shown the effect of parameter's variations on the active power's responses with the two different controllers applied respectively.

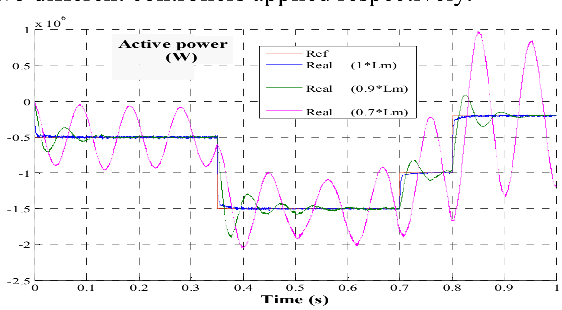

Fig. 9: Simulation results of active power to parameter's variations (PI controller).

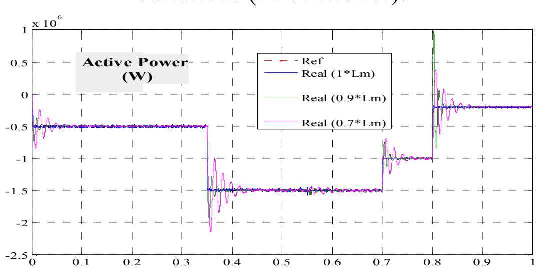

Fig. 10: Simulation results of active power to parameter's variations (AFL controller).

The results in Fig 10 show a good dynamic and static performance, such as very fast response time and no overshoot and minimal static error compared to Fig 9. From these results, we find that the Artificial Fuzzy Logic (AFL) regulator illustrate a satisfactory improvement, particularly in robustness via parameter variations of the machine and external perturbations, compared to the PI regulator.

C. *Comparison between the two controls*

The analysis of the two responses of the system, obtaining by the regulation with a proportional-integral controller (PI) and a Fuzzy controller (FL), yields to the following remarks Table II:

TABLE II. COMPARISON OF THE PERFORMANCES OF THE TWO REGULATORS

		Regulators	
Performances		PI	AFL
Response time (ms)		6	1.95
Overtaking (%)		6	6
Static error	(%)	0.6	0.42
	(W)	9000	6000
Robustness with regards to variation parameters		Bad	Acceptable
Design		Simple	Difficult
THD I_s(%)		1.44	1.88

From the Table II, we can conclude that using a Artificial Fuzzy Logic controller is more powerful and very fast response time, minimal static error than a PI controller.

V. CONCLUSION

This paper has presented the improved power control of DFIG used in wind turbine by the Artificial Fuzzy Logic (AFL) techniques control, after modelling the wind turbine and the DFIG in the d and q axis, we have established the indirect vector control of DFIG based on stator flux oriented. This latter is based on two types of controllers. The first one is chosen as the PI controller which is then replaced by an FL controller. The control by Artificial Fuzzy Logic allowed us on the one hand, to improve the dynamic and static performances of the DFIG (the follow-up is perfect, the regulation is very fast, without static error and without exceeding) and on the other hand, to ensure robustness with respect to parametric's variations of the DFIG machine than the PI controller.

APPENDIX

TABLE III. WIND TURBINE PARAMETERS

Blade radius, R	35.25 m
Number of blades	3
Gearbox ratio, G	90
Moment of inertia, J	1000 $Kg.m^2$
Viscous friction coefficient, f_r	0.0024 $N.m.s^{-1}$
Cut-in wind speed	4 m/s
Cut-out wind speed	25 m/s
Nominal wind speed, v	16 m/s

TABLE IV. DOUBLY FED INDUCTION GENERATOR PARAMETERS

Rated power, P_n	1.5 MW
Stator rated voltage, V_s Rated current, I_n	398/690 V 1900 A
Stator rated frequency, f	50 Hz
Stator inductance, L_s	0.0137 H
Rotor inductance, L_r	0.0136 H
Mutual inductance, L_m	0.0135 H
Stator inductance, R_s	0.012 Ω
Rotor inductance, R_r	0.021 Ω
Number of pair of poles, p	2

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