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Design of In-Wheel Type Switched Reluctance Motor for Electric Vehicle Traction and Wireless Charging

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Abstract - This paper presents the design of in-wheel type Switched Reluctance Motor (SRM) which can be used as both traction motor and power pickup device in a wireless charging system of electric vehicles. The SRM acts as a traction drive in driving mode and a power receiver in charging mode to avoid any additional weights. Double stator axial field SRM is used due to its structure that can be mounted inside the wheel. The charging circuit is integrated with the asymmetric converter and phase windings of SRM, reducing the cost and size of the system. Magnetic resonance is implemented to increase the efficiency. Simulations done in Maxwell and Simplorer verify the effectiveness of the proposed system.

Key Words : Wireless charging, Electric vehicle, In-Wheel, Switched reluctance motor

1. Introduction

In recent years, electric vehicle (EV) has been gaining interest due to the increasing problems of pollution and energy crisis. It is considered as the future for a sustainable automotive industry [1]. The development of EV is crucial in reducing carbon dioxide emissions which play a major role in global warming. The transition from ICE (Internal Combustion Engine) vehicle to EV cannot be made so sudden and therefore comes some steps in automotive electrification. Generally, there are three kinds of automotive electrification which are commonly found in our everyday lives: HEV (Hybrid Electric Vehicle), PHEV(Plug-in Hybrid Electric Vehicle), and BEV (Battery Electric Vehicle). The structure of each type is shown in Fig. 1.

The driving range and power components' efficiency of current EVs are increasing but eventually this range will run out and the vehicle needs to be charged. Most EV owners have short mileage and they can conveniently charge every night at home for the next day run. However, this could turn to be a tedious work to do and therefore comes the electric wireless charging system for EVs to improve the convenience of the owners, Furthermore, the development of wireless charging may lead to a lowered safety risk associated with the mechanical failures of conventional plug-in chargers.

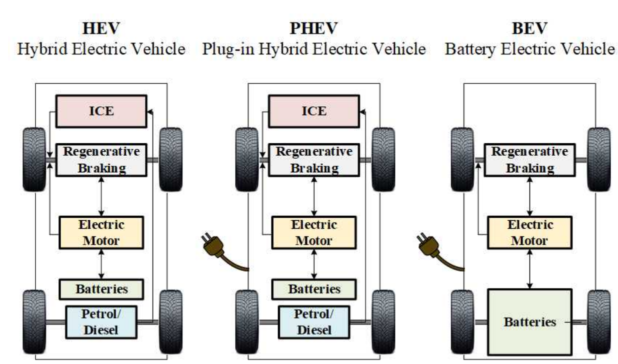

Fig. 1 Electric vehicle types

The conventional wireless charging system for EV consists of a three main components which are a charging controller, a power transmitter, and a power receiver or a pick-up device, as shown in Fig. 2. By using this kind of system, charging-while-driving can be made possible by planting the power grid under the road and the vehicle will charge itself only by driving above it. This leads to a

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reduced vehicle weight since charging at all time means less battery capacity needed and battery weight gives a huge impact on the total weight of a vehicle, thus the efficiency of the vehicle can be increased. However, the road has to undergo a significant construction work since the power source has to be embedded underneath and it is a costly process. The major drawback of this wireless system without the charging-while-driving technology, is the extra weight of the power pick-up device which increases the deadload of the vehicle during driving that may lead to a slightly decreased efficiency.

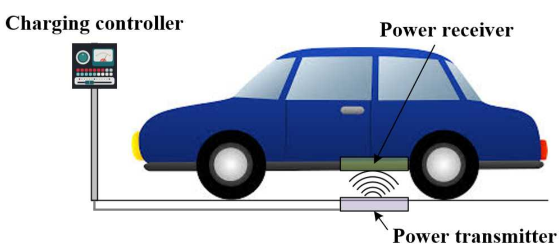

Fig. 2 Conventional wireless charging system

Switched reluctance motor (SRM) drives are ideally suitable for EV traction drive due to its doubly salient structure, which is light, fault tolerant, and easy to cool by nature [2]. This is important to fulfill the need of a more efficient, lightweight and compact electric propulsion system. SRM also has a wide speed range and high power density, which enables it to eliminate the reduction gears in the power train and mount the motors directly inside the wheel, which is known as in-wheel motors. In this paper, a wireless charging system of electric vehicle by using in-wheel type SRM as both power pickup device and traction motor is proposed. The stator windings are used as receiver coils during charging mode to avoid any additional weight to the vehicle. Integrated charging circuit shares the power switches of the motor converter without changing its topology, reducing the cost and size of the system.

2. Double Stator Axial Flux Type SRM

Switched reluctance motor is a doubly salient motor, which has no windings or permanent magnet on the rotor. This unique structure makes SRM simple, robust and low cost. Among many SRM topologies, axial flux (AF) type is one of the best candidates for electric vehicle applications due to its disc-shaped structure, which allows a direct coupling with the wheel. The previously developed motor was a 12/10 poles single-stator axial flux (SS-AF) SRM [3], as shown in Fig. 3. However, it experiences an eccentricity problem at the rotor since it was difficult to hold the rotor in place because it keeps getting pulled to the stator due to one side only excitation, as shown in Fig. 4. Even though a pair of coil located 180° apart are excited at the same time, due to some loss and faults, the rotor gets pulled more to one side of the coil and worsens the balance. The result of this eccentricity is that the rotor may hit the stator during load-condition and stall.

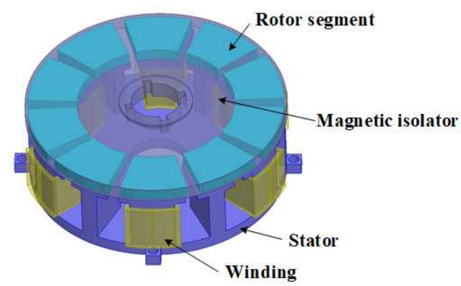

Fig. 3 Structure of 12/10 SS-AF SRM

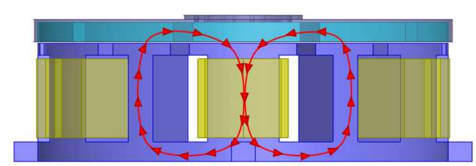

Fig. 4 Flux flow of 12/10 SS-AF SRM

Therefore, the newly developed motor is a 12/10 poles double-stator axial field (DS-AF) SRM [4]. The designed motor utilized segmented rotor type that results in a short-flux path during excitation and may lead to high torque density and increased efficiency due to a reduced core loss. The motor stator and rotor structures are shown in Fig. 5 and 6, respectively, and its parameters are described in Table 1. Also, the flux flow during phase excitation is shown in Fig. 7.

The static performance comparison of SS-AF and DS-AF type is shown in Fig. 8 and 9. In an SRM, by finding the inductance profile, the torque characteristic of that particular motor can also be known. The relationship between inductance L and torque T in an SRM is as follows,

$$T=\frac{1}{2}i^2\frac{dL}{d\theta} \tag{1}$$

where i is the phase winding current and θ is the rotor position. Therefore, by seeing the change of inductance, the torque characteristic can be defined. This newly developed

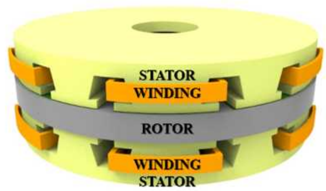

Fig. 5 Motor structure of 12/10 DS-AF SRM

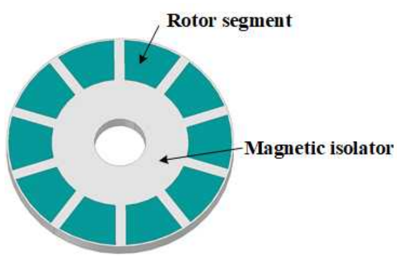

Fig. 6 Rotor structure of 12/10 DS-AF SRM

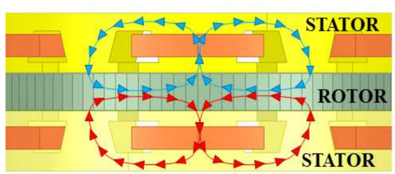

Fig. 7 Flux flow of 12/10 DS-AF SRM

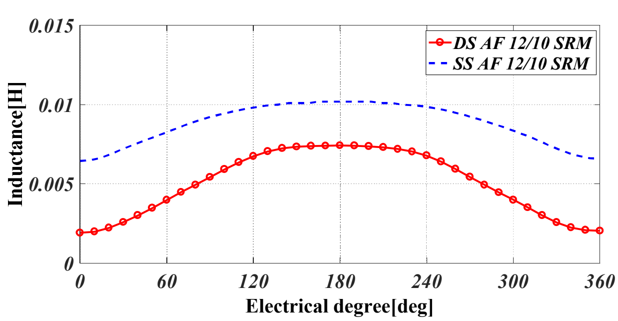

Fig. 8 Inductance comparison between SS/DS-AF SRM

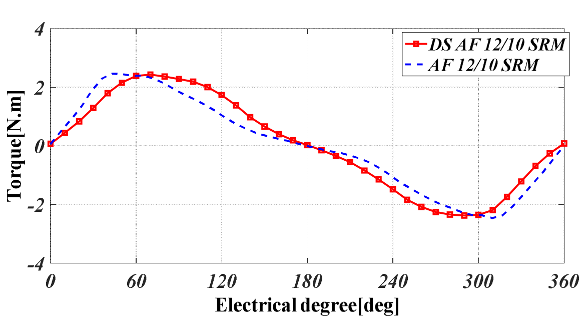

Fig. 9 Torque comparison between SS/DS-AF SRM

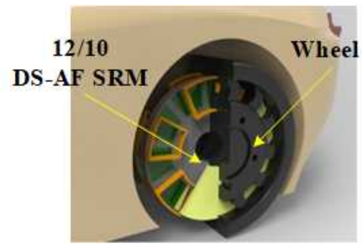

Fig. 10 In-wheel use

Table 1 Motor parameters

Parameters	Value
Number of phase	3
Stator pole	12
Rotor pole	10
Rated speed	2800 rpm
Rated torque	1.71 Nm
Output power	498.5 W
Efficiency	82.4 %

motor shows better performance than SS-AF. Fig. 10 shows the illustration of in-wheel use of the motor.

3. Charging Mechanism

The proposed charging system is illustrated in Fig. 11. Guidelines embedded into the platform and wireless communication between car and stations are used to minimize misalignment and improve the overall charging efficiency. The effect of distance on inductance and coupling coefficient is shown in Fig. 12. Take note that in this study, the motor used is only a prototype thus it is a downsized version of that of the actual in-wheel motor. Since the in-wheel motor is used here, the charging stations or power source are placed standing on both sides of the car, reducing infrastructure cost due to the re-construction of the pavement. Also, the charging stations are equipped with bluetooth device to enable communication between the vehicle and station in case of full-charge or danger to increase safety.

Fig. 11 Proposed charging system

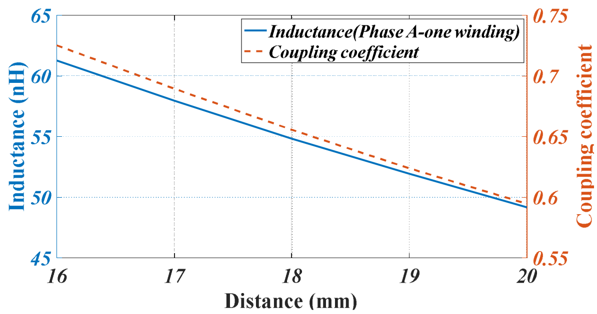

Fig. 12 Inductance and coupling coefficient according to the variety of distance

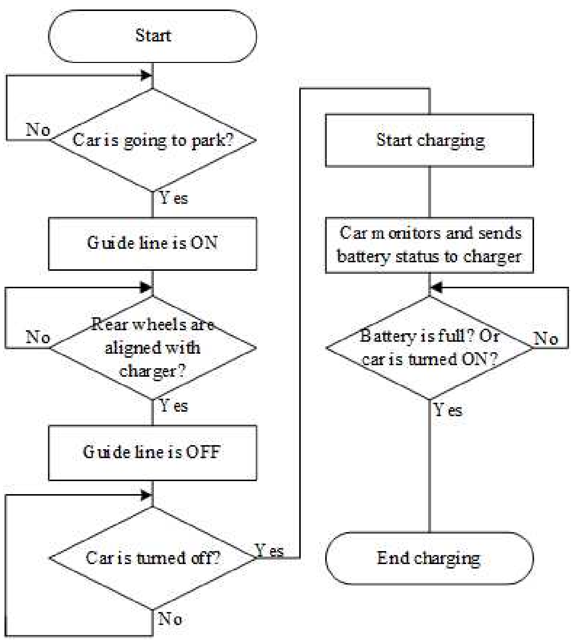

Fig. 13 Flowchart of the proposed system

Charging procedures are described in Figure 13. As mentioned before, the guideline helps driver to align the rear wheels with the charging station to minimize loss due to misalignment. Then, only when the car is off, the charging process will take place. This is to protect the motor drive due to the opposite current flow direction during motoring and charging. Further development may be needed to fix this problem, thus enabling charging-while-driving for the system. Then, the battery status will be monitored continuously by the car electronics and the stop signal will be sent to the charging station if the battery is full or the car is ready to leave.

3.1 Transmitter Design

In the charging system design, only transmitter is considered because the power receiver uses the existing traction motor winding without any change. Since the prototype motor is smaller than the actual wheel, scaling percentage is used to determine the size of transmitter. The comparison is provided in Table 2. For the actual wheel size, 21/9" type is chosen. It can be calculated that the motor is approximately in 1:5 ratio with the actual wheel.

The transmitter module consists simply of six spiral coils that are set to be aligned with SRM coils and a ferrite plate to support the coils and provide better magnetic coupling, as shown in Figure 14. Fig. 15 shows the simulation model. Note that here, the distance between the motor and transmitter is set as 20mm and air is the transmitting medium and environment around the system. Between the traction motor and transmitter, there is a tire rim frame, usually made of metal. If this frame is considered in the model, the thickness will be no more than 5mm and the air gap that is given in the model is sufficient to insert the rim in between transmitter and motor. By observing Fig. 16, it

Table 2 Comparison between prototype motor and actual wheel

Parameters	Value
Actual wheel rim diameter	533.4 mm
Actual wheel width	228.6 mm
Motor outer diameter	104 mm
Motor thickness	35 mm

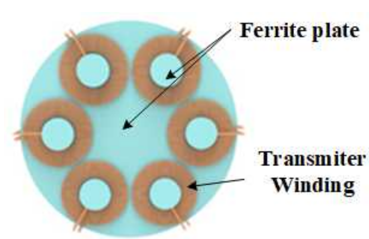

Fig. 14 Transmitter model

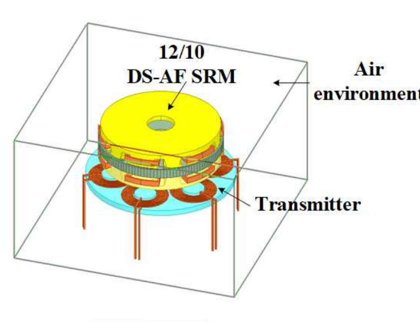

Fig. 15 Maxwell simulation model

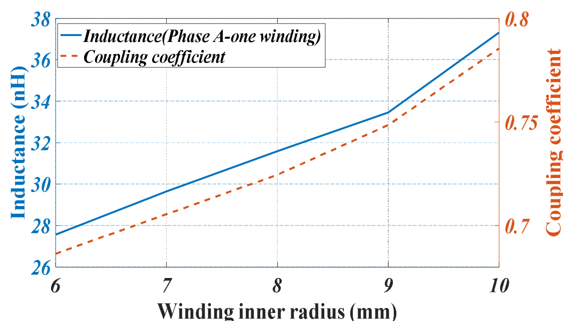

Fig. 16 Inductance and coupling coefficient according to the winding inner radius

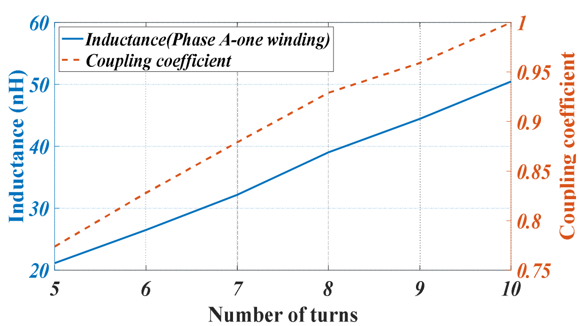

Fig. 17 Inductance and coupling coefficient according to the number of turns

Table 3 Transmitter design parameters

Parameters	Value
Inner radius of transmitter coil	10 mm
Number of turns	10
Outer radius of ferrite plate	65 mm
Thickness of ferrite plate	5 mm
Distance from motor	20 mm

can be known that the larger the inner radius of the transmitting coil, the better the performance is. Furthermore, more winding turns is also suggested as shown in Fig. 17. However, these factors contribute to the physical size of charging station. The selected parameters of the transmitter is presented in Table 3, which winding inner radius, number of turns, and ferrite's thickness have been optimized to get the optimum result.

3.2 Magnetic Resonance and Power Converter

The power transfer circuit consists of SRM asymmetric bridge converter, capacitors, battery, transmitter/resonator, and SRM coils as the pick-up module. Magnetic resonance in wireless power transfer is commonly used to increase efficiency. The capacitors are added to achieve this and one is implemented on each side. The equation for the resonant frequency is as follows,

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

where C is the capacitance and f is the desired resonance frequency. SRM coils are used as pick-up module and its converter is switched to demagnetization stage which allows the current to be transferred to the battery. Therefore, the current flow is the opposite as what it is during motoring. There are no additional components in this integrated system. Figure 19 shows the equivalent circuit of the proposed system.

The structure of axial field type SRM puts the windings between stator plates and separated by rotor plate. At high frequency, large eddy current is induced on the metal plate and shields magnetic fields generated by the resonator [5,6]. Magnetic resonance coupling at high frequency is difficult to achieve. Therefore, in this study, low resonant frequency is proposed to avoid skin effect.

4. Simulation Results

The simulation was done in Ansoft Maxwell for motor performance analysis and then the model is coupled with the circuit in Simplorer to achieve the result. Fig. 19 shows the simulation model in Simplorer. The efficiency varies with frequency as shown in Fig. 18 with variable capacitor values. Then, the search for highest efficiency narrows down between 400Hz to 500Hz. Finally, the optimum result is obtained at 486 Hz for 98.30%, as seen in Fig. 20. Fig. 20 also shows the resonance happened during transmission. Here, the transmitter and receiver capacitor value is 0.00253 Farad and 0.246 Farad respectively. The input and output power of the system are 735W and 722.5W respectively.

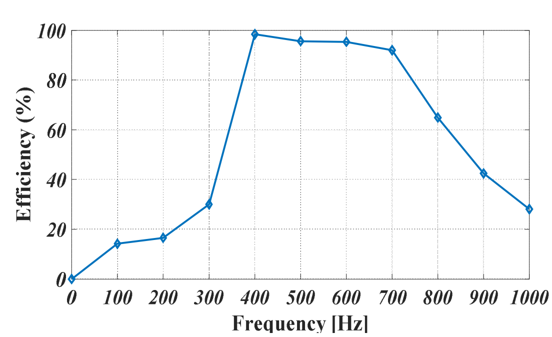

Fig. 18 Efficiency according to transmission frequency

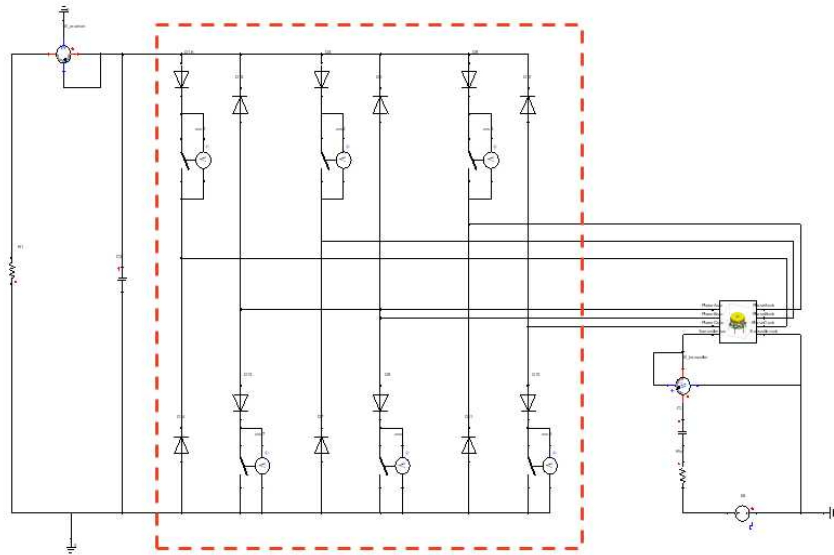

Fig. 19 Simplorer model of the proposed system

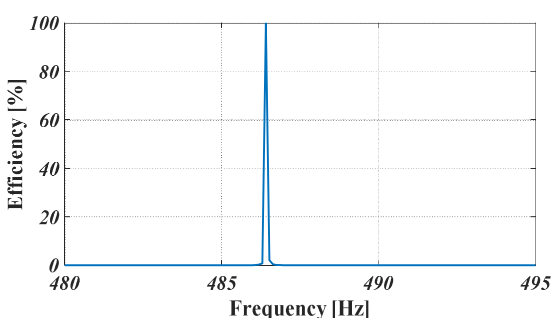

Fig. 20 Efficiency at 486Hz

5. Conclusion

A design of SRM that is used as traction during motoring and power pickup device during wireless charging in EV is proposed. Double stator axial field type is chosen due to its structure for in-wheel mount and reduced eccentricity. The charging circuit is integrated to SRM converter without any change to the motor drive. Charging stations or power transmitter are located on the rear side of the cars. The stator windings which are used as power receiver are located between stator plates, which produces large eddy current loss at high-frequency. Thereby, low frequency magnetic resonance is used to achieve maximum power transfer. The optimum result is achieved at 486 Hz with 98.30% of efficiency.

Acknowledgments

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