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Modeling and analysis of parallel connected permanent magnet synchronous generators in a small hydropower plant

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Abstract- The simulation of parallel operation of grid connected permanent magnet synchronous hydro generators with damper using MATLAB/Simulink is presented. The mathematical model of the synchronous generator in terms of two axes *d*-*q* variables is used. The hydro turbines connected to each PM generator in a so-called matrix arrangement give input shaft torque to the rotor of each PM generator. Matrix like arrangement of these small turbine generator units allows generation of electric power from waste water in river barrages, but needs parallel operation of the machines. The influence of changing operating conditions like sudden load change, blocking of rotor of a generator and three phase short circuit are investigated for parallel operation of 4 machines. Investigations are done for 300 kVA, three phase, 24 poles, 1.9 kV permanent magnet synchronous generators. All stationary results obtained are verified by analytical calculations.

Keywords- Dynamic Simulation, PMSM, Damper cage, HydroMatrix, Parallel-Operation, Grid-Connected

1 INTRODUCTION

In existing hydropower plants, the energy of water at the overflow of the dam is wasted. A new concept for hydropower plants is proposed by the *VA Tech Hydro, Austria* [1], [2]. Small water turbines (e.g. 300 kW) integrated with generators are arranged in matrix structure called HydroMatrix. For example 2×8, 3×3 or 4×4 turbines (meaning 2 rows of 8 units one above the other (Fig.1)) are integrated in the dam to transform the water energy into electric energy. So far the generators used for these matrix turbines are induction machines (Fig. 1). To get a higher efficiency, the induction machines should be substituted in the future by permanent magnet synchronous machines.

This paper deals with the question of the mutual influence of the generators that are used in parallel in the matrix structure. A dynamic simulation model of the permanent magnet synchronous machine with damper is developed in MATLAB/Simulink. The influence of load changes, disconnection of machines from the grid, different fault conditions like 3-phase short circuit and blocking of the rotor is investigated for the parallel generator operation. Simulink supports the simulation of continuous, dispersed or mixed linear and non linear differential equations systems graphically and is used to investigate continuous and asymmetric working conditions in parallel connection.

Fig. 1. *Jebel Aulia* power plant, *Sudan*
(Source: *VA Tech, Austria*)

2 PMSM with rotor damper

Permanent magnet synchronous machine (PMSM) is a class of synchronous machine which uses high quality magnet material in the rotor to produce the excitation field. It has the characteristics of high efficiency, simple structure and easy to control. The investigated machines have been built as prototypes in small power plant *Agonitz, Austria*. They consist of a slotted stator with the three phase distributed AC winding and the rotor containing not only the permanent magnets, but also a copper damper cylinder [2] for damping the oscillations of the rotor. Small PM synchronous machines operating with stiff grid (fixed voltage and frequency) may start asynchronously via the rotor cage and are pulled into the synchronism by the rotor permanent magnets. The PM generators in matrix are started via the turbine, so the damper cylinder can be reduced in size. Load steps at such PM synchronous machines will cause them to oscillate, but the oscillations will be damped by rotor damper. A 24 pole, 3 phase, cylindrical rotor permanent magnet synchronous machine with damper cylinder (Fig. 2) is constructed as straight flow turbine arrangement. The rotor is fixed to the turbine blades, being operated in water. The stator is sealed and arranged around the turbine rotor.

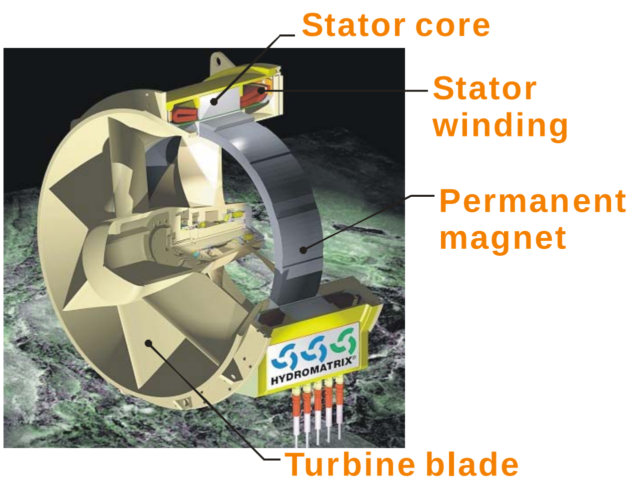

Fig. 2 PM Generator by *VA-Tech Hydro, Austria*

3 Mathematical model of PMSM with damper

The two axis (*d-q*) model is developed for the PM synchronous machine with rotor damper by modifying the mathematical model for the permanent magnet synchronous machine and the synchronous machine with damper cage given in [3]. The coordinate frame is the “two-axes“ or “*d-q*“ coordinate frame which orientates the equations to the rotor reference frame. The transformation from the stator to the rotor reference frame is the *PARK*-transformation. The following assumptions are made for the modelling:

1) The stator m.m.f. is sinusoidally distributed along the air gap,
2) The cylindrical rotor permanent magnets buried below the damper cylinder are considered to generate constant flux linkage with stator winding,
3) The influence of stator slotting on air gap field is neglected
4) Magnetic saturation and hysteresis of iron is neglected.

The following set of equations represents the mathematical model for the PM synchronous machine with damper in *d–q* rotor reference frame:

A) Voltage equations

$$U_d = R_s \cdot I_d + \frac{d\psi_d}{dt} - \Omega_L \cdot \psi_q \tag{1}$$

$$U_q = R_s \cdot I_q + \frac{d\psi_q}{dt} + \Omega_L \cdot \psi_d \tag{2}$$

$$0 = R_D \cdot I_D + \frac{d\psi_D}{dt} \tag{3}$$

$$0 = R_Q \cdot I_Q + \frac{d\psi_Q}{dt} \tag{4}$$

B) Flux linkage equations

$$\psi_d = L_d \cdot I_d + M_{dD} \cdot I_D + \Psi_{PM} \tag{5}$$

$$\psi_q = L_q \cdot I_q + M_{qQ} \cdot I_Q \tag{6}$$

$$\psi_D = L_D \cdot I_D + M_{dD} \cdot I_d + \psi_{PM} \tag{7}$$

$$\psi_Q = L_Q \cdot I_Q + M_{qQ} \cdot I_q \tag{8}$$

C) Torque equation

$$M_e = \frac{3}{2} \cdot p \cdot (\psi_d \cdot I_q - \psi_q \cdot I_d) \tag{9}$$

D) Mechanical angular speed equation

$$\Omega_L = p \cdot \Omega_m \tag{10}$$

E) *PARK’s* transformation equation

The *PARK’s* transformation equations [4] are used to transform the quantities like voltages, currents etc. from 3-phase system (*U*, *V*, *W*) into the system in rotor reference frame (*d*, *q*, *0*). The following transformation matrix (T) equ. is used:

$$\begin{pmatrix} U_d \\ U_q \\ U_o \end{pmatrix} = \begin{pmatrix} \frac{2}{3}\cdot\cos\gamma & \frac{2}{3}\cdot\cos\left(\gamma-\frac{2\pi}{3}\right) & \frac{2}{3}\cdot\cos\left(\gamma-\frac{4\pi}{3}\right) \\ -\frac{2}{3}\cdot\sin\gamma & -\frac{2}{3}\cdot\sin\left(\gamma-\frac{2\pi}{3}\right) & -\frac{2}{3}\cdot\sin\left(\gamma-\frac{4\pi}{3}\right) \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{pmatrix} \cdot \begin{pmatrix} U_U \\ U_V \\ U_W \end{pmatrix} \quad (11)$$

Transformation form (*d*, *q*, *0*) to (*U*, *V*, *W*):

$$\begin{pmatrix} U_U \\ U_V \\ U_W \end{pmatrix} = \begin{pmatrix} \sin\gamma & \cos\gamma & 0 \\ \sin\left(\gamma-\frac{2\pi}{3}\right) & \cos\left(\gamma-\frac{2\pi}{3}\right) & 0 \\ \sin\left(\gamma+\frac{2\pi}{3}\right) & \sin\left(\gamma+\frac{2\pi}{3}\right) & 0 \end{pmatrix} \cdot \begin{pmatrix} U_d \\ U_q \\ U_o \end{pmatrix} \quad (12)$$

Based on the above mathematical equations, a model for PM synchronous machine with damper cylinder connected to a stiff grid is developed using MATLAB/Simulink. The machine is operated as a generator with input as rated shaft torque applied in the form of water flowing over the turbine and permanent magnet flux linkage ψ_{PM} of the magnets embodied in the rotor. Due to high PM flux linkage ψ_{PM} and the "weak" damper cylinder, asynchronous starting torque is not sufficient to overcome PM flux linkage braking. So it is not possible to start the machine from grid without any additional accelerating torque (Fig. 3). For simulation the synchronous machine is started with an accelerating torque equal to 75% rated shaft torque. This may be physically realized by water flowing on the blades of hydromatrix turbine. This accelerating shaft torque is applied for first 3 seconds and then rated shaft torque is applied.

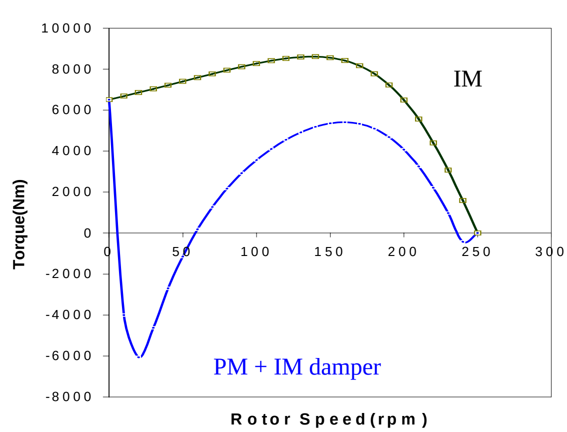

Fig. 3 Calculated speed vs torque characteristics for induction machine IM and PMSM

As an alternative, a turbine P controller can be used. The turbine is accelerated by the water flow, with open generator terminals. After reaching the machine synchronous speed the machine is connected to grid. Fig. 4 shows the schematic for such turbine P controller.

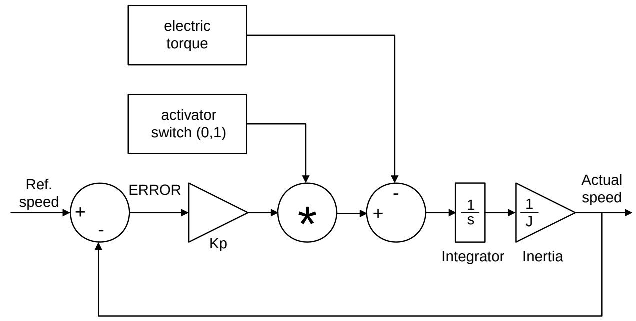

Fig. 4 Schematic for the turbine P controller

4 MODEL VERIFICATION

The accuracy of the developed model is verified in two steps by comparing with stationary analytical calculations.

A) Machine as an induction machine (ψ_{PM} = 0), considering only rotor damper cylinder.

Following stationary parameters are verified by comparing the simulation result with the analytically calculated values.

Table. 1 Verification as an induction machine

Data verified	Analytical value	Simulation value	Diff. %
Static breakdown torque	8616 Nm	8609 Nm	0.08
No load current	165.18 A	165.1 A	0.05
Slip at load of 5000 (Nm)	0.14	0.14	0.00
Current at load of 5000 Nm	176.08 A	176.18 A	-0.07

B) As a synchronous machine

Table. 2 Verification as synchronous machine

Data verified	Analytical value	Simulation value	Diff. %
Rated current	74.23 A	73.3 A	0.2
Rotor speed	250 rpm	250 rpm	0.00
Torque	-11.2 kNm	-11.2 kNm	0.00

The simulation results and the analytically calculated values show a good accordance for a single machine. The model is now extended to simulate the parallel operation of 4 permanent magnet synchronous generators. The generators are connected to the stiff grid via a 100 m cable as shown in Fig. 5.

(Cable resistance (100 m) R_C = 0.0178Ohm;
Cable inductance (100 m) L_C = 0.0274mH)

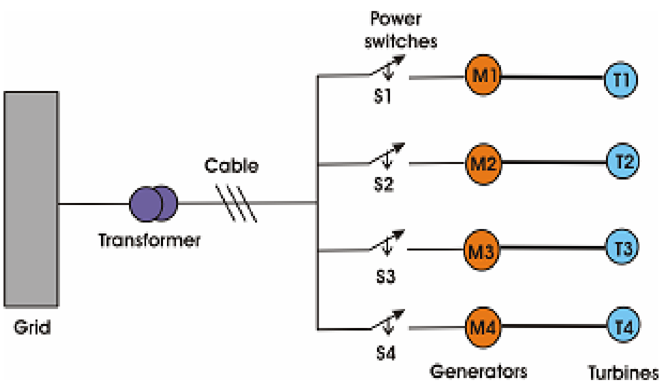

Fig. 5 Schematic for parallel operation of grid connected PM synchronous generators.

5 SIMULATION RESULTS AND ANALYSIS

A) Sudden load change on generator M1

Fig. 6 shows the dynamic curve for rotor speed of machine M1. After start up with 75% rated torque, the machine M1 is loaded with twice the rated load at instant t = 10s. Fig. 7 and Fig. 8 show the influence in rotor speed of this sudden load increase on other machines M2, M3 and M4 in parallel and zoomed speed view respectively. It is observed that fluctuation in speed of M1 is maximum and that of the other machines is negligible.

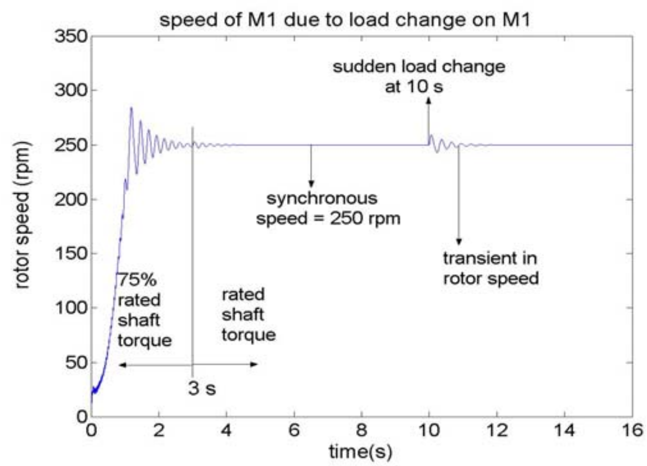

Fig. 6 Calculated speed of machine M1

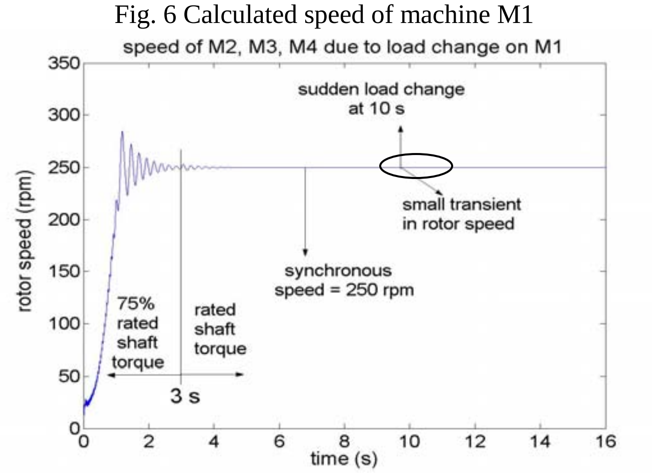

Fig. 7 Speed of machine M2, M3, M4

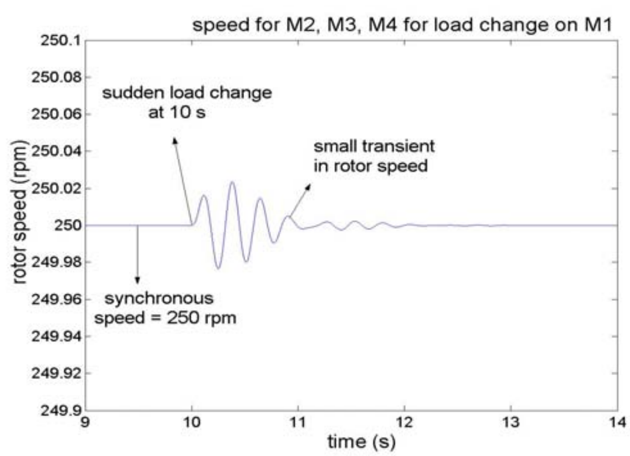

Fig. 8 Zoomed view of Fig. 7

B) Blocking of rotor of generator M1

Fig. 9 shows the calculated speed of machine M1, when rotor of machine is blocked for example due to some wood piece strucking to the turbine blades, reducing its speed immediately to zero at instant t =

15s. Here the machines are started with turbine P controller. Fig. 10 and 11 show the speed for the other machines M2, M3 and M4 in parallel and the zoomed speed view respectively. Rotor speed for these machines stabilizes to rated speed of 250 rpm after few transients.

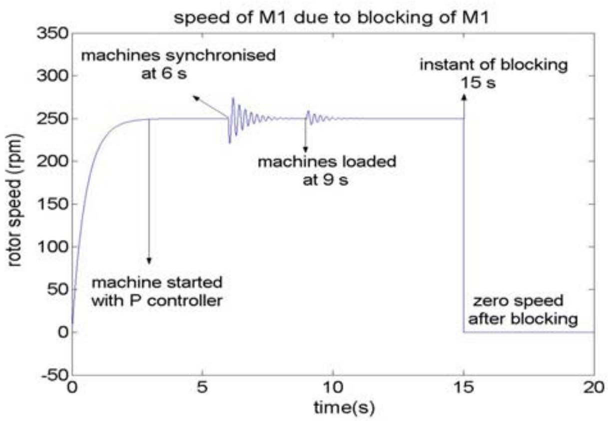

Fig. 9 Calculated speed of machine M1

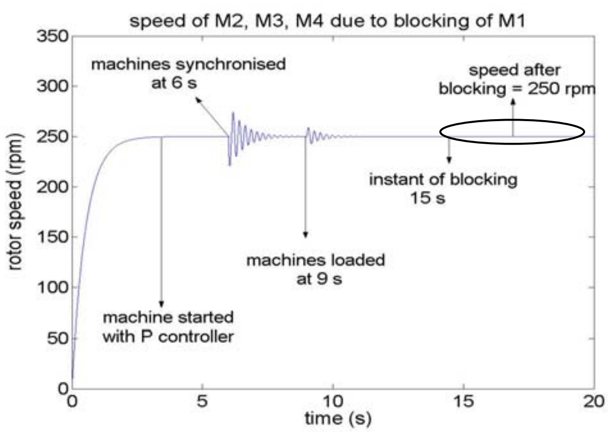

Fig. 10 Speed of machine M2, M3, M4

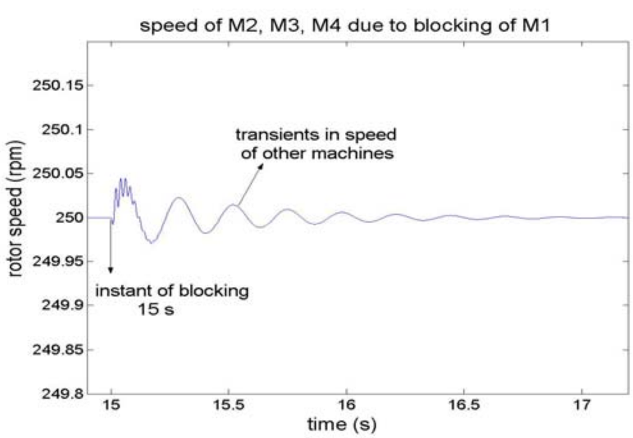

Fig. 11 Zoomed view for Fig. 8

Fig. 12 shows the torque for machine M1. It is clear that due to blocking, the machine M1 is de-synchronized and its torque oscillates with very high value around the rated torque of -11.2 kNm. Fig. 13 and Fig. 14 show the corresponding transient torque curves for machines M2, M3 and M4 in parallel. The torque for these machines undergoes the electrical transients of grid frequency just after the blocking with very short time constant, which are superimposed on the long time constant mechanical transients.

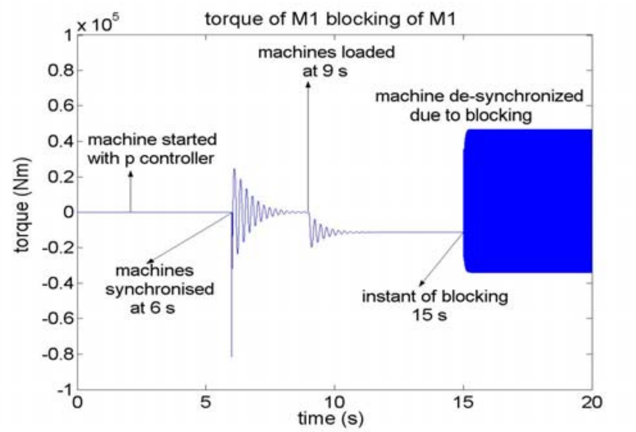

Fig. 12 Calculated torque for machine M1

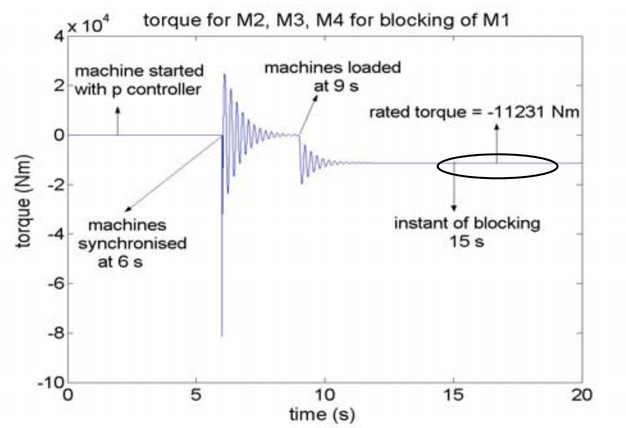

Fig. 13 Torque for machines M2, M3, M4

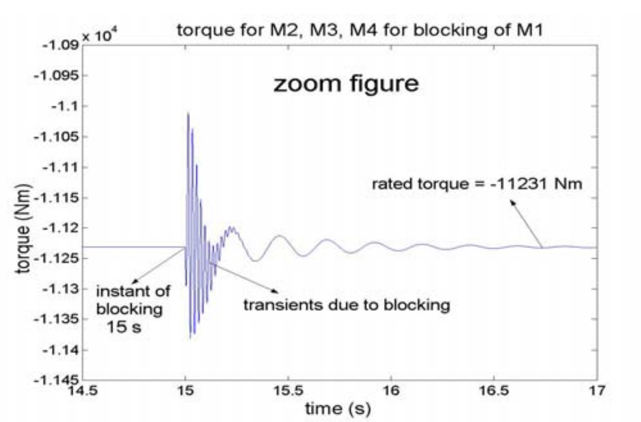

Fig. 14 Zoomed view of Fig. 13

6 CONCLUSIONS

This paper addresses the method of modeling and simulation of parallel operation of PM synchronous generators with damper cylinder being employed as hydro generators. For transient simulations MATLAB/Simulink is used. The parallel operated generators are of rather small power (300kW per unit), being arranged as a so called "hydro matrix" turbine in river barrages. The influence of disturbances in operating conditions like blocking of rotor and sudden load change of one machine, and its effect on the other parallel generators is simulated. The fluctuations caused in speed and torque of these parallel generators due to these disturbances are well within the tolerable limits. Thus parallel operated PM synchronous generators can be considered as a suitable replacement for induction generators in hydromatrix turbine arrangement for future projects.

7 Nomenclature

I	[A]	electric current
L	[H]	self inductance
M	[H]	mutual inductance
M	[Nm]	torque
p	[-]	number of pole pairs
t	[s]	time
U	[V]	electric voltage
ψ	[Vs]	magnetic flux linkage
Ω_L	[1/s]	rotor reference angular frequency
Ω_m	[1/s]	mechanical angular speed
γ	[rad]	circumference angle

SUBSCRIPTS

d	direct axis quantity
D	damper winding in direct axis
e	electric
m	mechanical
q	quadrature axis quantity
Q	damper winding in quadrature axis
s	stator quantities
PM	permanent magnet rotor

8 SIMULATION DATA

Stator voltage	U_s	1905 V
Rated current	I_s	52.5 A
Synchronous voltage	U_p	1917 V
Frequency	f	50 Hz
Number of poles	$2p = 24$	
Power factor	$\cos\varphi$	0.98
Rotor inertia	J	397.71 kgm^2
Main reactance	X_h	7.25 Ohm
Synchronous reactance	X_s	16.26 Ohm
Stator resistance	R_s	1.226 Ohm
Rotor resistance	R'_r	2.03 Ohm
Rotor reactance	X'_r	0.49 Ohm
Permanent magnet flux	Ψ_{PM}	8.628 Wb
Rated torque	M_N	11.23 kNm
Rated power	P_N	294 kW

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