Performance Enhancement of Outer-Rotor Dual Excitation Flux Switching Machine for In-Wheel Drive Applications

M.Z. Ahmad, E. Sulaiman, F. Khan and Z.A. Haron

ABSTRACT

Research and development of dual excitation flux switching machine (DEFSM) become an attractive research topic for almost a decade due to their advantages of robust rotor structure and flux control capabilities. The developed machine have been applied in wide range of applications includes in aerospace, automotive, power generation, domestic power tools, and etc. Nevertheless, the previous researches are mainly focused on inner-rotor configuration and hard to find outer-rotor DEFSM. The outer-rotor configuration offers some advantages of higher torque and power density that suitable for direct drive electric vehicle (EV) applications. The proposed machine eligible for independent wheel controllability and has more cabin space due to removal of conventional mechanical transmission and differential gears. Hence, more series batteries can be installed to have longer driving distance. Therefore, this research presents design analysis and performance enhancement of outer-rotor DEFSM with 12Slot-10Pole and 12Slot-14Pole configurations. Based on two dimensional (2-D) finite element analysis (FEA), the coil arrangement tests are examined to confirm the operating principles and polarity of each armature coil phase. Moreover, the flux linkage characteristics, induced voltage, and cogging torque profile are also investigated. Finally, the torque and power performances of both configurations are analyzed. The results obtained show that the proposed 12S-14P outer-rotor DEFSM has ability to provide better performances in terms of torque and power density.

INTRODUCTION

In this 21st century, global warming is among a major issue discussed all over the world by scientists and government agencies. The factors that might contribute to global warming are greenhouse effect due to human activities, heated by solar radiation, and geomagnetic variation (Andrew A. Lacis and Bucha. V, 1991). As reported in (J. King, 2008), among the main contributors for global warming issue is come from burning process of fossil fuel by means of conventional internal combustion engine (ICE) vehicles. Due to the price of fossil fuel is keep raising year by year, a lot of researchers and industries are looking for electric vehicles (EVs) as the most possible solution in transportation. Thus, it is expected that will reduce dramatically the air pollution and will meet the national energy strategy to seek for an energy future that would be secure, efficient, and environmentally sound (C.C. Chan, 1993). Generally, the propulsion system for conventional EVs consists of batteries, electric motors with drives, and transmission gears to wheels. This configuration led for torque and power loss on the transmission system and resulting less electric motor’s efficiency. In addition, it consumes a lot of space to locate the transmission and gearing system in vehicle’s cabin that increase the total vehicle weight. Therefore, in-wheel direct drive motor is an alternative mode for EV where the transmission system is minimized, and the operation efficiency and reliability is improved (Y.P. Yang et al., 2007). Moreover, more batteries can be installed in the space that would be occupied by the transmission, which help to increase the driving range per charge. On the contrary, due to the elimination of gears, the system needs to produce the total torque directly into the wheel shaft with higher torque and power density as compared with conventional EV (Wu et al., 2007 and K.M. Rahman et al., 2006).

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Previously, the electric motors used to drive conventional EVs are mostly interior permanent magnet synchronous machine (IPMSM) due to their advantages of high torque and power density. However, it may suffer from heat management, demagnetization effect, and mechanical damage due to the permanent magnet (PM) located on the rotor especially when used at extreme driving condition. Alternatively, switched reluctance machine (SRM) that consist very simple and rugged rotor structure by means of no PM, makes it predominantly robust against mechanical and thermal impacts. Nevertheless, SRMs have large torque ripple and creates noise that in-appropriate for direct drive applications. Recently, research and development on permanent magnet flux switching machine (PMF) has become an attractive research topic due to their advantages of physical compactness, robust rotor structure, higher torque and power density, and high efficiency. With both PMs and armature windings located on the stator and robust single piece rotor similar to SRM, the temperature rise is easily managed and suitable for high speed application. Thus, the PMF seems as combination advantages of conventional PMSM and SRM (S.E. Rauch et al., 1955, Y. Chen et al., 2006, Y. Amara et al., 1999, and E. Sulaiman et al., 2011 and 2014).

In conjunction for in-wheel direct drive EV applications, electric machine with outer-rotor configuration is considered the most appropriate motor due to its ability to provide higher torque density. In flux switching machine (FSM) family, an outer-rotor PMF has been initially proposed for urban and light electric vehicle as described in (W. Fei et al., 2009) and (W. Fei et al., 2012), respectively. The improvement of the initial design outer-rotor PMF has been made and the machine can deliver nearly 93% efficiency with 50% reduction of PM material (Weizhong Fei et al., 2013). Nonetheless, constant PM volume used as a main flux source make it difficult to control and may needs for field weakening flux controller at high speed condition. Therefore, to provide further attractive characteristics, a new design of outer-rotor PMF with additional excitation coil has been proposed by the authors as described in (M.Z. Ahmad et al., 2012 and 2013). The additional excitation coil is also allocated on the stator part to provide extra advantage of the machine as secondary flux sources that can improve torque and power performances with variable flux control capabilities. The machine is also called as outer-rotor dual excitation flux switching machine (ORDFSM). The design concept is based on inner-rotor machine that has been discussed in (E. Hoang et al., 2007 and 2009).

This paper presents design analysis and performance enhancement of 12Slot-10Pole and 12Slot-14Pole ORHEFSM for in-wheel drive EV applications. Initially based on two-dimensional (2-D) finite element analysis (FEA), the results of coil arrangement test are demonstrated to show and confirm the principle operation of the machine. Then, the machine’s flux linkage, back-electromagnetic force (back-emf), and cogging torque are also analyzed and compared. Finally, the torque and power performances of both configurations are also demonstrated.

1. Various Outer-Rotor Flux Switching Machine Topologies:

Recently, research on outer-rotor configuration of FSM is getting more popular in order to have higher torque and power density. The developed machines are mainly focus to be applied for direct drive applications to prevent high torque and power loss. Initially, the first outer-rotor FSM has been introduced in the recent research in which the flux source is only come from PM and the machine is called outer-rotor PMF (W. Fei et al., 2009). The machine consists of 12 stator slots, 22 rotor poles and the target application is only for urban and light EV. The overview structure of the outer-rotor PMF is illustrated in Figure 1(a). From Figure 1(a), it clearly shown that the machine has simple structure where the armature coil slot is in triangle shape and the PM is in rectangle shape. However, the iron core of the stator body is designed separately for each segment that makes it difficult to manufacture and assemble. With only PM as a main flux source, it is difficult to control the flux especially when used at high speed condition.

Due to these drawbacks, the authors have proposed a new candidate machine for in-wheel direct drive EV with the structure of 12 slot-10 pole configuration as shown in Figure 1(b) (M.Z. Ahmad et al., 2012 and 2013). The proposed machine have two flux sources namely PM and DC field excitation coil (FEC). The additional DC FEC is mainly to provide more magnetic flux and flux control capabilities that suitable for high speed applications. Even though, the structure of the original proposed machine looks more complicated compared to the outer-rotor PMF in Figure 1(a) but all the components slot area are in rectangular shape that easy to manufacture. In addition, the stator body is only single piece of iron core resulting in easy to assemble.

Instead of PMs and the combination of PM and FEC, a new outer-rotor configuration with employing a field winding to create the excitation field has proposed, thus reducing the total cost of the machine (M. Galea et al., 2012). A segmented rotor which has neither PMs nor windings is used to enhance the performances of the machine. The machine is named as outer rotor field wound flux switching (FWFS) machine with segmented rotor configuration. The model of 36 slot – 21 segment outer rotor FWFS is shown in Figure 1(c). From the diagram, it is show that the coil windings are non-overlap between the armature and DC FEC, respectively. The target designed machine is to be applied in aerospace industry.
2. Design Conditions and Specifications of the Proposed ORDEFSM:

The commercial FEA package, JMAG-Designer ver.13.0, released by Japan Research Institute is used as 2D-FEA solver in this design. The design requirements, restrictions and specifications of the proposed ORHEFSM are based on interior permanent magnet synchronous motor (IPMSM) employed in LEXUS RX400h and listed in Table I. In this design study, the target performance of maximum torque and power is expected can achieve more than 333 Nm and 123 kW, respectively with the same rating of the inverter used for IPMSM which are 650 V for voltage and 360 A_rms for current. Whilst, the maximum of both armature current density, \( J_a \) and FEC current density, \( J_e \) is set at 30 A/mm^2. The target weight of the proposed motor is set to be at least similar 30 kg which is less 5 kg compared to IPMSM. Therefore, it is expected that the proposed motor can achieve the maximum power and torque density of 11.1 Nm/kg and 4.1 kW/kg, respectively. In addition, the PM weight is reduced to 1.0 kg in order to reduce the total weight and manufacturing cost.

The proposed machine has very simple structure where all the components slots are in rectangle shape and all coils are in concentrated winding. In this study, the possible number of rotor pole and stator slot is defined by equation (1).

\[
N_r = N_s \left(1 \pm \frac{k}{2q}\right)
\]  

(1)

where \( N_r \) is the number of rotor poles, \( N_s \) is the number of stator slots, \( k \) is the integer number, and \( q \) is the number of phases. Whereas, the electrical frequency, \( f_e \) of the proposed machine can be expressed by equation (2).

\[
f_e = N_s \cdot f_m
\]  

(2)

Table 1: ORDEFSM Design Conditions and Specifications.

<table>
<thead>
<tr>
<th>Description</th>
<th>IPMSM</th>
<th>ORDEFSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. DC-bus voltage inverter (V)</td>
<td>650</td>
<td>650</td>
</tr>
<tr>
<td>Max. inverter current (A_rms)</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>Max. current density in armature coil, ( J_a ) (A_rms/mm^2)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Max. current density in FEC, ( J_e ) (A_rms/mm^2)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Motor radius (mm)</td>
<td>132</td>
<td>132</td>
</tr>
<tr>
<td>Motor stack length (mm)</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Shaft/Inner motor radius (mm)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Air gap length (mm)</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>PM weight (kg)</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Maximum torque (Nm)</td>
<td>333</td>
<td>&gt;333</td>
</tr>
<tr>
<td>Maximum power (kW)</td>
<td>123</td>
<td>&gt;123</td>
</tr>
</tbody>
</table>

where \( f_e \) is the electrical frequency, \( f_m \) is the mechanical rotation frequency and \( N_r \) is the number of rotor poles respectively. The proposed machines consist of 24 stator teeth with alternate DC FEC, PM and armature coil slot around the stator body. Initially, the DC FEC is wound alternately in counter-clockwise and clockwise polarity, while all the three-phase armature coils are wound in counter-clockwise direction. In addition, it is expected that the machine offers non-overlap winding between the DC FEC and armature coil to provide shorter end winding and hence contribute to reduce copper loss effect.

Furthermore, the material used in this design for PM is NEOMAX-35AH whose residual flux density and coercive force at 20°C 1.2T and 932 kA/km, respectively, while the electromagnetic steel, 35H210 is used for the rotor and stator core. The necessary area of armature coil, \( S_a \) to give optimum natural number of turns of armature coil \( N_a \) is calculated using equation (3) where the limits of armature current density, \( J_a \) is set to 30 A_rms/mm^2. Similarly for the area of FEC coil, \( S_e \) is determined by equation (4) where the maximum current density of FEC, \( J_e \) is set to 30 A/mm^2.

\[
S_a = \frac{I_{\text{rms}} N_a}{a J_a}
\]  

(3)

\[
S_e = \frac{I_{\text{rms}} N_a}{a J_e}
\]  

(4)
From equation (3) and equation (4), α is the filling factor, while \( I_a \) and \( I_e \) are rated armature current and FEC current, respectively.

3. Comparison Analysis of ORDEFSM Based-On 2-D FEA:

Initially, coil arrangement test is conducted on the original design machine to examine and to set the polarity of each armature coil phase and sequence, respectively. The original design machine of 12S-10P and 12S-14P ORDEFSM is shown in Figure 2. The DC FEC and PM polarities are set in alternate direction to create 12 north and 12 south poles, respectively. By put the armature and DC FEC current density at 0 A/mm², which having magnetic flux from PM only, flux linkages on each armature coil are observed and analyzed. Then, according to phase shifted of balance three-phase system, a three-phase of 12 armature coils are examined. From the coil arrangement test, it is found that for 12S-10P ORDEFSM, the armature coil denoted by C1, C4, C7, and C10 are defined as W-phase, while the armature coils labelled by C2, C5, C8, and C11 are represent the U-phase, and armature coils labelled by C3, C6, C9, and C12 are examined as V-phase. Furthermore, for 12S-14P ORDEFSM, the armature coils designated with C1, C4, C7, and C10 are defined as V-phase, while the armature coils labelled by C2, C5, C8, and C11 are presents as U-phase, and armature coils labelled by C3, C6, C9, and C12 are examined as W-phase. The three-phase flux linkages for both machine’s configuration is shown in Figure 3 and it is shown that the magnetic flux for both machines have sinusoidal three-phase waveforms. From the figure, the maximum flux obtained for 12S-10P and 12S-14P are 0.0038 Wb and 0.0113 Wb, respectively. Therefore, it is expected that the ORDEFSM with 12S-14P has better performance compared with 12S-10P configuration.

In effort to get the optimal performance, design free parameters, D1 to D9 are defined on the rotor and stator part as illustrated in Figure 4. Firstly, the necessary coil area \( S_c \) is calculated to give an optimum integer number of turns of armature coil, \( N_c \). Then, the maximum gap between armature coil-excitation coil and armature coil-permanent magnets is refinement to get the optimal torque. This is followed by designing the rotor diameter, salient pole arc and depth of teeth to get its maximum performance. The method of finding the maximum performance of this machine is by adjusting parameters D1 to D9 using ‘deterministic optimization approach’ with keeping the same volume of permanent magnets and air gap length. After several cycles of optimization process, the structure of the improved design machines is illustrated in Figure 5. From the diagram, the improved design of 12S-10P configuration has longer DC FEC depth and shorter PM depth compared with the original design. Besides, the armature coil slots became a trapezoidal shape and overlapped with DC FEC windings. The final number of turns of armature coil and DEC FEC is 7 turns and 44 turns, respectively. On the other hand, the different of the improved design of 12S-14P configuration which has longer PM depth and DC FEC compared with the original design. Obviously, the armature coil slot area has reduced due to less number of armature coils turns used in which only 6 turns on each phase. The number of turns of DC FEC is maintained at 44 turns.

Furthermore, the cogging torque in open circuit condition of the improved design machines are analyzed and plotted in Figure 6. It is clearly shown that the proposed machine with 12S-10P configuration has better peak-to-peak cogging torque which only 3.02 Nm, whereas for 12S-14P the peak-to-peak cogging torque is 8.00 Nm. Even the peak-to-peak cogging torque of 12S-14P has higher magnitude then 12S-10P, it is still in acceptable range with respect to the final target of maximum torque.

The comparison of back-emf for both improved design ORDEFSM at the speed of 3000 r/min is demonstrated in Figure 7. It clearly shows that the amplitude of back-emf for the improved design motor have achieved 66.16 V and 168.1 V for 12S-10P and 12S-14P, respectively. The magnitude of the back-emf of 12S-14P configuration is higher than 12S-10P for almost three times. However, the magnitude is not exceeding the supply voltage of the inverter. Finally, the performance comparisons are made on the torque and power versus speed profile as demonstrated in Figure 8. From the diagram, it is shown that the maximum torque achieved for 12S-10P and 12S-14P are 269.04 Nm and 298.46 Nm, respectively. It shows that the toque performance for both improved design machines have achieved 80.79% and 89.63% from the target maximum torque of 333 Nm. The maximum power obtained is 163.18 kW and 138.75 kW for 12S-10P and 12S-14P, respectively. Moreover, the output power for 12S-10P reached a constant value at high speed condition, whilst for 12S-14P the power start reducing after reach it maximum value at the speed of 6519 r/min.

Conclusion:

The performances of the improved design outer-rotor dual excitation flux switching machine for 12Slot-10Pole and 12Slot-14Pole configuration have been presented in this paper. Basically, from 2-D FEA results have been obtained the proposed machine with 12Slot-14Pole configuration has better performances compared to 12Slot-10Pole in terms of coggging torque, back-emf, output torque, and also the generated power. Therefore, 12Slot-14Pole ORHESM configuration will further improved to achieve the target performances by continuing a design refinement and optimization.
Fig. 2: The original structure of ORDEFSM (a) 12S-10P, (b) 12S-14P.

Fig. 3: Three-phase flux linkages generated by PM.

Fig. 4: Design parameters defined as $D_1 - D_9$.

Fig. 5: Improved design ORDEFSM.

Fig. 6: Cogging torque.
Fig. 7: Back-emf at 3000 r/min.

Fig. 8: Torque and power versus speed.

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