Optimization Method to Maximize Efficiency of a Drive Motor with Electrical Winding Changeover Technic for Hybrid EV

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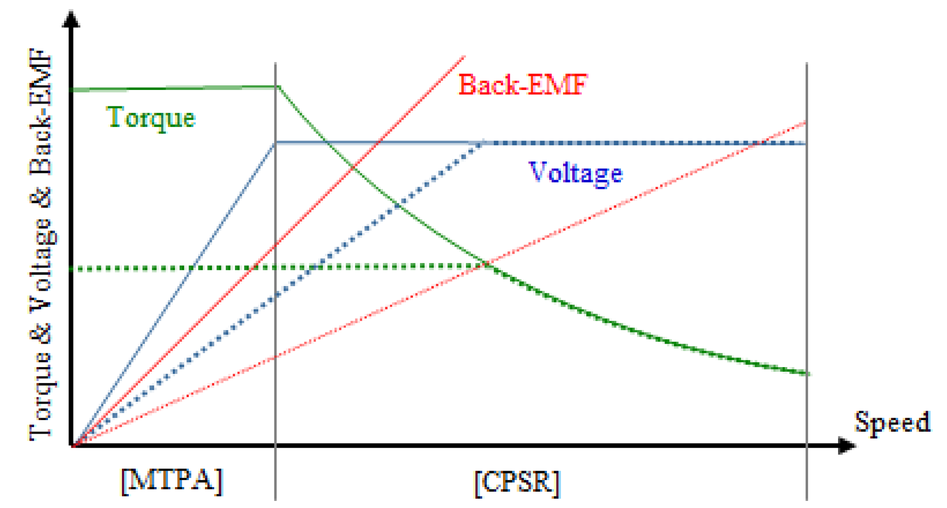
MT 26 International Conference on Magnet Technology
Vancouver, Canada | 2019

Introduction

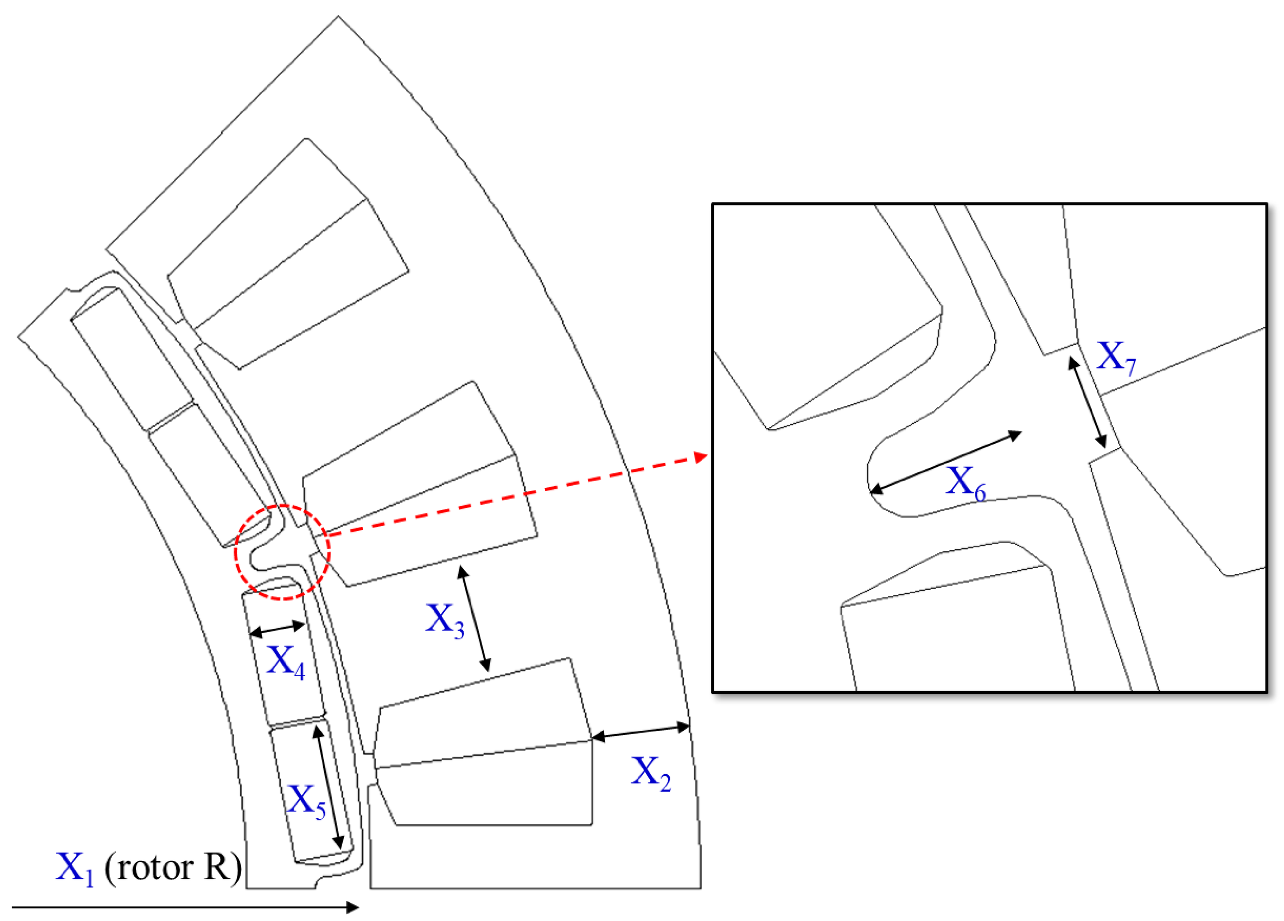
Recently, eco-friendly vehicles such as pure electric vehicles (EVs), hybrid EVs and plug-in hybrid EVs (PHEVs) have been the subject of many studies in a dramatically accelerated effort to increase the total driving distance on a single charge. The motors are required to operate over a wide operating speed range according to operating characteristics of HEVs, which should improve the efficiency in the frequent operating range. To achieve this improvement, this paper presents optimal design of interior permanent magnet synchronous motor (IPMSM) with electrical winding changeover technic (EWCT) to maximize the efficiency of hybrid EV based on finite-element analysis. Since IPMSM has outstanding performance in terms of wide operating speed range, high efficiency and power density, IPMSM has often been used in EV applications. However, because a back-electromagnetic force (EMF) of the IPMSM increases linearly with speed, the motor can be damaged by an excess voltage at an overspeed. The EWCT is a method to switch the number of turns to decrease the back-EMF at high speed, which can extend the operating speed range under a limited maximum voltage. For this motor, two switching steps of EWCT were adopted, where the turn number of the first step is twice that of another step. According to two switching steps, the performance of the IPMSG changes greatly in terms of field weakening control, winding resistance, magnitude and phase shift of current, etc. These characteristics also affect the efficiency including copper loss and iron loss. As a result, the two efficiency maps are presented, which can be operated for better efficiency.

Electrical Winding Changeover Technic

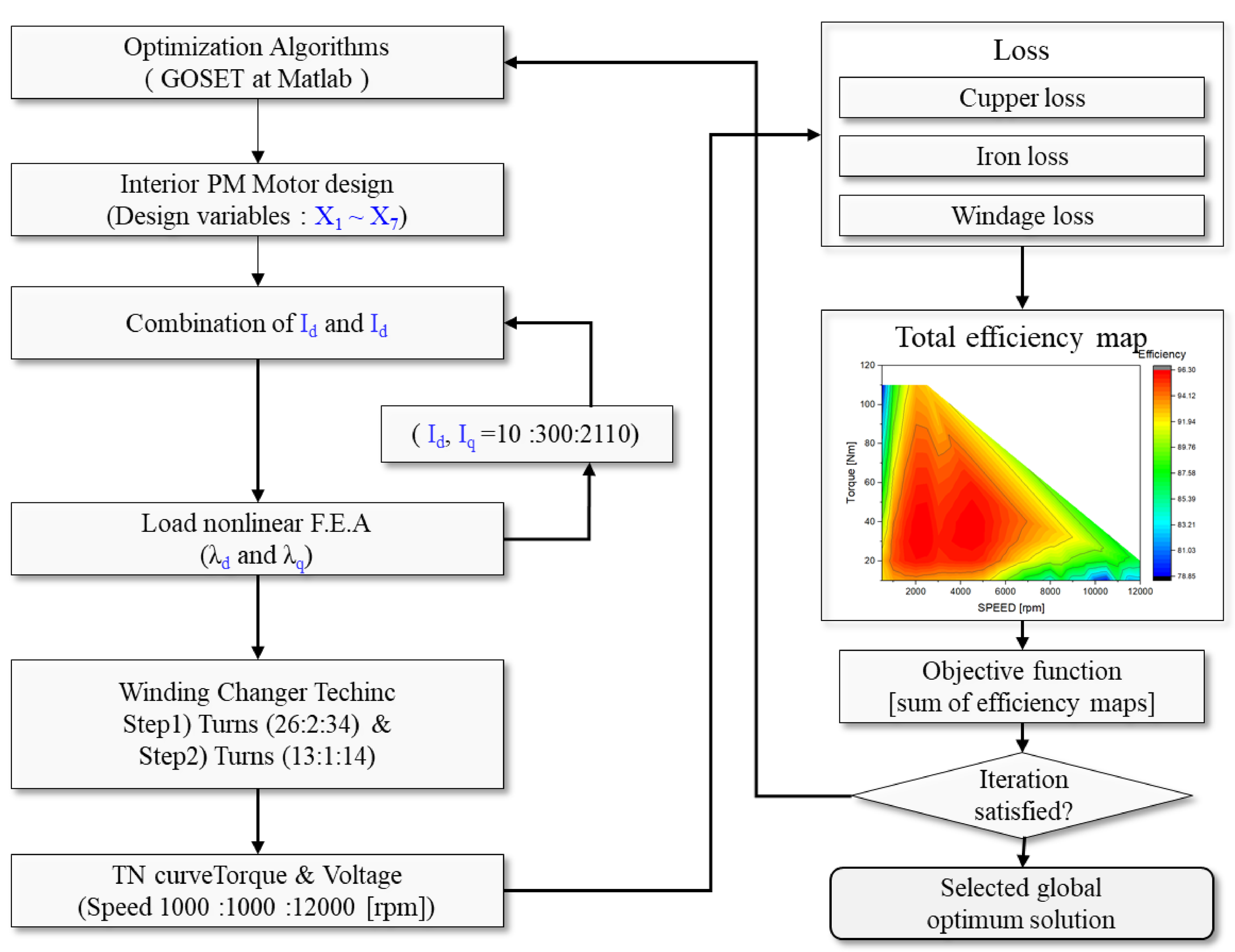


The key point to improve the total driving distance on a single charge is to increase an efficiency map of propulsion motor. The motor has wired operating ranges from low speed to high speed. Since increasing the efficiency are trade off according to speed, it is not easy to improve the efficiency at the whole operating rages. Also the counter back EMF can exceed over the inverter voltage limit, which affect series damage EV system. In hence, when designing motors, a magnitude of back EMF should be limited. In case of Electronic winding changeover can be solve that. The turn number is changed automatically by switching. Low turn number can be reduce a winding resistor and copper loss. Therefore, it expect high efficiency at the whole operating range. In particular, since its back-EMF becomes smaller than large turn number, propulsion system can be atable.

Optimization method



< Design variables for interior PM synchronous motor >



< Flowchart for maximizing efficiency map >

Procedure

► Procedure-1) Optimization Algorithms and Modeling

The Genetic Optimization System Engineering Tool of MATLAB was used as optimization algorithms for generating seven design variables from Table II.

► Procedure-2) Finite element analysis

At the beginning, Since winding turn and parallel number are linear to λd and λq, the turn number and parallel set up as 1 and 4, respectively. To obtain a performance and efficiency map of motor, λd and λq are calculated to compatible with combination of id and iq (10:300:2110) based on FEA. Where, λ is flux linkage and i is current. The flux density of IPMSG gives rise to the characteristics of the magnetic saturation according to the armature current. Therefore, the flux linkage numerically is obtained based on non-linear FEA for better accuracy.

► Procedure-3) Electrical Winding Changeover Technic

The combinations of λd and λq, are recalculated according to turns number (step-1=26:2:34, step-2=13:1:17) following as

$$\lambda_{ds} = \frac{N}{P_l}\phi_{ds},\ \lambda_{qs} = \frac{N}{P_l}\phi_{qs}$$

. Where is the parallel number and N is turns number.

► Procedure-4) Torque & voltage

According to speed (1000:1000:12,000 rpm), the torque and voltage equations are calculated by current and λ matric following as

$$V_{ds}=R_s i_{ds}+L_{ds}\frac{di_{ds}}{dt}-\omega_r L_{qs} i_{qs}=R_s i_{ds}-\omega_r\lambda_{qs} \quad V_{qs}=R_s i_{qs}+L_{qs}\frac{di_{qs}}{dt}+\omega_r(L_{ds} i_{ds}+\lambda_f)=R_s i_{qs}+\omega_r\lambda_{ds} \quad T_e=\frac{3}{2}\frac{P}{2}(\lambda_{ds} i_{qs}-\lambda_{qs} i_{ds})$$

where, and are d- and q- flux linkage of stator windings, respectively, is the pole number. Since several combination of id and iq can have same torque, minimum current was chosen among of them under voltage limit.

► Procedure-5) loss calculating

The copper loss, iron loss and windage loss are calculated.

$$W_{cu}=3I_{rms}^2 R_s=3I_{rms}^2 R_{20}(1+\alpha(T-20)) \quad W_{iron\_e}=\int_{iron}\sum_n K_e D(nf)^2(B_{r,n}^2+B_{\theta,n}^2)dv \quad W_{iron\_h}=\int_{iron}\sum_n K_h D\ (nf)(B_{r,n}^2+B_{\theta,n}^2)dv$$

where is the stator winding resistance [Ω] at 20℃, is the temperature coefficient, is frequency [Hz], and are the coefficient of hysteresis loss and eddy-current loss, is the lamination length [mm], and and are the n th harmonic order of the radial and peripheral components of flux density.

► Procedure-6) Efficiency map

Through procedure-3, there are efficiency maps of 5 step-1 and 5 step-2. As one-to-one correspondence, higher efficiency value at each operating point are chose at each turn number. Final 5 efficiency map can left.

► Procedure-7) Objective function

Objective function is sum of efficiency at all operating point of best turn number, which best efficiency map left through comparison each other.

$$f_{ob}(x)=\sum_{speed}\sum_{Torque} Efficiency$$

► Procedure-8) Termination condition

The procedures iterate by GOSET until termination condition. GOSET set up generator, Population:20, generation:20, compter:4.

Specification

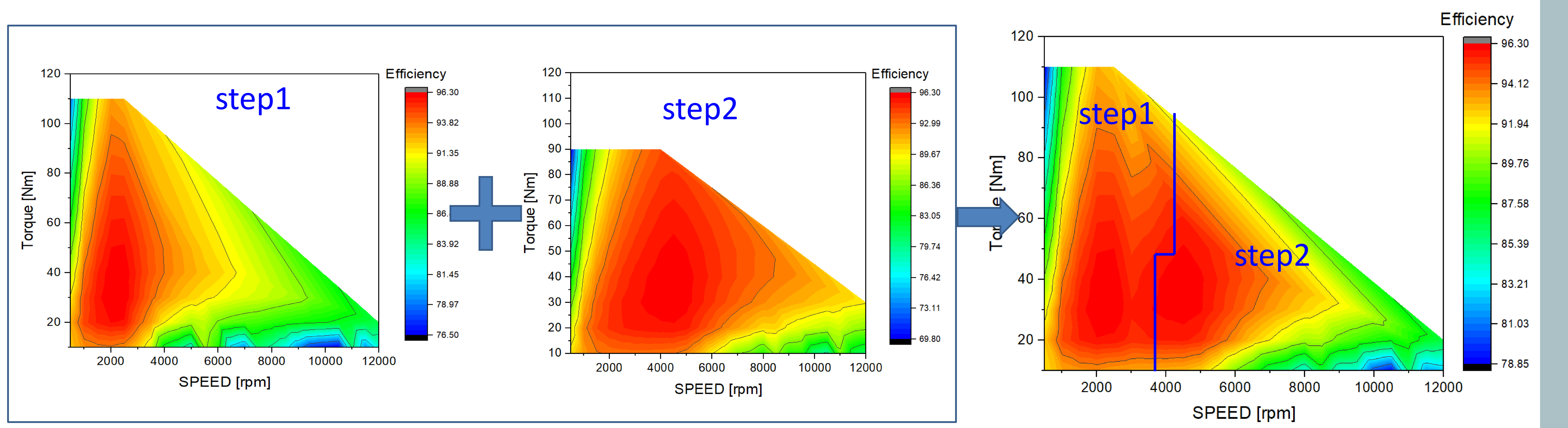
< Specification >

Section	Parameter	values	Unit
Performance	Rated Power	30	[kW]
	Rated speed	2500	[rpm]
General	No. of Pole/Slot	16 / 24	-
	No. of Phase	3	-
	Air-Gap	0.8	[mm]
Stator	Outer Diameter	140	[mm]
	Axial length	37	[mm]
	Core Material	Silicon Steel	-
Rotor	Permanent Magnet	1.2	[T]

< Boundary range and optimized variables>

Sym.	Defined	Upper	Lower	Optimized	Unite
X1	Rotor R	105	98	103.0	[mm]
X2	Yoke depth	25	15	24.1	[mm]
X3	Teeth	10	6	6.9	[mm]
X4	PM height	8	4	7.7	[mm]
X5	PM width	16	12	13.7	[mm]
X6	Slitting depth	1.2	0.5	0.57	[mm]
X7	Opening	1.5	0.7	0.92	[mm]

Results



Conclusion

This paper presented the proposed optimization method for hybrid EV with electrical winding changeover Technic. Since the electrical winding changeover Technic changed winding turns number, the efficiency maps are different according to the turns number. For maximizing the efficiency maps, GOSET of MATLAB is used. As results of efficiency, step-1 mode and step-2 mode are compared each other. As expected, step-1 mode has higher efficiency at low speed, while step-2 mode has higher efficiency at high speed. Finally, these two efficiency maps generate finalized efficiency maps. It shows higher efficiency map than baseline model.