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Investigation of Dual-Inverter-Fed Drives for Permanent Magnet Synchronous Motor with Winding Switching

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***Abstract*—A new method for Flux Weakening (FW) of Surface Permanent Magnet (SPM) motor is proposed. This method is termed a dual inverter-fed drive system with winding switching and can significantly extend the field weakening speed range of SPM. As a particular design example, the proposed method can increase the maximum output of a SPM motor by 73% without changing the battery ratingS, and can extend the constant power speed up to about 4 times the base speed without using demagnetizing current. The stator winding arrangement which allows the motor operate in various speed operations is discusses in this paper. The simulation and analysis of the drive system with respect to a SPM motor is implemented, and the simulation results show the motor operates reliably and flexibly by the proposed method.**

Keywords—PM motors; field weakeing; high speed operation; winding switching

I. Introduction

Among various types of ac motors, the Permanent Magnet Synchronous Motor (PMSM) has received widespread acceptance in industrial applications due to its advantages, such as high efficiency, high torque-to-current ratio, low noise and robustness [1]. For the electric vehicle (EV) application of a motor drive, wide speed range operation usually is required. In addition, the voltage amplitude of the vehicle battery tends to change during different load power condition [2]. As the motor speed is sufficiently high, the controller may need to force the machine into the Field Weakening (FW) region in order to achieve the demanded speed. For a vector controlled PMSM drive, the q-axis current (i_q) command is proportional to the demanded torque and the d-axis current (i_d) command is set to achieve minimum current amplitude operation in the constant torque limit region [3]. Furthermore, as the FW control is applied, the commanded current vector is located at the intersecting point of the demand torque equation and the voltage circle to achieve minimum current amplitude operation as well. That is to say, i_d (demagnetizing current) is used to oppose the flux from the magnets and the i_q. The traditional FW method is accomplished by applying a large

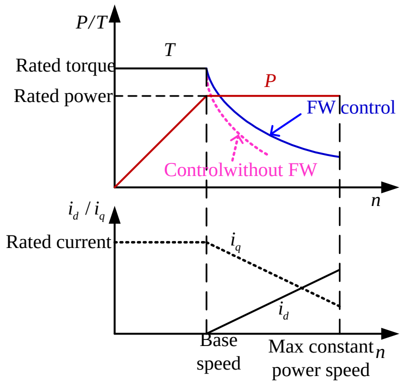


Fig. 1. Traditional operating strategy for control of a PMSM

demagnetizing current in d-axis, is a way of weakening the air-gap magnetic field and enlarge the constant-power operating range. However, FW obtained by this method increases the winding copper losses and risks irreversible demagnetization of the Permanent Magnets (PMs). The ability of demagnetizing component various with the design of the motor and a maximum speed beyond the point at which FW begins can typically only be extended to about twice or three times the onset of FW, which normally does not satisfy the FW range that most EV's require. Fig. 1 shows the traditional operating strategy for PMSM.

It has been a long-lived objective to develop an advanced motor drive that combines the advantages of dc motor drive of good speed controllability as well as the ac motor drive of high reliability, robustness. It should be noted that, the connections of windings of an ac motor are flexible. The ac motor stator windings can be rearranged by splitting the stator windings into two branches, hence, making the control of motor operation more flexible. A new electrical two-speed propulsion system for induction motor is proposed in [4]. The two-speed propulsion is achieved by connecting the motor stator windings in series for staring an EV and then switching the windings to parallel connection for normal speed operation, which produces a high starting torque yet maintains the inverter within its rated power range. A new method for FW by winding switching in SPM motors has been demonstrated in [5], in which the usual three phase windings are separated into two portions and each portion is connected to an inverter. The stator windings are connected in parallel for normal speed operation. The windings are then switched to reverse series for high speed operation. And the maximum Constant Power Speed Region (CPSR) achieved using the technique without using demagnetizing current is 3.73:1.

In this paper a new technique for SPM is proposed and is called dual inverter-fed drive system with winding switching. The proposed technique is aimed to double the maximum output power without changing the rate of battery rate, to extend the constant power speed of the motor about 4 times the base speed without using demagnetizing current, and to make the drive system flexible, robust, and reliable.

II. The Dual Inverter-Fed Drive System With Wingding Switching

A. *The Structure of the System and Control Method*

Fig. 2 shows the diagram of the proposed drive system. The three phase motor windings are separated into two portions, P1 (left half portion on Fig. 2) and P2 (right half portion on Fig. 2). Both ends of the windings are brought out of the motor, resulting 12 leads. Three of the leads from P1 are connected to one inverter and three of the leads from P2 are connected to another inverter. The rest 6 leads are connected together in each phase with 6 diodes as shown in Fig.1. The dual-inverter drive system controller is used to give signals to two switches (S1 and S2), a thyristor (SW1) and 12 IGBTs.

The operation of SPM motor is divided into three regions according to speed and torque, and they are: the Low-speed region, Middle-speed region and High-speed region. The basic principle of the drive system is:

Low speed: SW1 and S2 are off, S1 is on, and the right half of the 6 IGBT are inactive and only the left 6 IGBT are used. The upper three IGBTs of the right part along with the upper three diodes form a Y-connection for Winding 2.

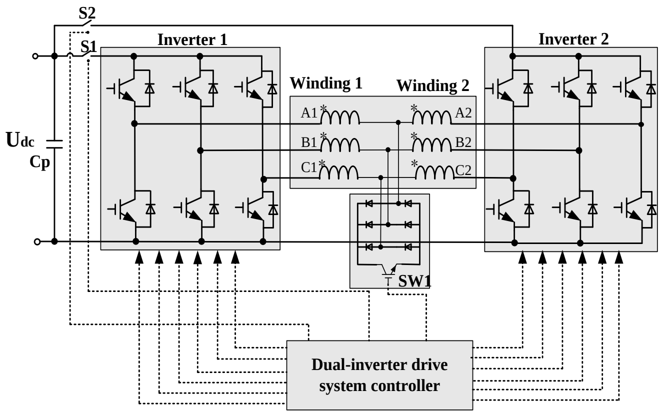


Fig. 2. The dual inverter-fed drive system

Middle speed: S1 and S2 are on, SW1 is off, the dual inverters are cascaded, and the control of 12 IGBT is similar to 3-level SVPWM.

High speed: SW1 and S1 are on, S2 is off, only A1, B1, C1 work, inverter 1 is active while inverter 2 is inactive.

B. *Operation Principle of Dual Inverter*

Stemmler and Guggenbach [6] through their extensive research have first demonstrated that three-level voltage vector can be synthesized with the dual-inverter scheme comprising of two conventional 2-level inverters, connected at either ends of the open-end winding induction motor. Many researchers have carried out investigations on this dual-inverter configuration and presented several sine-triangle and space vector based PWM switching techniques for achieving multi-level inversion [7].

There are 64 space phase combinations possible from the drive scheme of Fig. 3. But due to the open-end winding structure for motor, the drive scheme of Figure can introduce a substantial number of common-mode currents in the motor phase windings. A detailed analysis of common-mode contribution from various space phase combinations is presented in [8], and the third harmonic contributions from the space-phase combinations is shown in Table I.

So, by using those combinations without common-mode voltage, the operation of dual inverter can be realized, and only one dc voltage source is need. For the convenience of realizing DSP control, the combinations 13’, 24’, 35’, 4’6, 51’,62’ are utilized, which comprise space vectors OS, OH,

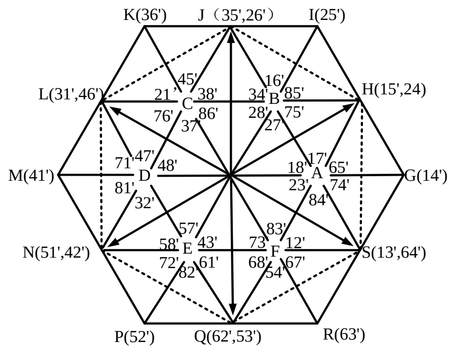


Fig. 3. The space vector and combinations of dual 2-level inverter

TABLE I. Thrid Harmpnic Contributions from the Space-phaser Comtributions

$-V_{DC}/2$	$-V_{DC}/3$	$-V_{DC}/6$	0	$V_{DC}/6$	$V_{DC}/3$	$V_{DC}/2$
8,7’	8,4’	8,5’8,3’	8,8’ 5,5’ 5,3’	5,8’3,8’	4,8’	7,8’
	8,6’	4,4’3,4’	3,5’ 3,3’ 4,4’	4,5’4,3’	6,8’	
	8,2’	8,1’5,6’	5,1’ 3,1’ 4,6’	4,1’1,8’	2,8’	
	5,7’	5,2’3,6’	4,2’ 1,5’ 1,3’	6,5’6,3’	7,5’	
	3,7’	3,2’4,7’	6,4’ 2,4’ 1,1’	2,5’2,3’	7,3’	
	1,7’	1,4’1,6’	6,6’ 6,2’ 2,6’	7,4’6,1’	7,1’	
		2,7’1,2’	2,2’ 7,7’	2,1’7,6’		
		6,7’		7,2’		

OJ, OL, ON, and OQ, besides that, combinations 77'and 88' are chosen to compose zero vector. The maximum linear magnitude of the output AC voltage is VDC (DC bus voltage), which is 1.732 times that when using a traditional 2-level inverter.

C. Operation Principle of Drive System

A brushless surface permanent magnet motor is considered as a simulation drive motor in this paper. Fig. 4 shows the cross-section and the basic dimension of the motor.

Fig. 5 shows the lap winding configuration of phase A in which the slot-pitch angle is 30^o and the number of slots per phase is 2. Phase A contains a1, a2, a3 and a4. The per unit value of induced EMF of 4 coils can be expressed as:

$$E_{a1}=e^{-j\frac{\pi}{6}} \qquad E_{a2}=1 \qquad E_{a3}=1 \qquad E_{a4}=e^{j\frac{\pi}{6}} \qquad (1)$$

One can define $|E_{As}|$ as the EMF of phase A when SW1 is off and SW2 is on in which case a1, a2, a3, a4 are connected in series. When Sw1 is on and SW2 is off, only a1 is connected in the circuit. So

$$ratio=\frac{|E_{A1}|}{|E_{An}|}=\frac{1}{4\times\cos(\frac{\pi}{12})}=\frac{1}{3.732} \qquad (2)$$

This result means that with the same DC source and inverter, by winding switching, the maximum no-load speed can be increased to 3.732 times the base speed without using demagnetizing current. Using the same DC bus voltage, the magnitude of maximum line voltage of dual inverter is 1.732 times of that of single one. So, the basic control method is described as follows:

Firstly, the rotor position and motor speed can be obtained by means of a position sensor, and the motor speed then used to determine the operation mode of the overall drive system. The dual inverter drive system controller is used to determine whether to open or closed S1, S2 and SW1, to determine the system works in single inverter or dual inverter mode and to determine the id by Maximum Torque Per Ampere (MTPA) or FW.

When speed is below n_1 ,the system operates in the Low speed area and the dual inverter drive system controller gives signals to close S1 and open S2. The winding switch SW1 is open, and the control ensures the upper three IGBTs of inverter 2 are on, which creates a wye for Winding 1 and Winding 2 with the two windings connected in series. Inverter 1 supplies power to the circuit, and the control signals of the six IGBTs of inverter 1 can be obtained by traditional SVPWM methods. And the system control method is i_d = 0, which is also the MTPA of a surface mounted PMSM.

When the motor speed is between n_1 and n_2, the drive system operates in the middle speed condition. The drive system controller issues signals for closing S1 and S2, and the winding switching SW1 is open. The two inverters operate in cascade and the two windings are connected in series. The control signals of the 12 IGBTs of inverter 1 and inverter 2 can be developed by the dual inverter SVPWM method. Also, the system control method is gain i_d = 0, which is also the MTPA of a surface mounted PMSM.

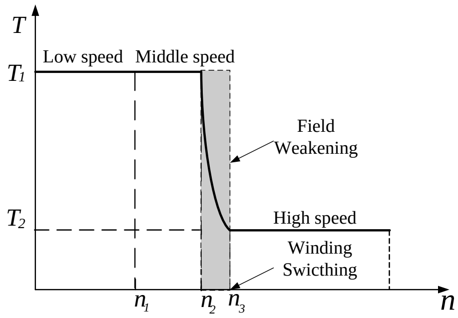


Fig. 4. The theoretical prediction of the drive system

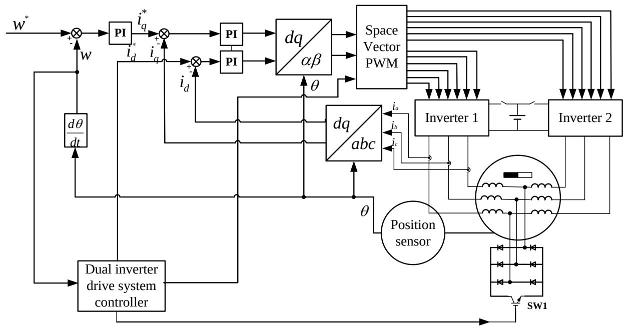


Fig. 5. The strategy of dual inverter drive system

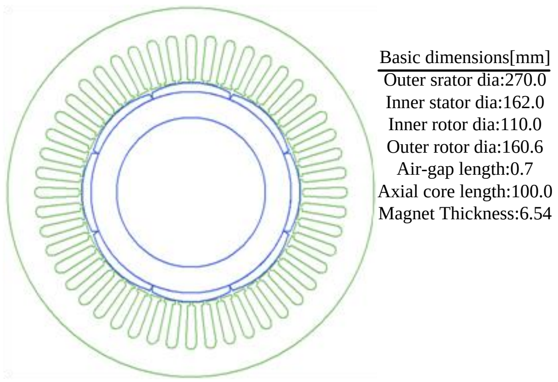


Fig. 6. Basic dimension of the drive motor

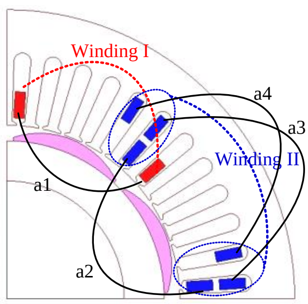


Fig. 7. Two layer lap winding of stator phase A

When speed is faster than n_2 , the control method no more demands i_d=0, but employs field weakening control. The output torque will now become smaller. When speed reaches n_3 , the output torque is the same as the maximum output torque of Winding 1, and the system works in the High speed area. It is now time for winding switching. The dual inverter drive system controller provides the signal to close S1 and open S2, and the winding switching SW1 closes, which forms a wye for Winding 1, and only Winding 1 functions, Winding 2 is shorted. Inverter 1 supplies power to the circuit, Inverter 2 is in idle, and the control signals of the six IGBTs of inverter 1 can be obtained by traditional SVPWM methods. The system control method is $i_d = 0$,, which is also the MTPA of a surface mounted PMSM. To increase the use ratio of inverter, it can also operate in two modes. In this situation, the two inverters work in parallel, the dual inverter drive system controller gives the signal to close S1 and S2, and the winding switching SW1 closes, which forms wye connections for both Winding 1 and Winding 2. The two inverters now operate independently. Fig. 6 shows the theoretical prediction of drive system and

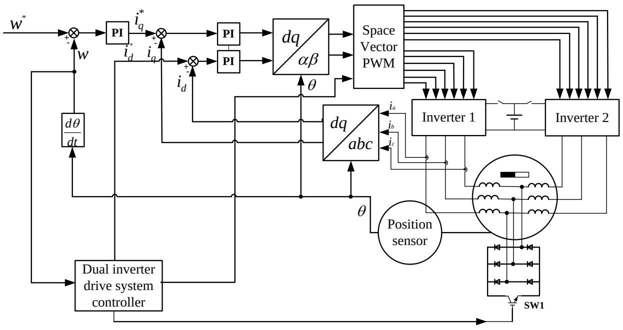


Fig. 7 shows the strategy of dual inverter-fed drive system.

III. Modeling and Simulation

The individual inverter-fed and dual inverter-fed driver system for a SPM motor with winding switching has been established. Simulink is used to characterize the SVPWM control system. Co-Simulation of MATLAB/Simulink and Simplorer is put into use. Simplorer is used to establish the drive system model, and signals for opening or closing 12 IGBTs obtained from Simulink. Maxwell is used for designing the motor.

Fig. 8 shows the response during the transition from the Low-speed region to Middle-speed region. The command speed is 1200 rpm (the turning point n_1); the load torque is 250 Nm (rated load). Switching time is 0.3s, the output power is 32.4 kW. As can be seen in Fig. 8, the motor speed reaches the command speed quickly in about 0.2s. The torque ripple is limited to 5% which is very small, and d-axis current is 0A. After switching, the speed drops slightly and then reaches the command speed quickly in about 0.05s, the torque ripple is limited in 5%, and d-axis current remains at -73A.

Fig. 9 shows the response during operation from Middle-speed region to the FW region. The command speed is 2200 rpm (the turning point n_2); the load torque is: t = 0s: 250 Nm, t = 0.25s: 100N.m. Switching time is 0.25s. The output power before switching is 57.6kW, which is 1.78 times the rated power.

As can be seen in Fig. 9, the motor speed reaches the command speed quickly in about 0.22s, the torque ripple is limited in 5% which is very small, and d-axis current is 0A.

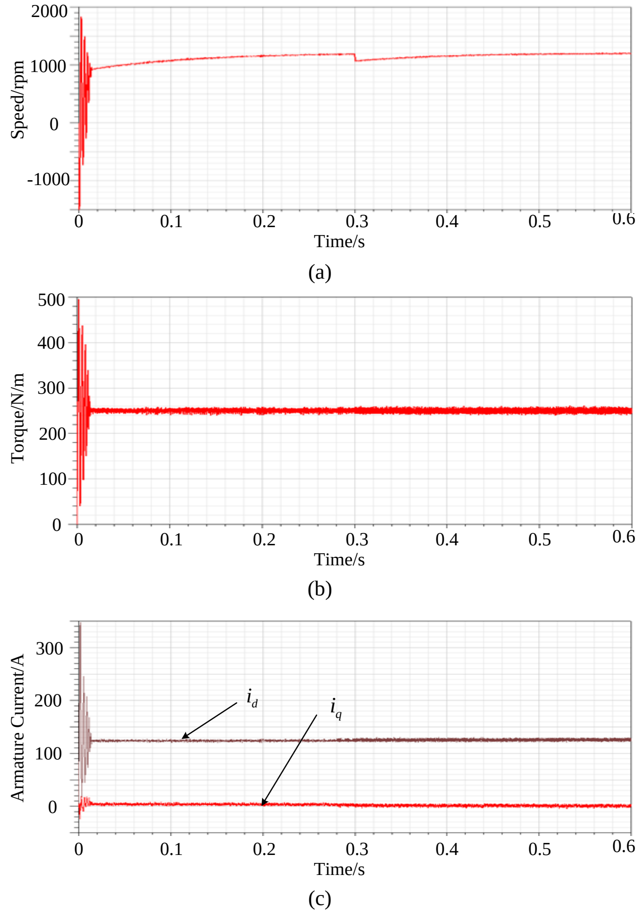
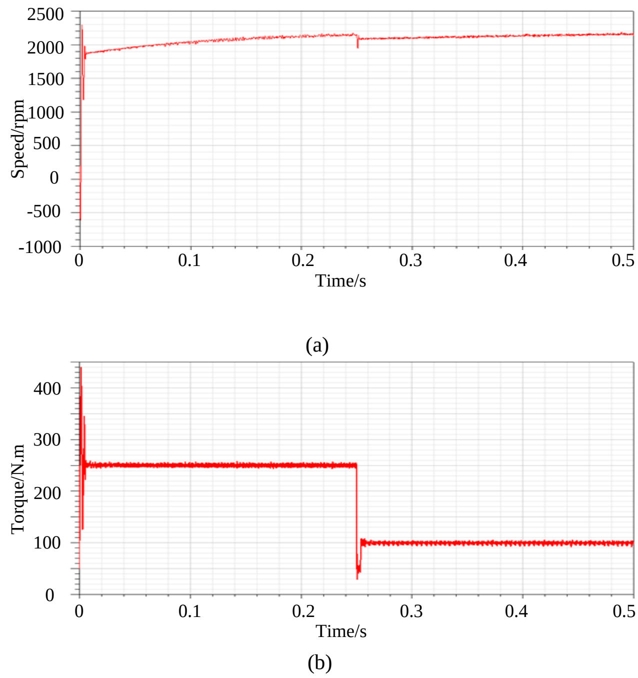
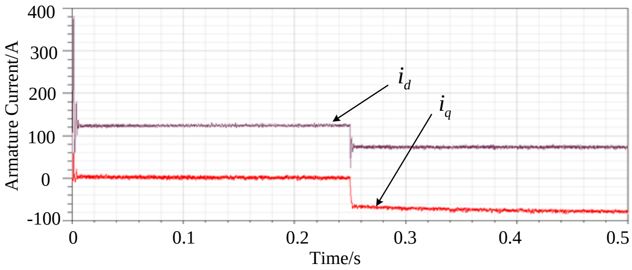


Fig. 8. Low speed region to Middle speed region.
(a) Speed.(b) Torque.(c) Armature current.



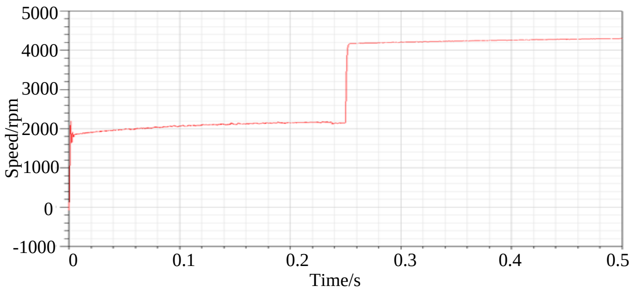
The q-axis current is almost 125A. After switching, the speed drops slightly and then reaches the command speed quickly. The torque ripple is limited to 5%, and d-axis current is maintained at -71A and the q-axis current remains at 80A.

Fig. 10 shows the response to the operation from the FW region to the High-speed region. The command speed is: t=0s: 2200 rpm (the corner point n_3), t=0.25s: 4400 rpm (3.7 times base speed without using demagnetizing current); the load torque is 63N.m. Switching time is 0.25s.

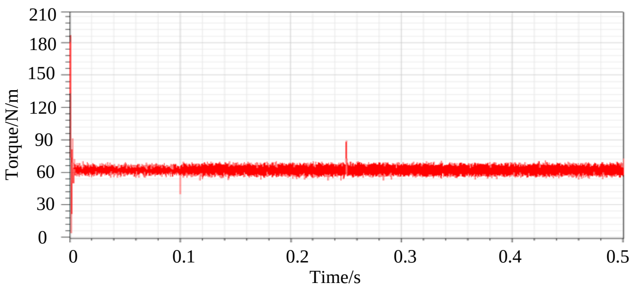


(c)

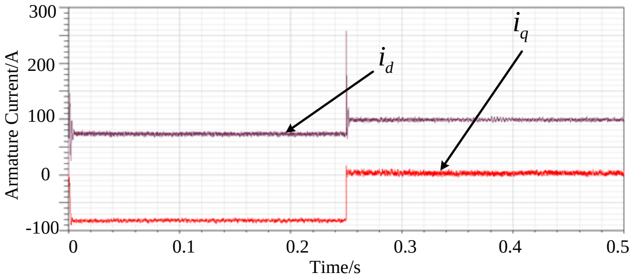
Fig. 9. Middle speed region to FW region.
(a) Speed.(b) Torque.(c) Armature current.



(a)



(b)



(c)

Fig. 10. FW region to High speed region.
(a) Speed.(b) Torque.(c) Armature current.

As can be seen in Fig. 10, the motor speed reaches the command speed in about 0.18s, the torque ripple is limited in 10% which is somewhat larger than the other regions. This result may be because the PI is not set accurately. The d-axis current is -79A, q-axis current is 58A. After switching, the speed increases rapidly and reaches the command speed in about 0.1s, the torque ripple is limited in 10%, and d-axis current keeps 0A while the q-axis current eventually remains at 100A.

As can be seen in the above simulation results, when starting the motor or increasing speed, the phase current and the output torque will rise in a short time, and the peak current is serious. Because the modeling tool is a Co-Simulation System, it is difficult to add current limiting is the simulation. For use in an actual application, the current should be limited by software or hardware.

IV. CONCLUSION

The proposed dual inverter-fed drive system with winding switching has provided a convenient way of extending the operation speed and maximum output power of pm motor. The analysis and simulation results has shown that the maximum output power is extended about 1.7 times the traditional drive system without changing the dc bus voltage, and the constant power speed of the motor is increased about 4 times the base speed without using demagnetizing current. Moreover, the drive system has potential fault tolerant performance.

APPENDIX

TABLE II MACHINE SPECIFICATION AND PARAMETERS

Base speed	1200rpm
Rated torque	250N.m
DC Bus Voltage	400V
Line Curret	70A
Stator slots	48slots
Number of pole pairs	4pairs
Stator turn per coil	8turns
Stator phase resistance	0.1Ω
D and Q axis inductance	3.98mH

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