

Grid Voltage-Oriented Vector Control for the Grid Side Converter of the Wind Turbine Doubly-Fed Induction Generator

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Abstract: One of the generators that are widely used in MW scales wind turbines is the doubly fed induction. This paper presents control method which is called the grid voltage-oriented vector control method that is used to control a grid side converter of the doubly fed induction generator. This control method is capable to solve the grid side converter problems which include regulating the power flow of the rotor side circuit and maintaining a unity power factor for overall system. The used mathematical model is presented in d-q reference frame. For solving the mentioned grid side converter problems, the study is validated through simulation using software MATLAB/Simulink, studies including a modeling, control, and simulation on a 2 MW on-grid doubly fed induction generator wind generation system. The aim of this paper is to validate the operation of the model by obtaining a constant value for the DC link voltage at different wind speeds and reactive power values. The DC link voltage performance results of the MATLAB/ Simulink model will be presented and analyzed.

Keywords: Wind turbine, Doubly fed induction generator, Grid voltage oriented vector control, DC link voltage, Grid side converter

1. Introduction

A wind turbine is system designed to convert kinetic energy into mechanical energy using the rotor then from mechanical into electrical using the generator. The wind turbine produces 17 – 39 times as much energy as needed for its operating until it is lifetime end [1]. The doubly fed induction generator (DFIG) is simply a wound rotor induction motor (WRIM) that could work as a motor as well as a generator. The reason to call it DFIG is as follows: Doubly fed because it is fed from two sides or from two power sources. Hence, the DFIG is fed from the stator and rotor. An induction because of the principle of its operation is induction. Generator because it works as a motor as well as a generator.

DFIG is a variable speed fixed frequency generator, which means the frequency is determined in the DFIG by the grid, which is the electricity company. Hence, the frequency will not change when the rotational speed of the generator changes. The advantages of DFIG including, it is cheap, generate power even at low speed of wind, the power factor can be controlled, and the frequency of DFIG is constant and it does not change with the speed.

a) Wound Rotor Induction Motor

The Induction motor work as a motor and generator. Synchronous speed separates the operation of the induction motor as a motor or as a generator. In the wind turbines, before the wind comes, the induction motor works as a motor, then when the wind comes and the speed increases, then the gearbox increases the speed to a speed greater than the speed of the synchronous speed, then it starts to work as

a generator, and when it reaches the maximum possible speed as a generator, it stops working automatically because it will become out of control. Wound rotor induction motor consists of rotor, stator, slip ring brushes, and wires. From the stator, there are 3 wires connected to the transformer or to the grid, and from the rotor, there are 3 wires that connected to the converter through slip rings and brushes holding them at the end of the rotor's wires. The brushes are holding the slip rings, so the brushes do not rotate but the slip ring rotates.

b) Betz Limit or Betz Coefficient

In this model, Newton's laws of mechanics will be applied. It is assumed here that the wind flow is axial and concentrated towards the rotor and that the winds are not dispersible. The power produced by the turbine is given by the following equation:

$$P = \frac{1}{2} \times m \times (v_1^2 - v_2^2) \quad (1)$$

Where, v_1 : The wind speed before hitting the turbine.

v_2 : The wind speed after the turbine.

And the mass m is equal to:

$$m = \rho \times A \times v \quad (2)$$

Where, ρ : Density of the air. A : Swept rotor area.

v : Wind speed.

Average speed of the wind turbine rotor is given by:

$$v_{avg} = \frac{1}{2} \times (v_1 + v_2) \quad (3)$$

When substituting equation 3 into kinetic power equation the result is:

$$P_{kin} = \frac{1}{4} \times \rho \times A \times v_1^3 \times \left[1 - \left(\frac{v_2}{v_1} \right)^3 - \left(\frac{v_2}{v_1} \right)^2 + \left(\frac{v_2}{v_1} \right) \right] \quad (4)$$

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To find the point at which the maximum power is achieved, the equation 6 with respect to v_2 is derived as following:

$$dP_{kin} / dv_2 = \frac{1}{4} \times \rho \times A \times [(-3) \times v_2^2 - 2 \times v_1 \times v_2 + v_1^2] = 0 \quad (5)$$

$$3 \times v_2 - v_1 = 0 \Rightarrow v_2 = \frac{1}{3} \times v_1 \quad (6)$$

When substituting v_2 into P_{kin} equation, the following is concluded:

$$P_{kin} = (0.5925) \times \frac{1}{2} [\rho \times A \times v_1^3] \quad (7)$$

$$P_{kin} = 0.5925 P_{wind} \quad (8)$$

Where, P_{kin} : The kinetic power gained by the wind turbine.
 P_{wind} : Power of the wind.

The number 0.5925 means that the power gained by the wind turbine is only 59.25% from the wind power, and this percentage is called Betz coefficient or Betz limit. Simply, out of every 100 units, the wind turbine benefits from 40 units only. Therefore, methods have been developed to control the turbine so that it makes the most of the wind power possible.

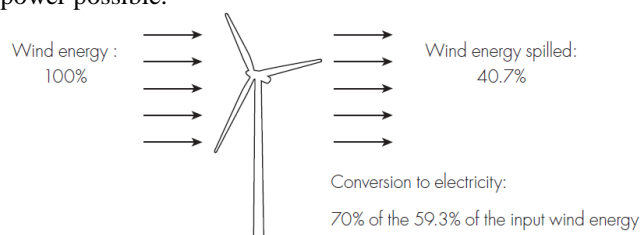


Figure 1: Effect of Betz coefficient [2]

2. Doubly Fed Induction Generator

a) Construction of DFIG

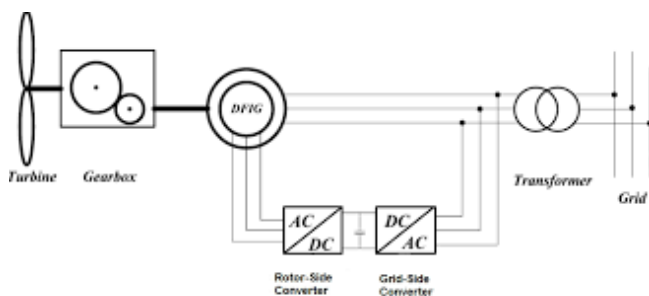


Figure 2: DFIG schematic [3][4]

DFIG consists of rotor and stator circuits. The stator is connected and feeds active power directly to the grid directly. The rotor is connected to the grid through a bidirectional back-to-back ac/dc/ac connection of the rotor side converter (RSC) and grid side converter (GSC). There is a dc link bus between GSC and RSC that is a low pass filter to reduce the ripple present in the signal. In the rotor, the power flows in two directions that depend on the mode of operation which is either from the grid side toward the rotor or from the rotor toward the grid.

Because of the wind fluctuation the deviation in power is managed through the rotor. In DFIG 70% of the energy flows in the path of the active power that is from the stator towards the grid, and only 30% of the energy is in the direction from the rotor to the grid. This means the

converter sizing is only 30% in size. The power converter is usually rated at 25-30% of the generator power rating [5].

b) The Principle of Operation of DFIG

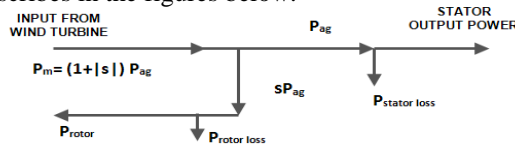
Simply, the principle of operation of DFIG is the speed of the rotor varies though, through the suitable adjustment of the frequency of the rotor it is still can be got a constant value of the frequency of the stator as can be noticed from the equation below that describes the DFIG stator frequency:

$$f_{Stator} = \frac{\text{Rotor Speed} \times \text{Number of Poles}}{120} \pm f_{Rotor} \quad (9)$$

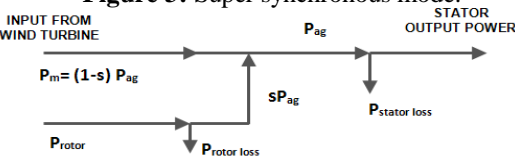
If the generator is running at speed higher than the synchronous speed η_s that is called super synchronous mode, that means power flow in rotor circuit is fed from rotor side to grid side. At this mode to remain or keep the frequency of the rotor constant, a negative frequency component ($-f_{Rotor}$) must be added. ($-f_{Rotor}$) means that power is flowing from the rotor to the grid. Also, if the generator is running at speed less than the η_s a positive frequency component ($+f_{Rotor}$) must be added to remain the f_{Stator} constant. However, when the generator is running at a η_s the f_{Rotor} is zero that means a constant dc is fed to the rotor. In that case, it can be said that DFIG is acting as a synchronous generator. DFIG nowadays is used in Mega scale projects, the operation modes of it are sub and super synchronous [6].

More simply, When the wind turbine's speed is higher than the η_s the energy and speed of the rotor increases. In this case the DFIG control scheme helps to remain the speed and output frequency of the rotor constant by extracting the extra power and fed it to the grid.

Otherwise, at the sub synchronous mode the power is flowed from the grid to the rotor side. This mode appears if the rotor tries to decrease its speed, then power is fed to the rotor and it does the work of the motoring to maintain its speed at η_s . The path of the power of DFIG in both modes is describes in the figures below.



POWER FLOW IN DFIG DURING SUPER SYNCHRONOUS MODE OF OPERATION
 Figure 3: Super synchronous mode.



POWER FLOW IN DFIG DURING SUB SYNCHRONOUS MODE OF OPERATION
 Figure 4: Sub synchronous mode

c) Modelling of DFIG

Note: **The LIST OF SYMBOLS is given in appendix A.**

The DFIG includes 2 level full bridge converters connected through a dc link bus. The first level is the RSC, and the second level is the GSC. The RSC and GSC according to the mode sub or synchronous mode might act either as

($V_{dg} = V_g$) and $V_{qg} = 0$. That will change the power equations as shown below:

$$P_g = \frac{3}{2}(V_{dg}i_{dg}) \tag{24}$$

$$Q_g = -\frac{3}{2}(V_{dg}i_{qg}) \tag{25}$$

The DC bus voltage control loop was developed based on the power balance principle on both sides of the GSC. So mathematically can be described as shown:

$$V_{dc}i_{dc} = V_{dg}i_{dg} + V_{qg}i_{qg} \tag{26}$$

As the d – axis of the reference frame is oriented to the grid that will make V_{qg} and $i_{qg} = 0$. So, the above equation will be:

$$V_{dc}i_{dc} = V_{dg}i_{dg} \tag{27}$$

But,

$$i_{dc} = i_c + i_1 = C \frac{dV_{dc}}{dt} + i_1 \tag{28}$$

After substitution into the equation:

$$\frac{dV_{dc}}{dt} = \frac{V_{dg}i_{dg}}{C V_{dc}} - \frac{i_1}{C} \tag{29}$$

V_{dc} can be controlled through i_{dg} in case i_1 is used as a disturbance. In this case as can be seen in figure above the DC link voltage and reference DC link voltage are compared with each other. The reference value of DC link voltage is determined by:

$$V_{dc,min} \geq \sqrt{3} V_{gm} \text{ (For SVPWM Switching)} \tag{30}$$

To get the reference value of i_{gd}^* the difference between the voltages is calculated then fed to a PI controller. Also, the reference value of i_{gq}^* is got through the Q_g . The reference value i_{gd}^* and the reference value of i_{gq}^* are compared with the grid current dq – original values (i_{gd} and i_{gq}).

The resulting signal is fed back to the PI controllers to get the reference values of V_{gq}^* and V_{gd}^* . The resulting signals are then turned into the $\alpha\beta$ – reference frame and finally fed to a space vector pulse width modulation (SVPWM) to generate the control pulses.

The PI controller parameters are determined depending on the parameters of the system and the system’s parameters values will definitely change when time passes.

The figure below shows the grid voltage-oriented vector control scheme block diagram which has been implemented on MATLAB / Simulink.

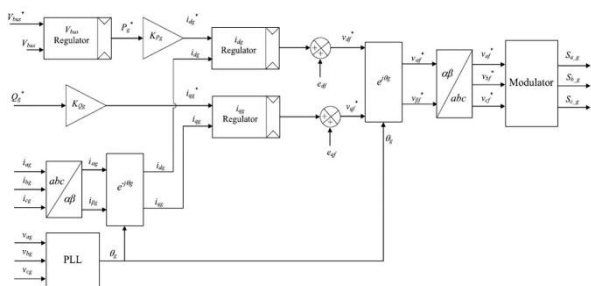


Figure 8: Grid voltage-oriented vector control block diagram

4. Simulation and Interpretation

In this section, the behavior of the DFIG was carried out using the MATLAB/Simulink environment under the DFIG parameters, PI controller gains, and three blade wind turbine model parameters that are given in appendix B. The PI controller is used with its parameters (K and I) that are initially adjusted according to the nominal parameters of the machine [5]. The values of V_{wind} (the wind speed) and Q_g (reactive power at the grid) are the simulation inputs. To verify the validity of the model, 2 cases have been tested. Figure 9 shows the value of reactive power of the grid Q_g which is zero. The figure 10 and 13 show that in an open-loop system, dc bus voltage fluctuation or ripple is very large. To reduce this fluctuation one of the solutions is to increase the DC link capacitor size which is difficult to be applied in real life. The blue line represents the DC link voltage which is 1150 v in the ideal case, and the green line represents the DC link that has been got. The figure 11 and 14 shows the DC link voltage after implementing the grid voltage-oriented vector control. Here the by suitable control of the converter a constant DC voltage value has been got. The blue line represents the DC link voltage which is 1150 v in the ideal case, and the green line represents the DC link that has been got.

a) The Performance of DC-Link Voltage

Table 1: The input parameters case 1.

Values with symbol	Name
$V_{wind} = 7.5$	% Wind Speed (m/s)
$Q_g = 0$	% Reactive Power (VAR)

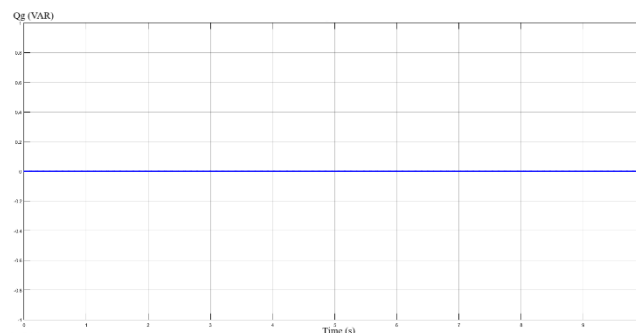


Figure 9: Reactive power of the grid

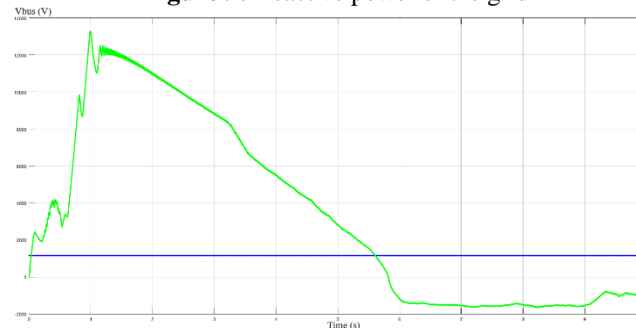


Figure 10: DC-link voltage without GSC control in case 1

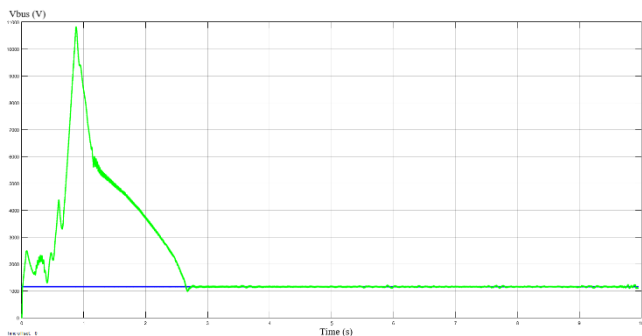


Figure 11: DC-link voltage with GSC control in case 1

Table 2: The input parameters case 2

Values with symbol	Name
$V_{wind} = 11$	% Wind Speed (m/s)
$Q_g = -400e3$	% Reactive Power (VAR)

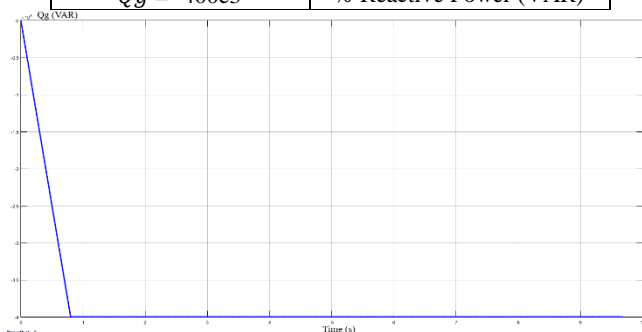


Figure 12: Reactive power of the grid in case.

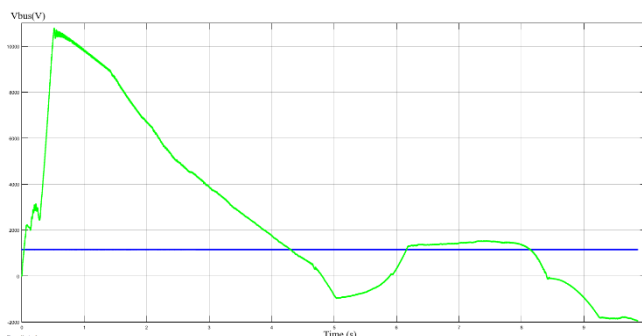


Figure 13: DC-link voltage without GSC control in case 2

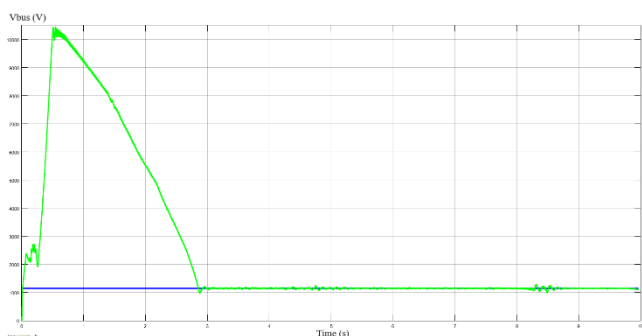


Figure 14: DC-link voltage with GSC control in case 2.

b) Simulation Notes

Between the wind turbine driven DFIG and the grid, a converter is employed to control the power flow from the Wind turbine to the grid. The results in the graphs can be explained in the following two scenarios. In the first scenario, a constant DC voltage value is needed must pass through the GSC for effective power flow and maintain the overall system power factor as a unity by fed reactive power

to the DFIG. From the DFIG parameters, it shows that the DC link voltage is 1150 v and after implementing the control scheme it the 1150 v has been achieved. Second scenario, the grid voltage-oriented vector control scheme is applied to maintain the overall system power factor as a unity by fed reactive power to the DFIG. The reactive power is determined by the grid. From the results can be noticed that the model worked well, and a constant DC link voltage has been achieved.

5. Conclusion and Future Work

a) Conclusion

As mentioned in the previous chapters, nowadays DFIG is used in huge MW wind turbine farms. So, it is very important to consider improving control strategy of it. The most important point needs to be cared of is the regulating the power of the converter because every control method is aiming to regulate the power in different section of the DFIG. The grid voltage-oriented vector control is used to control the rotor side circuit of the DFIG, and it is highly influential on maintaining constant DC link voltage for effective power flow and maintaining the overall system power factor as a unity by fed reactive power to the DFIG.

b) Future Work

In the future, a high-efficiency DFIG with energy storage could be applied. Moreover, it is important in another field that uses the same type of generator with energy storage applications, smart systems, and hybrid systems. Also, other controllers will be used in controlling DFIG such as the neuronal controller that provides a robustness control.

6. Appendices

a) Appendix A

Table 3: List of symbols

P_o	Power of wind
P_m	Output power of WT or Mechanical input power
ρ	Air density 1.225 Kg/m ³
A	Area created by the rotor
V_o	Speed of the wind m/s
C_p	Power coefficient
f_{Stator}	Stator frequency
f_{Rotor}	Rotor frequency
η_s	Synchronous speed
s	Rotor slip
P_{ag}	Air gap power or power provided to the rotor
P_s	The active power of the stator circuit
Q_s	The reactive power of the stator circuit
P_r	The active power of the rotor circuit
Q_r	The reactive power of the rotor circuit
ϕ_{ds}	Flux component of d – axis of the stator
ϕ_{qs}	Flux component of q – axis of the stator
ϕ_{dr}	Flux component of d – axis of the rotor
ϕ_{qr}	Flux component of q – axis of the rotor
L_{ss}	Inductance of the stator
L_{rr}	Inductance of the rotor
L_m	Magnetization inductance
R_s	Effective resistance of the stator
R_r	Effective resistance of the rotor

V_{ds}	The voltage component of the d – axis stator
V_{qs}	The voltage component of the q – axis stator
V_{dr}	The voltage component of the d – axis rotor
V_{qr}	The voltage component of the q – axis rotor
ω	Angular velocity
C	DC link bus capacitor
V_{dg}	The voltage component of the d – axis grid
V_{qg}	The voltage component of the q – axis grid
I_{dg}	The grid current d – axis component
I_{qg}	The grid current q – axis component
L_g	Grid filter inductance
R_g	Grid filter resistance
P_g	GSC grid side input active power
Q_g	GSC grid side input reactive power
V_{dc}	DC link voltage
P_o	Power of wind
P_m	Output power of WT or Mechanical input power
ρ	Air density 1.225 Kg/m
A	Area created by the rotor
V_o	Speed of the wind m/s
C_p	Power coefficient
f_{stator}	Stator frequency
f_{rotor}	Rotor frequency
η_s	Synchronous speed
s	Rotor slip
P_{ag}	Air gap power or power provided to the rotor
P_s	The active power of the stator circuit
Q_s	The reactive power of the stator circuit
P_r	The active power of the rotor circuit
Q_r	The reactive power of the rotor circuit
ϕ_{ds}	Flux component of d – axis of the stator
ϕ_{qs}	Flux component of q – axis of the stator
ϕ_{dr}	Flux component of d – axis of the rotor
ϕ_{qr}	Flux component of q – axis of the rotor
L_{ss}	Inductance of the stator
L_{rr}	Inductance of the rotor
L_m	Magnetization inductance
R_s	Effective resistance of the stator
R_r	Effective resistance of the rotor
V_{ds}	The voltage component of the d – axis stator
V_{qs}	The voltage component of the q – axis stator
V_{dr}	The voltage component of the d – axis rotor

$L_{si} = 0.087e-3;$	% Leakage inductance (stator & rotor) (H)
$L_m = 2.5e-3;$	% Magnetizing inductance (H)
$R_r = 2.9e-3;$	% Rotor resistance referred to stator (ohm)
$L_s = L_m + L_{si};$	% Stator inductance (H)
$L_r = L_m + L_{si};$	% Rotor inductance (H)
$V_{bus} = 1150;$	% DC de bus voltage referred to stator (V)
$F_s = V_s * \sqrt{2/3} / (2 * \pi * f);$	% Stator flux (aprox.)
$f_{sw} = 4e3;$	% Switching frequency (Hz)
$T_s = 1/f_{sw}/50;$	% Sample time (sec)

Table 5: GSC parameters

Values with symbol	Name
$C_{bus} = 80e-3;$	% DC bus capacitance
$R_g = 20e-6;$	% Grid side filter's resistance
$L_g = 400e-6;$	% Grid side filter's inductance
$K_{pg} = 1/(1.5 * V_s * \sqrt{2/3});$	
$K_{qg} = -K_{pg};$	
$\beta = 0;$	% Pitch angle
$C_{bus} = 80e-3;$	% DC bus capacitance
$R_g = 20e-6;$	% Grid side filter's resistance
$L_g = 400e-6;$	% Grid side filter's inductance
$K_{pg} = 1/(1.5 * V_s * \sqrt{2/3});$	
$K_{qg} = -K_{pg};$	

Table 6: PI regulations parameters

Values with symbol
$\tau_{ig} = L_g/R_g;$
$\omega_{nig} = 60 * 2 * \pi;$
$k_{p_idg} = (2 * \omega_{nig} * L_g) - R_g;$
$k_{p_iqg} = k_{p_idg};$
$k_{i_idg} = (\omega_{nig}^2) * L_g;$
$k_{i_iqg} = k_{i_idg};$
$k_{p_v} = -1000;$
$k_{i_v} = -300000;$

Table 7: Three blade wind turbine model parameters

Values with symbol	Name
N = 100;	% Gearbox ratio
Radio = 42;	% Radius
$\rho = 1.225;$	% Air density
$\beta = 0;$	% Pitch angle

b) Appendix B

Table 4: Rotor parameters referred to the stator side

Values with symbol	Name
$f = 50$	% Stator frequency (Hz)
$P_s = 2e6$	% Rated stator power (W) (Active Power)
$n = 1500$	% Rated rotational speed (rev/min)
$V_s = 690$	% Rated stator voltage (V)
$I_s = 1760$	% Rated stator current (A)
$T_{em} = 12732;$	% Rated torque (N.M)
$p = 2$	% Number of pole pair
$u = 1/3;$	% Stator/rotor turns ratio
$V_r = 2070;$	% Rated rotor voltage (non-reached) (V)
$s_{max} = 1/3;$	% Maximum slip
$V_{r_stator} = (V_r * s_{max}) * u;$	% Rated rotor voltage referred to stator (V)
$R_s = 2.6e-3;$	% Stator resistance (ohm)

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