VOL. 10, NO. 16, SEPTEMBER 2015 ISSN 1819-6608

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

FLUX ANALYSIS OF A NOVEL DUAL ROTOR HYBRID EXCITATION FLUX SWITCHING MACHINE (DRHEFSM)

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ABSTRACT

Hybrid Excitation Flux Switching Machine (HEFSM) mainly utilizes Field Excitation Coil (FEC) and Permanent Magnet (PM) as main flux sources. The motor exhibits high performance compared to Permanent Magnet Flux Switching Machine (PMFSM) and Field Excitation Flux Switching Machine (FEFSM) because of its flux sources consist of both FEC and PM. The performance of HEFSM can be further improved by introducing Dual Rotor HEFSM (DRHEFSM). The DRHEFSM is designed in order to create high performance motor in terms of torque speed characteristic and efficiency. This newly design motor also has an advantage in controlling the rotor rotation whether for single rotor rotation, inner rotor or outer rotor as well as both rotor rotations. Moreover, when only outer rotor rotates, the outer stator active part produces flux and vice versa when only inner rotor rotates. The purpose of this paper is mainly to validate the operating principle of DRHEFSM in performing the three phase operating principle. It has been proven that the DRHEFSM can work properly by following the operating principle of three phase machine based on the analysis that has been conducted. This motor is expected to perform much better than the existing HEFSM motor.

Keywords: dual rotor, HEFSM, flux analysis, three-phase.

INTRODUCTION

Production of high torque, high power density and high efficiency motor utilized in various range of application are getting higher and higher each year, due to concerns over urban air quality, global warming and saving fossil fuel. Many electric machine companies have produced high efficiency machine equipped with Interior Permanent Magnet Synchronous Motors (IPMSM). Most of operating torque-speed range of this machine exhibits high torque and power density and high efficiency. Since IPMSM utilizes constant permanent magnet (PM) as their main flux source, their flux capability in low torque and high speed condition are difficult to control. Moreover, long armature coil end possess by this machine gives high copper loss.

In effort to overcome this problems, some researchers have employed several new design which consist of Field Excitation Flux Switching Machine (FEFSM) in which field excitation (FE) (Husin *et al.* 2014) are the main flux source and Hybrid Excitation Flux Switching Machine (HEFSM) in which FE and PM as the main flux sources. Among these, HEFSM exhibits higher torque and speed characteristic. Various combination of HEFSM has been developed for high-speed application (Ahmad & Sulaiman 2015; Sulaiman & Amin 2013), for example 12Slot-10Pole HEFSSM has been proposed.

The proposed design, HEFSM can perform much better than IPMSM, PMFSM and FEFSM where the main advantage are the controllable flux, all of the active parts, namely armature coil, FEC and PM are located on the stator and robust rotor structure which suitable for high-speed application (Kamiya 2005). Furthermore, since all the components are located in the stator body, it is expected to have simpler cooling system compared to water jacket system used in IPMSM.

A novel Dual Rotor HEFSM is introduced in order to create high performance motor compared to existing HEFSSM. The machine is expected to perform in much higher performance, double than existing single rotor HEFSSM produced. The machine never been investigated before but from previous design of Dual Rotor Switch Reluctance Machine (DRSRM), the dual rotor machine exhibits high reliability, wide constant power region and wide speed adjustable range (Yang *et al.* 2010). The motor is expected to produce torque over range of rotor speeds while operating at fixed frequency, equal torque can be maintained on both rotor even when rotor speed are different (Kelecy & Lorenz n.d.). Moreover, the efficiency of the machine can be improved significantly due to the compact winding distribution (Baun & Krotsch 2013). In addition, compared to single rotor machine, the torque density can be increased by factor 1.28. By applying dual rotor, the magnetic path become shorter thus the iron loss is less. Lastly, by possess dual rotor structure; give it biggest advantage in variable control such as controlling inner or outer torque or both rotor torques.

Principle Operation of DRHEFSM

The flux switching machines (FSMs) concept was first invented in the middle of 1950's (Rauch & Johnson 1955), while in 2007; HEFSM was published (Ecole *et al.* 2007). The term "flux switching" is introduced by shifting of polarity of the flux linkage by following the motion of a salient pole rotor.. For HEFSM, all the active parts are located on the stator with the armature while PM (DC field winding) placed in alternate stator teeth. The machine is suitable for high speed applications because it possess robust rotor structure. Furthermore, the flux generated can be controlled using the FEC. The possible number of rotor poles and stator slots for this proposed DRHEFSM is defined by,

$$N_r = N_s(1 \pm \frac{k}{2q}) \tag{1}$$

Where Nr is the number of rotor poles, Ns is the number of stator slots, k is the natural number, and q is the number of phases. For the proposed motor, q equals to 3 for three phase while Ns equals to 6 for three phase. Lastly, Nr is the number of rotor which is designated for 6 Slot, 7 Pole configurations and has been chosen for the initial analysis thus 6Slot-7Pole DRHEFSM has been relatively proposed.

The proposed motor rotates 1/7 through a revolution, the armature flux linkage has one periodic cycle, and thus, the armature coil of back-emf induced frequency is seven times than the frequency of mechanical rotational. Generally, the relation between the mechanical rotation frequency, fm and the electrical frequency, fe for this machine can be expressed as;

$$fe = Nr \cdot fm \tag{2}$$

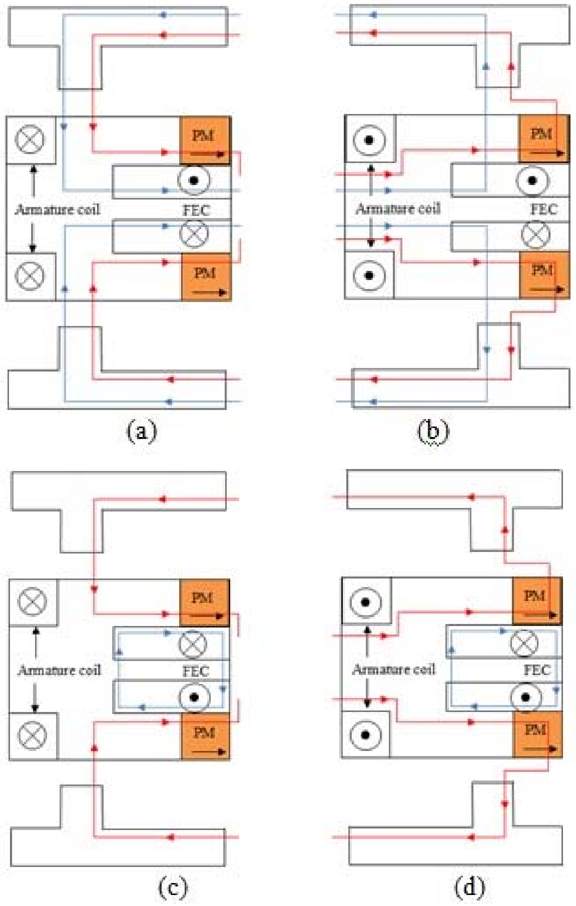
where fe is the electrical frequency, fm is the mechanical rotation frequency and Nr is the number of rotor poles respectively.

The combination between PM and FEC where PMs is utilize as primary excitation and DC FEC as a secondary source describe hybrid excitation flux switching machines (HEFSMs). When PMFSM is operating beyond base speed in the flux weakening region, the armature winding current needed to be control. The applied negative d-axis current will counteracted the flux of PM however it will increase the copper loss and the efficiency and power capability will be reduce and also PMs is possible to experience irreversible demagnetization. Hence, the new alternative, HEFSM which combine PM and DC FEC give some advantages. HEFSM have been researched in the recent years due to the potential to improve flux weakening performance, power and torque density, variable flux capability, and efficiency (Owen *et al.* 2009; Zhao & Yan 2005).

The operating principle of the proposed DRHEFSM is identical to HEFSM where the only difference is the DRHEFSM possess outer stator and outer rotor structure. The operating principle of the DRHEFSM is shown in Fig. 1. The PM flux is indicated with the red line while the FEC flux is indicated with the blue line. Both red and blue indicator directions are in the same polarity in Fig. 1(a) and (b). As the fluxes move from stator to rotor, both fluxes are combined. Hybrid excitation flux is produced, as large amount of fluxes generated by both FEC and PM. Meanwhile, Fig. 1(c) and (d) show the reverse polarity of FEC. Less flux excitation are resulting from the PM flux flows into the outer rotor shown by the red indicator and FEC flux moving at the outer yoke only, shown by the blue indicator. Variable flux control capabilities, field strengthening and or field weakening excitation are the advantages of DC FEC.

Proposed Machine Design Restrictions, Specifications, Parameters and Dimension

The design restrictions and specifications for the proposed DRHEFSM are listed in Table I while the initial machine configuration is illustrated in Figure-2. The weight of PM is limited to 1.0kg while the outer rotor diameter is 264 mm, the motor stack length is 70mm and the shaft radius is 30mm. The corresponding electrical restrictions such as the inverter are set to maximum, 360Arms and the DC bus voltage set to maximum, 415V. Meanwhile armature current density, Ja and FEC current density, Je is set to 30Arms/mm2 and 30A/mm2, respectively. This current density is maximum allowable current in electric machine that comfort the water jacket system. It is also inducing maximum current and then



(a) (b) (c) (d)

Figure-1. Principle operation of DRHEFSM (a) *e*=0° and (b) *e*=180° flux moves from stator to rotor (c) *e*=0° and (d) *e*=180° flux moves from rotor to stator.

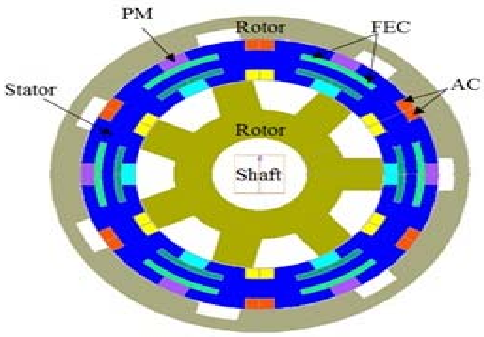


Figure-2. Initial design of the DRHEFSM.

will generate maximum flux thus maximum torque and speed can be gained . The machine efficiency is expected to increase due to compact winding distribution by the outer and inner rotor. Additionally, un-overlap winding between the FEC and armature coil will make shorter end winding.

The 2D-FEA solver for this design is simulated by the commercial FEA package, JMAG-Designer ver.13.0, released by Japan Research Institute. Fig.3 and Fig.4 illustrate the configurations of the proposed machines. NEOMAX-35Ah is used as the PM material whilst the electromagnetic steel, 35H210 is used as the rotor and stator body material.

Basically, the dimensions of the DRHEFSM are divided into two groups related to rotor and stator structure. The stator core design consists of three groups of active parts, such as the PM slot shape, FEC slot shape and armature slot shape. The rotors are divided into two, outer and inner rotor. For outer rotor, its parameters consist of outer rotor radius (D1), outer rotor pole height (D2) and outer rotor pole width (D3). Meanwhile, for inner rotor, its parameters consist of inner rotor radius (D4), inner rotor pole height (D5) and inner rotor pole width (D6). The stator core parameter is the stator radius (D7) while the PM slot shape parameters are included in PM width (D8) and PM length (D9). Likewise, D10 and D11 are the width and height of FEC in FEC slot shape. Lastly, the armature slot shape parameters are armature coil width (D12) and armature coil height (D13). The initial design parameters of the proposed DRHEFSM are depicted in Table I, whereas the design motor parameters from D1 through D13 are illustrated in Fig.5.

DESIGN RESULTS AND PERFORMANCES BASED ON 2D- FINITE ELEMENT ANALYSIS

Armature Coil Observation

The armature coil observation is conducted in order to observe the generated flux of each armature coil. The test is conducted during no load analysis, in order to ensure position of each armature coil phase is valid for operating principle of DRHEFSM. By placing 12 pairs of armature coil and FE coil wound in counter clockwise rotation, the flux linkage of each coil is observed. In result, 12 waveforms are obtained proving that the DRHEFSM follow the operating principle of 3-phase machine, Fig.6 show the waveforms obtained.

Furthermore, based on the conventional 3-phase system, U, V and W, the result for flux linkages at each coil are compared. For the initial test, the U, V and W circuit for both inner and outer has been combine in order to study the flux behaviour. The U flux of PM is shifted to 4.5 degree mechanical anti-clockwise in order to get the U flux intercept with 90° and 270°, thus the zero rotor position is obtained. Several flux linkage conditions of PM, FE coil and PM with FE coil are shown in the Fig.7. Approximately, 0.005Wb maximum amplitude is obtained from generated flux in PM condition only while 0.25Wb maximum amplitude is obtained from generated flux in PM with FEC condition. It can be seen from Fig.7 that the generated flux obtained from PM with FEC condition is higher than PM only because it has two flux sources of the machine.

Rotor Flux Observation

Since dual rotor HEFSM never been investigated, effect of each single rotor; inner and outer to the resulting

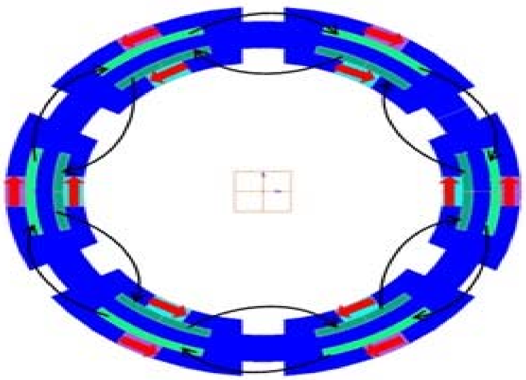


Figure-3. PM and FEC coil arrangement.

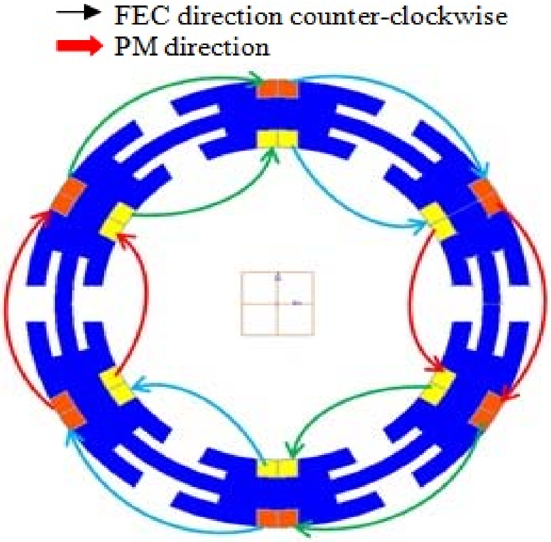


Figure-4. Armature coil windings.

Table-1. The proposed DRHESM initial design parameters.

Parameter	Detail	Value
	PM volume(kg)	**1.0**
D1	Outer Rotor radius (mm)	132
D2	Outer Rotor pole height (mm)	9
D3	Outer Rotor pole width (mm)	13.384
D4	Inner Rotor radius (mm)	78
D5	Inner Rotor pole height (mm)	24.52
D6	Inner Rotor pole width (mm)	13.384
D7	Stator Radius (mm)	112.4
D8	PM width (mm)	4.35
D9	PM height (mm)	18.124
D10	FEC width (mm)	4.35
D11	FEC height (mm)	23.873
D12	Armature coil width (mm)	18.124
D13	Armature coil height (mm)	23.6

fluxes are being observed. Three conditions are tested namely only outer rotor on, only inner rotor on and dual rotor on. In the first condition; only outer rotor on, the motion of the outer rotor are set to rotate while the inner rotor have no motion and remain static. This test conducted in order to observe the resulting flux produced. Figure-8 shows the flux produced under this condition. It can be observed that only six sinusoidal waveforms of fluxes are produced while the other six flux remains constant. Based on the observation, when only outer rotor rotates, incomplete flux cycles are obtained.

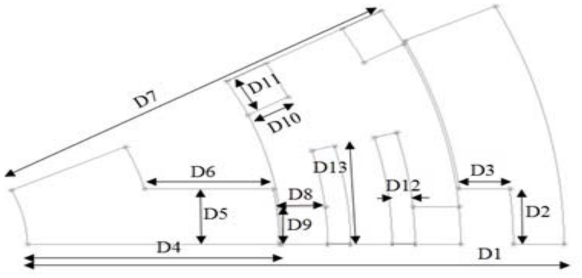


Figure-5. Design parameter for DRHEFSM.

In the second condition, opposite condition are set. Figure-9 shows the flux produced that initially produces sinusoidal waveform become constant while oppositely the flux that initially produce constant waveform become sinusoidal waveform. From this two conditions, it can be concluded that the rotating rotor only effect the active parts near it while the active parts located far from it are producing constant flux due to the presence of PM. In the last condition, both outer and inner rotor motion are set to simultaneously rotate and thus Figure-10 shows the complete 12 flux sinusoidal waveform cycle.

Various FEC Current Densities Magnetic Flux Linkage

Variety FEC current densities are examined in order to validate the flux behaviour. Figure-11 demonstrates the flux linkage of PM and various DC FEC current densities. It shows that when the DC FEC current density, J_e increases with regards to the flux linkage and reaches the maximum value when J_e is set to 10A/mm^2. Approximately 0.025Wb maximum flux is obtained; three times higher when compared with the flux linkage of PM only. When J_e is further increased, only small increment is seen and is expected to occur because of the flux has become saturated. This observation has proven that the DC FEC can improve the generated PM flux thus make the flux easily controllable.

Flux Line

Figure-12 demonstrates the flux path of PM with maximum FEC for 6S-7P DRHEFSM at open circuit condition. Obviously that most of PM flux flows from stator to rotor meanwhile in DC FEC, the remaining flux flows through it in order to complete 12 cycle flux. Additionally, unnecessary flux leakage and flux cancelation will occur if huge number of flux flows in the rotor.

The induced voltage generated at open circuit condition from FEC with speed of 1200 rpm is shown in Figure-13 DRHEFSM has amplitude of 16V and in a sinusoidal waveform. The induced voltage obtained is small, approximately 2.5% of the supplied voltage.

Cogging Torque

The proposed model cogging torque is illustrated in Figure-14. The peak to peak cogging torque value obtained

Table-2. Design restrictions and specifications of DRHEFSM.

Items	DRHEFSM
Max. DC-bus voltage inverter (V)	415
Max. inverter current (A)	360
Max. current density in armature winding, J_a(A_{rms}/mm^2)	30
Max. current density in excitation winding, J_e(A/ mm^2)	30
Outer Rotor outer diameter (mm)	264
Motor stack length (mm)	70
Shaft radius (mm)	30
Outer and Inner Air gap length (mm)	0.4
PM weight (kg)	1.0

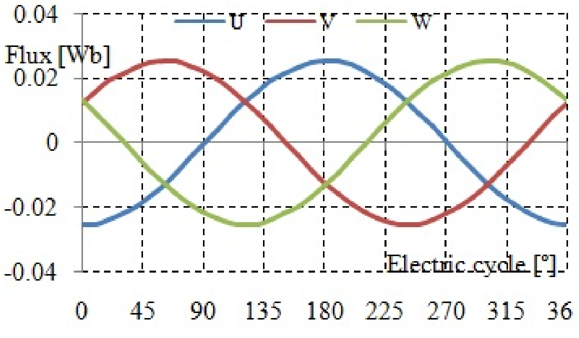


Figure-6. U, V, W phase of magnetic flux.

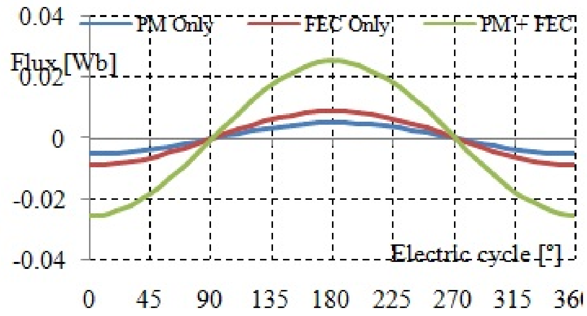


Figure-7. Combination of U flux for PM only, FEC only and PM + FEC.

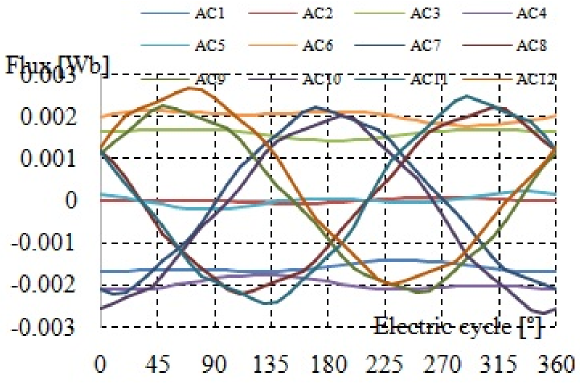


Figure-8. Only outer rotor on condition.

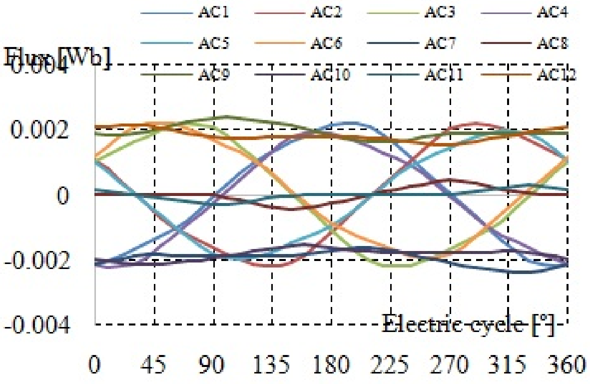


Figure-9. Only inner rotor on condition.

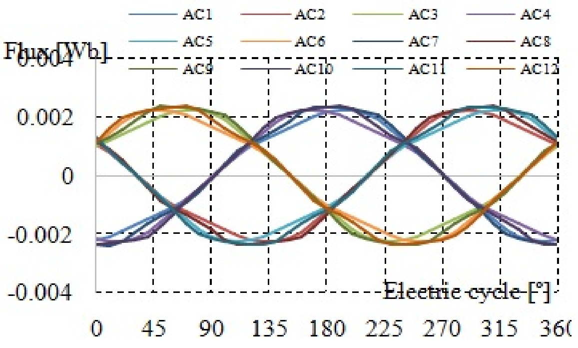


Figure-10. Dual rotor on condition.

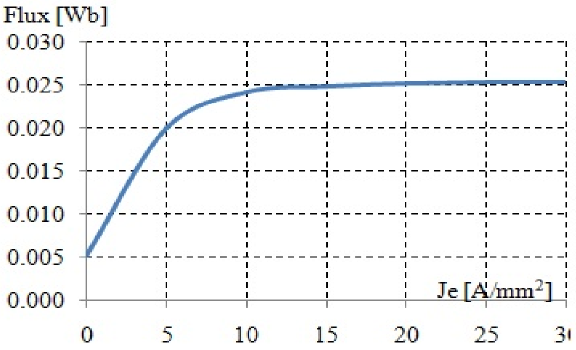


Figure-11. Flux behavior of FEC at Different $J_{e.}$

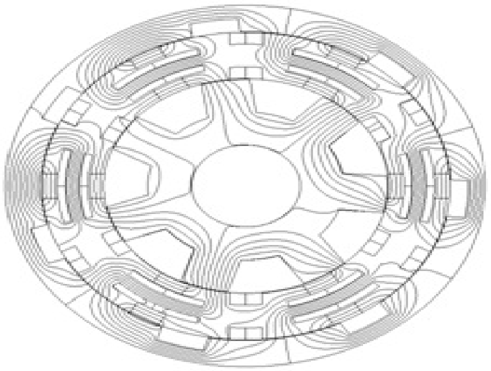


Figure-12. Flux path of PM with maximum FEC.

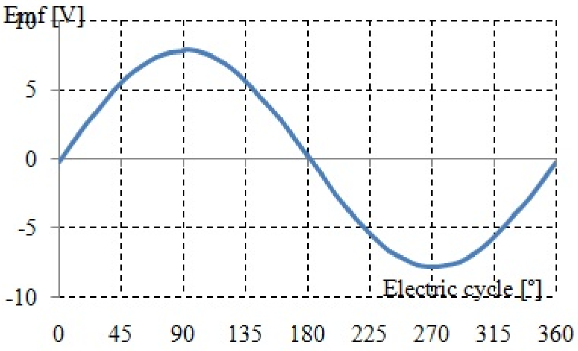


Figure-13. Induced voltage at 1200 r/min.

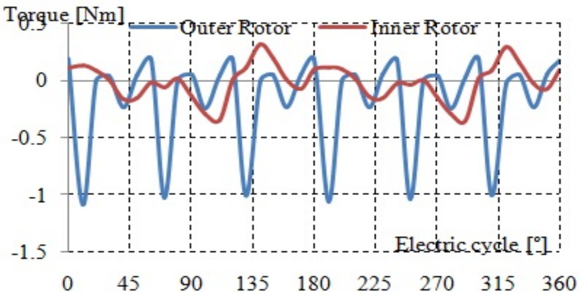


Figure-14. Cogging torque.

for outer rotor is 1.3 Nm while the peak to peak value for inner rotor is 0.7 Nm. Although the cogging torque for outer rotor is higher than inner rotor but it can be ignored due to less value.

CONCLUSIONS

As conclusion, analysis and design study of DRHEFSM has been investigated in this paper. The design procedure for DRHEFSM has been clearly explained. The operating principle for DRHEFSM has been proven by coil arrangement test. The performances of the proposed motor such as flux capability, cogging torque and back-emf characteristic have been investigated. Hence, further load analysis and design modification are expected to meet the target performances of DRHEFSM.

ACKNOWLEDGEMENTS

This work funded by Research Innovation, Commercialization and Consultancy management (ORICC) with Vot No E15501, Universiti Tun Hussein Onn Malaysia (UTHM) and Ministry of Education Malaysia (MOE).

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