

Self-Excited Wound-Field Synchronous Motors for xEV

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ABSTRACT

Compact, high efficiency and high reliability are required for an xEV motor generator. IPM rotors with neodymium magnets are widely applied for xEV motors to achieve these requirements. However, neodymium magnet material has a big impact on motor cost and there is supply chain risk due to increased usage of these rare earth materials for future automotive xEV's. On the other hand, a wound-field rotor does not need magnets and can achieve equivalent performance to an IPM rotor. However, brushes are required in order to supply current to the winding coil of the rotor. This may cause insulation issues on xEV motors which utilize high voltage and high currents. Therefore, it is suggested to develop a system which supplies electric energy to the rotor field winding coil from the stator without brushes by applying a transformer between stator coil and rotor field winding. Specifically, add auxiliary magnetic poles between each field winding pole and wind sub-coils to these poles. The magnetic flux generated from the stator induces a field current in the sub-coils. Rectifying the induced current by a diode enables applying direct current to the field windings of the rotor. This paper confirms the equivalent performance between an IPM rotor and wound-field rotor by FEM simulation.

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INTRODUCTION

These days, the automotive industry has two main challenges on energy and environment. In particular, regulations about fuel consumption and CO₂ emissions are becoming more severe. For leading regulations, the EU members and the Council of Europe (CE) showed the target to reduce CO₂ emissions to less than 95 g/km by 2021. To deal with these issues, the automotive industry is trying to develop technologies which reduce CO₂ emission by improving fuel efficiency. Hybrid Electric Vehicle(HEV), Plug-in Hybrid Vehicle and Battery Electric Vehicle(BEV) which nowadays are called "xEV", emits very low or no CO₂, are latest trends of technology development. These vehicles can reduce CO₂ emission greatly when driven with electric motors. Currently Interior Permanent Motors (IPM) have been essential and frequently adapted as electric motor for xEVs, because of its merits: smaller size, lighter weight and higher efficiency. However, IPM for vehicle traction motor requires large amounts of rare-earth magnet. We may face a serious situation of material price fluctuations and unstable supply chain as global demand for xEV expands. In addition, high speed and high torque IPM generates more than 1000V of back-EMF which requires higher breakdown voltage capability for inverter switching device. This is a disadvantage to high voltage resistance and cost of devices. Since the power source gets higher voltage, boosting loss and cost for boosting will also increase. Whereas, IPM has no-load losses and other losses caused by current for weakening magnetic field so that inverter can operate IPM under high back-EMF condition. Thus IPM has certain risks and negative factors by utilizing rare earth magnet. Therefore, study for using no rare earth magnet was conducted to avoid these risks which might be a huge problem for xEV future expansion of market demand.

PRE-STUDY FOR MOTOR TYPE SELECTION

Table 1 shows typical automotive traction motor types, induction motor and synchronous motor. Synchronous motors have different rotor magnetic field excitation types such as IPM, wound-field or reluctance. An internal study shows induction motor has 1.5 times larger volume and half torque compared to synchronous IPM under same input conditions. In this paper, a more detailed comparison has been done for these three types of synchronous motors.

Table 1. Comparison of motor type

	Asynchronous Motor	Synchronous Motor		
	Induction	IPM	Wound-field	Reluctance
Size	1.5*	1.0*	(Studied in this paper)	
Performance	0.5*	1.0*		

*Assumed IPM performance/size as 1.0

Synchronous motors (IPM, Wound-field, and Reluctance) specifications are shown in Table 2. These three type of rotor with same size stator (O.D. 120mm x core stack 66mm) and same stator design are compared. IPM type is an in-house example of 10kW output IPM. Wound-field rotor has standard pole structure and Reluctance rotor has similar pole design as Wound-field rotor without coils. These performances are compared by potential of maximum torque and maximum power under same input voltage/current. Wound-field rotor has 25 coil turns at each pole.

Table 2. Parameters for synchronous motor comparison study

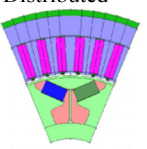
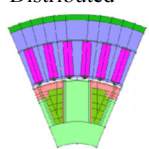
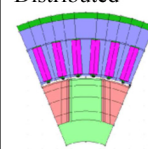
	IPM	Wound-field	Reluctance
Structure	Distributed 	Distributed  Poles + Coils	Distributed  Poles
Voltage	280Vdc	←	←
Current	150Arms	←	←
Size	D120×66	←	←
Remark	Magnet Flux	25turns/Pole	

Figure 1 shows speed-torque performance of three types of synchronous rotor. Wound-field rotor performance has been simulated with 4 different field current condition, 40 to 70A (2000-3500AT). Result shows Reluctance rotor has only 50% torque of that of IPM rotor. Wound-field rotor can generate equivalent torque as IPM rotor at 2500-3000AT field current. Therefore, performance target is set for wound-field rotor in Table 3 and is studied optimal design parameters. In case of target field strength 3000AT and a space factor for stator slot 60%, current density at field winding coil is 15A/mm². In this case, liquid cooling system must be required based on in-house study. Next study is the method of supplying field current to rotor coils.

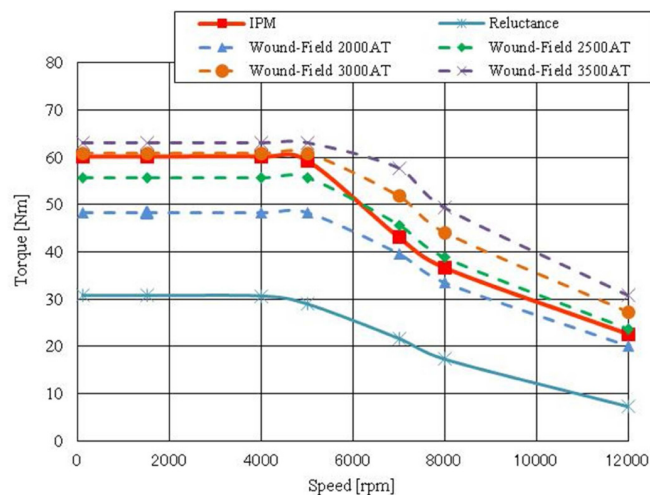


Figure 1. Speed-Torque characteristics of three types of synchronous motor

Several ideas to supply current to rotor coils are shown in table 4. First, standard type is a continuous contact supply method by slip-ring and brush. This method has certain concern for high voltage insulation since these traction motors need to be used under high voltage and liquid cooling. Next idea is to fix field coil and to rotate only rotor core steel, which can be realized by claw pole type rotor. However, claw pole type needs intermediate rotor between stator and fixed field coil, so additional air gap is required. This additional gap causes torque reduction due to the flux leakage at air gap in high flux density operation such as xEV motoring mode. In addition, motor size gets larger because of intermediate rotor structure. On the other

hand, wireless supply field current by using a transformer needs at least 100W power supply. Thus, additional stator and rotor is required only for supply field current.

Table 3. Parameter for wound-field motor study

	IPM	Wound-field
Voltage (DC)	280V	←
Current (rms)	150Arms	←
Torque	60Nm	←
Torque Ripple	± 6% @Max torque	←
Stator	O.D	D120
	I.D	D80.2
Rotor	O.D	D78.8
	Magnet	Nd
	Coil turns	-
	Current density	15A/mm ²
	Space Factor	60%
	Cooling	Liquid cooling

Table 4. Comparison for Wired and Wireless power supply method

	Wired power supply		Wireless power supply	
	Brush	State excitation	Transformer excitation	Direct excitation from stator
Excitation method	Brush and slip ring	Separated claw pole rotor	Transformer	Stator coil and Rotor coil
Merit	High capability of power transfer	Remove brush by fixing field coil	Brushless	No additional subcomponent part
Demerit	Wearing of brush and ring. Debris powder	Lower efficiency due to additional gap between stator/rotor	Low capability of power transfer. Large volume	Ripple caused by interference b/w field excitation and output
Performance	○	○	○	○
Size	△	×	×	◎
HV Resistance	×	○	○	○
Cooling	×	○	○	○
Reliability	×	○	○	○
Tq Ripple /NVH	○	○	○	△
Rotor winding excitation	○	○	○	△
Total	×			

Consequently, excitation rotor field coil directly from stator coil is suggested. Wound-field type can be considered as composing a transformer circuit between the stator and rotor. Conceivable concern is excitation method and magnetic impact against high magnetic excitation.

Figure 2 is showing the concept of Direct-excitation-method for rotor winding. There is one kind of transformer composed by stator winding, rotor winding, stator core and rotor core. This concept can create a field current in the rotor winding by harmonic current superimposed with stator current. Harmonic current induces current to the rotor winding and this induced current can be used as field current after rectified by the diode.

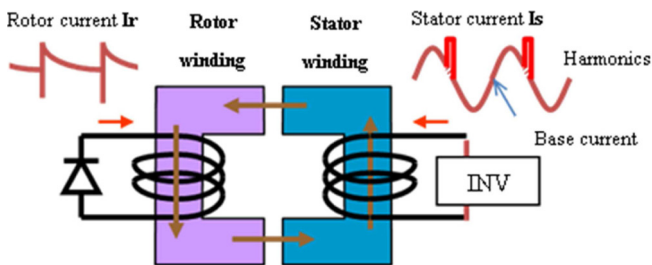


Figure 2. Basic concept of direct excitation method with using base current and harmonic current

According to the basic concept, three designs shown in Table 5 are suggested. There are two designs for direct-excitation which is Design [1] using continuous harmonic current superimposed in stator current, and Design [2] using pulse harmonics mixed in stator current. Design [3] is an indirect-excitation method by utilizing sub-pole and sub-pole winding in rotor. Design 3 stator flux goes into sub-pole and induces current on sub-pole winding to create current in rotor winding. Design 3 has indirect excitation using sub-pole and sub pole winding, so it will reduce magnetic negative effect on direct-excitation method. Here, the detail of each designs are described.

Table 5. Concepts for direct excitations

	Direct-excitation with harmonic current onto rotor main pole		[3] Sub pole excitation
	[1] Intermittent harmonics	[2] Pulse harmonics	
Geom etry			
Rotor circuit			
Stator and rotor current			

Figure 3a is showing magnet flux flow of design [1], in this design stator base current is shown in Figure 4a which is 90degE earlier than base flux flow of rotor in electrical angle. To consider it conversely, rotor base flux is 90 degree later than stator base current. Thus harmonic current for inducing rotor winding current is also 90degree later than stator base current as shown in Figure 4b. This harmonics is to be superimposed into base current and synthesized currents are shown in Figure 4c. This is actual input current into stator in design [1]. In this design, base current makes stator field flux, harmonic current makes induced current in rotor winding, this rotor current is rectified by diode and makes rotor field flux, and then it produces torque by stator field flux and rotor field flux.

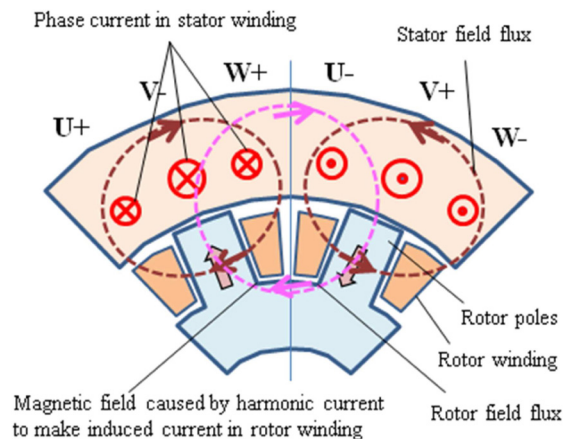


Figure 3a. Pattern diagram of flux flow design [1]

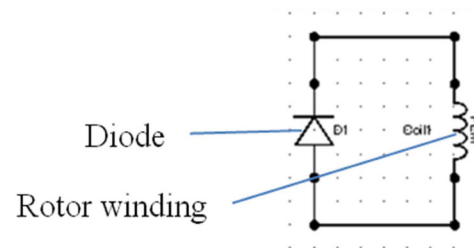


Figure 3b. Equivalent circuit of intermittent harmonics design[1]

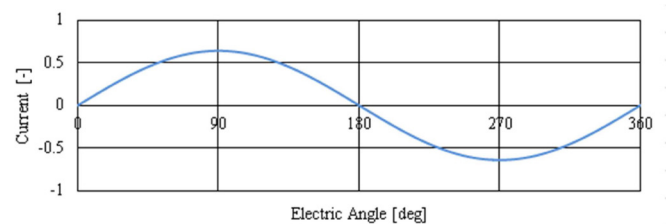


Figure 4a. Base sinusoidal waveform of stator current

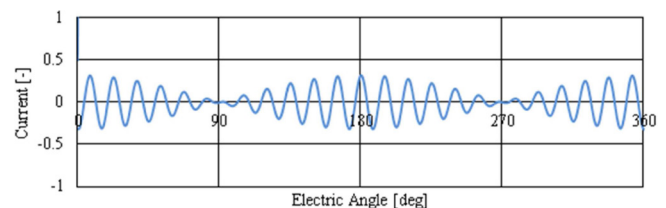


Figure 4b. Harmonics waveform for design [1]