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Performance Analysis of a New Structure Hybrid Excitation Flux Switching Motor for High-Speed Hybrid Electric Vehicles

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AbstractHybrid excitation machines (HEMs) that consist of permanent magnet (PM) and field excitation coil (FEC) as their main flux sources has several attractive features compared to interior permanent magnet synchronous machines (IPMSM) conventionally employed in hybrid electric vehicles (HEVs). Among various types of HEM, the machine with both permanent magnet and field excitation coil located on the stator has the advantage of robust rotor structure similar with switch reluctance machine (SRM). In addition, the variable flux control capabilities from FEC make this machine becoming more attractive to be applied for high-speed motor drive systems. This HEM can be categorized as hybrid excitation flux switching machine (HEFSM). In this paper, a newl 12Slot-10Pole HEFSM in which the FEC is wounded in radial direction on the stator is proposed for traction drives in HEVs. The design target of the proposed motor is a maximum torque of 210Nm with reduction gear ratio of 4: 1, a maximum power of 123kW, a maximum power density of more than 3. 5kW/kg, and a maximum speed of 20, 000r/min with similar restrictions and specifications in IPMSM used for Lexus RX400h. Deterministic design optimization method based on 2D-FEA is used to treat design parameters defined in rotor, armature coil slot and FEC slot until the target performances are achieved, under maximum current density condition for both armature coil and FEC. The final results show that the final design HEFSM is able to keep the same torque density in

existing IPMSM installed on commercial HEV. 1. IntroductionA demand for vehicles using electrical propulsion drives is getting higher and higher from the standpoints of preventing global warming and saving fossil fuel recently. As one of the vehicles, many automotive companies have commercialized Hybrid Electric Vehicles (HEVs) in which Interior Permanent Magnet Synchronous Motors (IPMSM) have been employed as a main traction motor in terms of high torque and/or power density, and high efficiency over most of operating torque-speed range. This is due to the restriction of motor size to ensure enough passenger space and the limitation of motor weight to reduce fuel consumption. As an example, the historical progress in the power density of main traction motor installed on Toyota HEV show that the power density of each motor employed in Lexus RX400h '05 and GS450h ' 06 has been improved approximately five times and more, respectively, compared to that installed on Prius '97 [1]. Although the torque density of each motor has been hardly changed, a reduction gear has enabled to elevate the axle torque necessary for propelling the large vehicles such as RX400h and GS450h. As one of effective strategies for increasing the motor power density, the technological tendency to employ the combination of a high-speed machine and a reduction gear would be accelerated. With the significant achievements and improvements of permanent magnet materials and power electronics devices, the brushless machines excited by PM associated with FEC are developing dramatically. This type of machine is called hybrid excitation machine (HEM) that can be classified into four categories. The first type consists of both PM and FEC at rotor side such as combination rotor hybrid excitation (CRHE) machine and synchronous/PM

hybrid AC machine [2-4]. The second type consists of PM in the rotor while FEC is in the stator [5]. The third type consists of PM in the rotor while the FEC is in the machine end [6-7]. Finally, the fourth type of HEM is the machine, which has both PM and FEC in the stator [8-10]. It should be emphasized that all HEMs mentioned in the first three have a PM in the rotor and can be categorized as " hybrid rotor-PM with field excitation machines" while the fourth machine can be referred as " hybrid stator-PM with field excitation machines". Based on its principles of operation, the fourth machine is also known as " hybrid excitation flux switching machine (HEFSM)" which is getting more popular recently. HEFSM with all active parts, namely permanent magnet, DC field excitation coil and armature coil located on the stator has an advantage of robust rotor structure being similar to the switch reluctance machine (SRM), which makes it more suitable for high-speed drive applications compared to " hybrid rotor-PM with field excitation machines" and conventional IPMSM [11]. Furthermore, since all active parts are located in the stator body, it is expected that a simple cooling system can be used for this machine when compared with a water jacket system used in IPMSM. In addition, the additional DC FEC can also be used to control flux with variable flux capabilities. Various combinations of stator slot and rotor pole for HEFSM have been developed for high-speed application. For example, 12Slot-10Pole HEFSM has been proposed such as in [12-13]. However, the proposed machine in [12] has a separated PM and C-type stator core that makes it difficult to manufacture, and the design is not yet optimized for HEV applications while the machine in [13] has a limitation of torque and power production in high current density condition. This is due

to insufficient stator yoke width between FEC and armature coil slots resulting in magnetic saturation and negative torque production [14]. However, after some design refinements and improvements especially on the stator yoke mentioned above and both armature and FEC slots area, the improved machine is capable to operate at desired performances for HEV application [15-16]. To reduce the supply frequency of inverter, 6Slot–5Pole HEFSM for HEV application has been proposed by the authors. Although the proposed machine has met the target performances, the problem of unbalanced pulling force due to odd number of poles is difficult to overcome [17-18]. Other than that, some researchers have proposed 6Slot-8Pole machines but these types of machines have problems of high torque ripple and back-emf waveforms, which are usual concerns for this kind of eight pole machine [19-20]. It should be noted that all HEFSM mentioned above are having an arrangement of armature coil and FEC in theta direction. In this paper, based on the topology of HEFSM discussed above, a new 12Slot-10Pole HEFSM in which the arrangement of FEC in radial direction is proposed for HEV applications. The comparison between the optimize design of 12Slot-10Pole HEFSM in [15] and the initial design of the proposed HEFSM is illustrated in Fig. 1 and Fig. 2, respectively. It is obvious that the main difference between these two machines is the FEC configurations that are wounded in theta and radial polarity, respectively. From Fig. 2, the proposed motor is composed of 12 PMs and 12 FECs distributed uniformly in the midst of each armature coil. In this 12Slot-10Pole motor, the PMs and FECs produce six north poles interspersed between six south poles. The three-phase armature coils are accommodated in the 12 slots for each 1/4 stator body

periodically. As the rotor rotates, the fluxes generated by PMs and mmf of FECs link with the armature coil alternately. For the rotor rotation through 1/10 of a revolution, the flux linkage of the armature has one periodic cycle and thus, the frequency of back-emf induced in the armature coil becomes ten times of the mechanical rotational frequency. Generally, the relation between the mechanical rotation frequency and the electrical frequency for this machine can be expressed as;(1)where fe is the electrical frequency, fm is the mechanical rotation frequency and Nr is the number of rotor poles respectively. The cross-sectional view of flux paths caused by both PM and mmf of FEC of the initial design HEFSM is depicted in Fig. 3. The presence of DC FEC makes this type of motor becoming more attractive in terms of modulating the PM flux. The design restrictions and specifications for the target HEV applications are discussed in Section II. Initially, the performance of the proposed machine is calculated using 2D- finite element analysis (FEA), but the target torque and power are not achieved for the target HEV applications. Therefore, design optimization studies are conducted to get maximum performances for HEV applications. The method of getting the maximum performances is explained in Section III. In addition, the flux line of PM and FEC at open-circuit condition, the rotor mechanical strength, the PM demagnetization at high temperature, the torque and power factor versus FEC current density characteristics, the torque and power versus speed characteristics, the loss and the efficiency are also predicted and discussed in Section IV. Finally some conclusions are drawn in Section V. Fig. 1. 12Slot-10Pole HEFSM with FEC in theta polarityFig. 2. Initial design of a novel12Slot-10Pole HEFSM withFEC in radial polarityFig. 3. Flux paths of permanent

magnet and FEC for theproposed 12Slot-10Pole HEFSMStator

yokeRotorExcitation coilArmature CoilShaftPermanent magnetStator

yokeRotorExcitation coilArmature CoilShaftPermanent magnet

2. Design Restriction and Specifications for Hybrid Electric Vehicle Application

The design restrictions and target specifications of the proposed HEFSM for

HEV applications are listed in Table 1. The table includes the available and

estimated specifications of the motor for same items with IPMSM for Lexus

RX400h as in [11] and HEFSM in [15-16]. The electrical restrictions related

with the inverter such as maximum 650V DC bus voltage and maximum

240V inverter current are set. Assuming that only a water cooling system is

employed as the cooling system for the machine, the limit of the current

density is set to the maximum of 20Arms/mm2 for armature winding and

20A/mm2 for FEC. The outer diameter, the motor stack length, the shaft

radius and the air gap of the main part of the machine design being 264mm,

70mm, 30mm and 0. 8mm respectively, are identical with those of IPMSM.

Under these restrictions, the weight of the PM is set to be 1. 0kg. It can be

expected that the rotor structure is mechanically robust to rotate at high-

speed because it consists of only stacked soft iron sheets, so that the target

maximum operating speed is elevated up to 20, 000r/min. The target

maximum torque of 210Nm is determined from the realization of comparable

maximum axle torque with the present IPMSM via reduction gear ratio of 4:

1. The target maximum power is set to be more than 123kW and the motor

weight to be designed is less than 35kg, resulting in that the proposed

HEFSM promises to achieve the maximum power density of 3. 5kW/kg similar

to that estimated of HEFSM in [15-16] and IPMSM in Lexus RX400h. Commercial FEA package, JMAG-Designer ver. 12. 0, released by Japanese Research Institute (JRI) is used as 2D-FEA solver for this design. The PM material used for this machine is Neomax 35AH whose residual flux density and coercive force at 20C� are 1. 2T and 932kA/m, respectively while the electrical steel 35H210 is used for rotor and stator body. Table 1. HEFSSM Design Restriction and Specifications for Hybrid Electric Vehicle ApplicationItemsIPMSM RX400h12S-10P HEFSSMMax. DC-bus voltage inverter (V)650650Max. inverter current (Arms)Confidential < 240Max. current density in excitation winding winding, Ja (Arms/mm2)Confidential < 20Max. current density in excitation winding, Je (A/mm2)NA < 20Stator outer diameter (mm)264264Motor stack length (mm)7070Shaft radius (mm)3030Air gap length (mm)0. 80. 8PM weight (kg)1. 1 (est.)< 1. 0Maximum speed (r/min)12, 40020, 000Maximum torque (Nm)333> 210Reduction gear ratio2. 4784Max. axle torque via reduction gear (Nm)825> 840Max. power (kW)123> 123Power density (kW/kg)3. 5> 3. 5

3. Design Parameters and Procedures

Initially, performance of the proposed HEFSM is calculated using 2D-FEA, but the target torque and power are not achieved for the target HEV applications. To overcome this problem, design free parameters, D1 to D8 are defined in rotor and stator sides as illustrated in Fig. 4. Basically, the design parameters are divided into four groups such as those related to rotor core, FEC slot shape, armature coil slot shape and PM. The rotor parameters are rotor radius (D1), rotor pole height (D2), and rotor pole width (D3). The FEC slot shape parameters are PM height (D4), FEC slot width (D5) and FEC

sloth height (D6). The armature coil slot shape parameters are armature coil width (D7), and armature coil height (D8), respectively. The first step is carried out by updating rotor parameters, D1, D2 and D3 while keeping D4 to D8 constant. Generally, since the torque increases with the increase in rotor radius, D1, which is considered as the dominant parameter to improve the torque, is firstly treated. Here, D4 to D8 are shifted by following the change of D1. Then, by selecting D1 at the maximum torque and power capabilities, both the rotor pole height D2 and the rotor pole width D3 are varied until the combination of maximum torque and power are achieved. Once the maximum torque and power for D2 and D3 are determined, the second step is carried out by updating the FEC slot parameters D4, D5 and D6 while keeping the rotor parameters D1 to D3, and the armature coil slot parameters D7 and D8, constant. Then, by using the combination of D4 to D6 that bring out the maximum torque and power at the second step, the third step is carried out by varying the armature coil slot parameters D7 and D8 with keeping other parameters discussed above constant. The necessary armature coil slot area, Sa is determined by varying armature coil height, D7 and armature coil width, D8 to accommodate natural number of turns, Na for armature coil. This design method is treated repeatedly by changing D1 to D8 until the target maximum torque and maximum power are achieved. All design parameters are adjusted with keeping 0. 8mm air gap length and 1. 0kg PM constant under maximum current density condition for both armature coil and FEC. This method of optimization is also known as " deterministic optimization method" and the general flow diagram of this method is illustrated in Fig. 5. After several cycles of optimization are

conducted, the HEFSM with 1. 0kg PM has successfully achieved the target torque of 210Nm, but the power obtained at maximum torque is approximately 81kW, which is less than expected. Further design refinements and optimization will be conducted to solve this problem. The final design of the proposed HEFSM is shown in Fig 6, while the flux line due to the flux of PM and combination of flux of both PM and mmf of FEC is illustrated in Fig. 7 and Fig. 8 respectively. The parameters between initial and final HEFSM design are compared and listed in Table 2. Fig. 4. Design parameter defined as D1 to D8D4D5D6D7D8StatorFEPMD1D2D3Air gap(0. 8mm)RotorShaftFig. 6. Improved design of a new 12Slot-10Pole HEFSMStator yokeRotorExcitation coilArmature CoilShaftPermanent magnetFig. 5. General flow diagram of deterministic design approachYesStartChange Rotor ParametersD1, D2, D3Change Field Excitation Parameters D4, D5, D6Change Armature Slot Parameters D7, D8P= 123kWT= 210NmEndNoTable 2. Initial and Final Design Parameters of 12S-10P HEFSM for HEV ApplicationsParametersDetailsPM yolume (kg)Initial1. 0Final1. 0D1Rotor radius (mm)84. 293. 2D2Rotor pole height (mm)21. 229. 2D3Rotor pole width (mm)10. 011. 0D4PM height (mm)23. 623. 0D5FEC width (mm)14. 012. 0D6FEC height (mm)7. 06. 3D7Armature coil width (mm)6. 57. 5D8Armature coil height (mm)23. 626. 7NaNo. of turns of armature coil710TTorque (Nm)146. 0210. 2PPower (kW)81. 181. 1pfPower factor0. 4240. 424

4. Design Results and Performances Based on 2D-Finite Element Analysis

A. Rotor Mechanical Stress at High-Speed

The mechanical stress prediction of the rotor structure at the maximum speed 20, 000r/min is executed by centrifugal force analysis based on 2D-FEA. Fig. 9 illustrates the principal stress distributions of the rotor core for the finally designed HEFSM. The highest stress can be found at a point highlighted in circle. The maximum stress reaches 107. 87MPa which is much smaller than 300MPa being allowable as the maximum principal stress in conventional electromagnetic steel. This is a great advantage of HEFSM with robust rotor structure that makes it applicable for high-speed application compared to IPMSM.

B. Torque Characteristics

Fig. 10 illustrates the final torque waveforms of the new HEFSM based on FEA and analytical method for one electrical cycle at 3000r/min. It is obvious that good agreements are achieved between both methods with the peak-peak value being approximately 53. 2Nm.

C. Torque and Power versus Speed Characteristics

The torque and power versus speed curves of the final design HEFSM is plotted in Fig. 11. The solid black line depicts the torque-speed curve of the finally designed motor while the dotted black line represents the torque-speed of HEFSM in Fig. 1 for comparison. For the new design HEFSM, at base speed 3, 684r/min, the torque obtained is 210. 2Nm, while for the HEFSM in Fig. 1, at base speed 5, 556r/min, the torque obtained is 212. 5Nm as the

maximum, respectively. The corresponding power obtained from the new design HEFSM at the maximum torque is 81. 1kW, approximately 34% less from the target 123kW power with the power factor of 0. 43. In contrast with the other design, the power obtained at maximum torque is 123. 1kW with the power factor of 0. 64. The average power of 87. 6kW is achieved between 5, 000 - 7, 000r/min. The total mass of the finally designed motor estimated including rotor, stator, PMs and coil end of both armature and field excitation windings is 28. 1kg, yield the maximum torque density and power density of 7. 48Nm/kg and 3. 12kW/kg, respectively. 107. 87MPaFig. 9. Principal stress distribution of rotor at 20, 000r/minFig. 11. Torque and power versus speed characteristics comparison between HEFSM in Fig. 1 and the new design HEFSMFig. 10. Final torque waveforms based onFEA and analytical at 3000r/min

D. Motor Loss and Efficiency

The motor loss and efficiency are calculated by finite element analysis considering copper losses in the armature winding and iron losses in all laminated cores. Fig. 11 also demonstrates specific operating points under light load driving condition noted as No. 1 to No. 4. Table 3 summarizes motor efficiency of the designed HEFSM under the frequent operating points. Although HEFSM in Fig. 1 realizes good efficiency above 94% over the most of operating region, the new design HEFSM can also work with high-efficiency as much as 91% to 93%. The overall performances of the new HEFSM and the HEFSM in Fig. 1 based on finite element analysis are compared and summarized in Table 4. Despite the target power and power density of the new design HEFSM are not successfully achieved, it should be noted that the

proposed and discussed HEFSM in this paper has proof the principle of the flux switching concept which lead to the new design contribution of hybrid excitation machine. Table 3. Performance Comparison of the Final Design 12S-10P HEFSM for HEV ApplicationsNo. of operating pointCopper lossMotor efficiency [%]Iron lossOutput power(1)6. 242. 4891. 28(2)4. 203. 1192. 69(3)4. 923. 2291. 86(4)2. 914. 0493. 05Table 4. Performance Comparison of the Final Design 12S-10P HEFSM for HEV ApplicationsItemsHEFSM(Original)HEFSM(New)PM weight (kg)1. 01. 0Maximum speed (r/min)20, 00020, 000Maximum torque (Nm)212. 5210. 2Reduction gear ratio44Maximum axle torque via reduction gear (Nm)850840. 8Maximum power at 5000-7000r/min (kW)131. 187. 6Rotor mechanical stress at 20, 000r/min (MPa)70. 6107. 9Torque density (Nm/kg)27. 328. 1Power density (kW/kg)4. 803. 12Motor efficiency over most of operating region> 94%> 91%

5. Conclusion

In this paper, a novel 12Slot-10Pole HEFSM with PM, FEC and armature windings located in the stator are proposed based on the flux switching topology. The novelty of the proposed design is the arrangements of FEC in radial direction in contrast with traditional HEFSM with the FEC arrangements in theta direction. Design optimization studies and performance analysis of the HEFSM for traction drive in the target HEV is also presented and clearly demonstrated. The rotor mechanical stress predicted is good enough for the motor to run in high-speed region. Even though the target torque of the final motor is successfully achieved, but the power obtained is less than the

target power, further design refinements will be conducted to solve this problem.