Multi-Objective Optimization Design of In-Wheel Switched Reluctance Motors in Electric Vehicles

X. D. Xue, *Member, IEEE*, K. W. E. Cheng, *Senior Member, IEEE*, T. W. Ng, and N. C. Cheung, *Senior Member, IEEE*

***Abstract*—The method of the optimization design with multi-objectives for switched reluctance motors (SRMs) in electric vehicles (EVs) is proposed in this paper. It is desired that electric motors for EVs have high torque, high efficiency, and high torque density. Thus, the developed optimization function is selected as the correct compromise between the maximum average torque, maximum average torque per copper loss, and maximum average torque per motor lamination volume, by using three weight factors and three base values. The stator and rotor pole arc angles are selected as the optimized variables. Furthermore, the authors also discuss the design requirements and some constraints on the optimization design. The results of the optimization design show that the proposed method meets the requirements of EVs on electric motors well. A prototype of the optimally designed in-wheel SRM for EVs has been manufactured. This paper provides a valuable method to implement the optimal design of SRMs for EVs.**

***Index Terms*—Design, electric vehicles, in-wheel, optimization, switched reluctance motors (SRMs).**

Nomenclature

d_{ev}	Outer diameter of EV wheels.
D_r	Outer diameter of rotor.
D_s	Outer diameter of stator.
D_{sh}	Outer diameter of shaft.
F_{obj}	Objective function with multi-objectives.
F_{opt}	Optimization function with multi-objectives.
H_{rp}	Height of rotor pole.
H_{ry}	Thickness of rotor back iron.
H_{sp}	Height of stator pole.
H_{sy}	Thickness of stator back iron.
i	Phase current.
i_r	Rated phase current.
L_a	Inductance at fully aligned position.
L_g	Length of air gap.
L_s	Length of stator lamination.
L_u	Inductance at completely unaligned position.
N_r	Number of rotor poles.
N_s	Number of stator poles.
P_{Cu}	Copper loss.
R_{ph}	Phase resistance.
T_{ave}	Average torque.
T_b	Base value of average torque.
TP	Average torque per copper loss.
TP_b	Base value of average torque per copper loss.
TV	Average torque per motor lamination volume.
TV_b	Base value of average torque per motor lamination volume.
V_{core}	Volume of motor lamination.
v_{max}	Maximum vehicle velocity.
V_r	Volume of stator lamination.
V_s	Volume of rotor lamination.
W_a	Co-energy at fully aligned position.
w_{sp}	Width of stator pole.
w_t	Weight factor of average torque.
w_{tp}	Weight factor of average torque per copper loss.
w_{tv}	Weight factor of average torque per motor lamination volume.
W_u	Co-energy at completely unaligned position.
β_r	Pole arc angle of rotor.
β_r^{opt}	Optimal pole arc angle of rotor.
β_s	Pole arc angle of stator.
β_s^{opt}	Optimal pole arc angle of stator.
θ_{rp}	Pitch angle of rotor pole.
θ_{sp}	Pitch angle of stator pole.
ω_{max}	Maximum motor speed.

I. Introduction

In-wheel switched reluctance motors (SRMs) are well suited for electric vehicle (EV) applications due to their numerous advantages, such as simple and rugged motor construction, low weight, potentially low production cost, easy cooling, excellent power-speed characteristics, high torque density, high operating efficiency, inherent fault tolerance, direct-drive, high transmission efficiency, highly reliable and simple drivetrain system. As for EV applications, it is desired that electric motors have a high starting torque for initial acceleration, high torque density, and high efficiency to extend the battery serve-life and a wide operating speed range [1]–[4]. Consequently, design of SRMs in EVs has to give consideration to the three above requirements.

In [2], the design of SRMs for EVs was investigated and the three requirements mentioned above were summarized.

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The authors are with the Department of Electrical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong (e-mail: eexdxue@polyu.edu.hk; eeecheng@polyu.edu.hk; eetwng@polyu.edu.hk; norbert.cheung@polyu.edu.hk).

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However, how to accomplish those three requirements during designing SRMs was not mentioned. Rahman *et al.* discussed the effects of the stator and rotor pole arc angles on the constant-power range and the rated torque [3]. Rahman and Schulz proposed that the torque density is increased through the selection of a material having high saturation flux density, a small air gap, and a rectangular magnet wire [4]. In [5], the design features, drive circuits, and performance of single-phase SRMs for low power variable-speed drives are described. An illustration of the design method was given for an SRM excited with rectangular blocks of current in [6]. In [7], the torque production capability of two SRMs with different structures is compared theoretically. Miller described the fundamental theory for the practical development of a design calculation of SRMs [8]. DSP controller of SRM drives for high dynamic performance in EVs has been reported in [9]. Husain and Hossain presented the modeling, simulation, and control of four-quadrant SRM drives [10]. A dynamic two-phase excitation model of the SRM was presented and an experimental procedure to obtain the flux linkage data was described in [11]. In [12], an autocalibrating method for the proposed analytical model of a phase inductance was introduced and explained in detail. Xue *et al.* developed a new method to predict the performance of SRM drives [13]. A new type of linear SRM (LSRM) with twin stators and a translator was designed, simulated, analyzed in [14]. The integrated motor design was also examined for vehicle applications [15]. The authors of [16] discussed the effect of several geometrical parameters on the performance of a LSRM.

Those studies exhibit contributions to the development of SRMs. However, the three requirements mentioned above were not taken into account simultaneously in previous studies. Thus, it is noticeably beneficial for boosting EV performances to develop a systematic optimization design.

In this paper, three criterions will be proposed to evaluate the design of SRMs in EVs. These are the average torque, the average torque per copper loss, and the average torque per motor lamination volume. These three criterions imply torque, efficiency, and torque density, respectively. To obtain high torque, low copper loss, and high torque density, by using three weight factors and three base values, the authors will develop the optimization function with multi-objectives, which is defined as the correct compromise between maximum average torque, maximum average torque per copper loss, and maximum average torque per motor lamination volume. The optimized valuables are selected as the stator and rotor pole arc angles. In the meantime, the design requirements for EVs and constraints on the design will also be discussed. The design results match the three requirements of EVs on electric motors well.

II. Optimization Design of In-Wheel SRMs

A. Criterions

From the requirements of EVs on electric motors, in this paper, three criterions are proposed to evaluate the design of SRMs in EVs. They are the average torque, the average torque per copper loss, and the average torque per motor core volume. It can be seen that they imply torque, efficiency, and torque density, respectively.

The computation of the average torque is given as

$$T_{\mathrm{ave}} = \frac{(W_{\mathrm{a}} - W_{\mathrm{u}})N_{\mathrm{s}}N_{\mathrm{r}}}{4\pi} \tag{1}$$

$$W_{\mathrm{a}} = \int_0^{I_{\mathrm{r}}} L_{\mathrm{a}} i di \tag{2}$$

$$W_{\mathrm{u}} = \frac{1}{2} I_{\mathrm{r}}^2 L_{\mathrm{u}} \tag{3}$$

where I_{r} represents the rated phase current, L_{a} represents the inductance at the fully aligned position, and L_{u} represents the inductance at the completely unaligned position.

The copper loss is computed as

$$P_{\mathrm{Cu}} = I_{\mathrm{r}}^2 R_{\mathrm{ph}} \tag{4}$$

where R_{ph} represents the phase resistance.

Hence, the average torque per copper loss can be expressed as

$$TP = \frac{T_{\mathrm{ave}}}{P_{\mathrm{Cu}}}. \tag{5}$$

The motor lamination volume is calculated as

$$V_{\mathrm{core}} = V_{\mathrm{s}} + V_{\mathrm{r}} \tag{6}$$

where V_{s} represents the volume of stator lamination and V_{r} represents the volume of rotor lamination.

Consequently, the average torque per motor lamination volume is determined as

$$TV = \frac{T_{\mathrm{ave}}}{V_{\mathrm{core}}}. \tag{7}$$

B. Optimization Function With Multi-Objectives

The three criterions above are selected as the three design objectives of SRMs in this paper. Clearly, it is difficult to simultaneously maximize these objectives. Consequently, the correct compromise between the maximum average torque, maximum average torque per copper loss, and maximum average torque per motor lamination volume, is defined as the optimization function, which is expressed as

$$F_{\mathrm{opt}} = \max\left\{ w_{\mathrm{t}} \frac{T_{\mathrm{ave}}}{T_{\mathrm{b}}} + w_{\mathrm{tp}} \frac{TP}{TP_{\mathrm{b}}} + w_{\mathrm{tv}} \frac{TV}{TV_{\mathrm{b}}} \right\} \tag{8}$$

$$T_{\mathrm{b}} = \max\{T_{\mathrm{ave}}\} \tag{9}$$

$$TP_{\mathrm{b}} = \max\{TP\} \tag{10}$$

$$TV_{\mathrm{b}} = \max\{TV\} \tag{11}$$

$$w_{\mathrm{t}} + w_{\mathrm{tp}} + w_{\mathrm{tv}} = 1 \tag{12}$$

where T_{ave} denotes the average torque, TP denotes the average torque per copper loss, TV denotes the average torque per motor lamination volume, w_{t}, w_{tp} and w_{tv} represents the weight factors of the average torque, the average torque per copper loss and the average torque per motor lamination volume, respectively, T_{b} represents the base values of the average torque, TP_{b} represents the base value of the average torque per copper loss, and TV_{b} represents the base value of the average torque per motor lamination volume.

It can be seen from (8) that the optimization with three objectives has been simplified to an optimization function by using three weight factors and three base values. The maximum value of the optimization objective function is unity. Various weight factors indicate the shares, which are taken up by the average torque, torque per copper loss and torque per motor lamination volume in the objective function. For instance, its weight factor may be selected a larger value than the other two factors if one of the three objectives is desired to be emphasized.

C. Computation of Base Values

The base value of the average torque can be found by optimizing the defined parameters when maximizing the average torque. Similarly, the base value of the average torque per copper loss can be computed via optimizing the defined parameters when maximizing the average torque per copper loss, and the base value of the average torque per motor lamination volume can be determined through optimizing the defined parameters when maximizing the average torque per motor core.

D. Optimized Parameters

In principle, all the geometrical design parameters could be selected as the optimized parameters. The geometrical design parameters of an in-wheel SRM mainly include the outer diameter of rotor (D_{r}), the thickness of rotor back iron (H_{ry}), the height of rotor pole (H_{rp}), the pole arc angle of rotor (β_{r}), the length of air gap (L_{g}), the outer diameter of stator (D_{s}), the height of stator pole (H_{sp}), the thickness of stator back iron (H_{sy}), the pole arc angle of stator (β_{s}), the outer diameter of shaft (D_{sh}), and the length of stator lamination (L_{s}). Fig. 1 illustrates the configuration of the stator and rotor in a four-phase in-wheel SRM.

For direct-drive in-wheel SRMs, the outer diameter of the rotor depends on the size of the EV rims and thus it cannot be selected as the optimized parameter. Similarly, the length of stator lamination will be limited by the EV size and consequently it is also not suitable for the optimized parameter. For EVs, the short length of stator lamination is desired. Generally, it is expected that the length of air gap is made as short as manufacturally possible. Clearly, the length of air gap should not be considered as the optimized parameter. Due to the magnetic saturation in motor steel lamination, the outer diameter of stator, the height of stator pole, the thickness of stator back iron, the height of rotor pole, and the thickness of the rotor back iron should not be regarded as the optimized parameters. Different from traditional motors, the stator and the rotor pole arc angles are two flexible design parameters for SRMs. The values of both have significant effect on the average torque. Therefore, the stator and the rotor pole arc angles are selected as the optimized parameters in this paper.

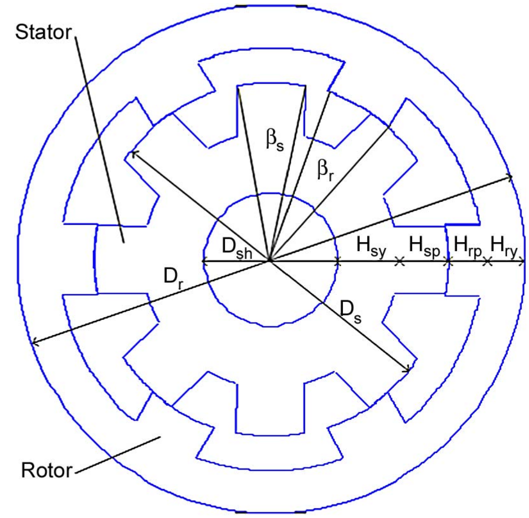

Fig. 1. Geometrical parameters of the stator and rotor in a four-phase in-wheel SRM.

Therefore, the objective function can be expressed as

$$F_{\mathrm{obj}}(\beta_{\mathrm{s}}, \beta_{\mathrm{r}}) = w_{\mathrm{t}}\frac{T}{T_{\mathrm{b}}} + w_{\mathrm{tp}}\frac{TP}{TP_{\mathrm{b}}} + w_{\mathrm{tv}}\frac{TV}{TV_{\mathrm{b}}}. \quad (13)$$

Consequently, the optimization function is defined as

$$F_{\mathrm{opt}}\left(\beta_{\mathrm{s}}^{\mathrm{opt}}, \beta_{\mathrm{r}}^{\mathrm{opt}}\right) = \max\left\{w_{\mathrm{t}}\frac{T}{T_{\mathrm{b}}} + w_{\mathrm{tp}}\frac{TP}{TP_{\mathrm{b}}} + w_{\mathrm{tv}}\frac{TV}{TV_{\mathrm{b}}}\right\}. \quad (14)$$

E. Constraints on Stator and Rotor Pole Arc Angles

On one hand, to obtain maximum average torque, the stator and rotor pole arc angles should be limited by the constraints, which are given as [17]

$$0.4 < \frac{\beta_{\mathrm{s}}}{\theta_{\mathrm{sp}}} < 0.5 \quad (15)$$

$$0.3 < \frac{\beta_{\mathrm{r}}}{\theta_{\mathrm{rp}}} < 0.45 \quad (16)$$

$$\theta_{\mathrm{sp}} = \frac{360}{N_{\mathrm{s}}} \quad (17)$$

$$\theta_{\mathrm{rp}} = \frac{360}{N_{\mathrm{r}}} \quad (18)$$

where θ_{sp} represents the stator pole pitch angle, θ_{rp} represents the rotor pole pitch angle, N_{s} represents the number of stator poles, and N_{r} represents the number of rotor poles.

On the other hand, the inductance at the fully aligned position gives rise to the peak current possible in the torque generation. Furthermore, the fully aligned inductance is sensitive to the ratio of the rotor arc angle to the stator pole arc angle. If only a variation of 15% in the fully aligned inductance value is allowed and the self-starting requirement is considered, the rotor pole arc angle to the stator pole arc angle should be confined in the range as [17]

$$1.0 < \frac{\beta_{\mathrm{r}}}{\beta_{\mathrm{s}}} \leq 1.2. \quad (19)$$

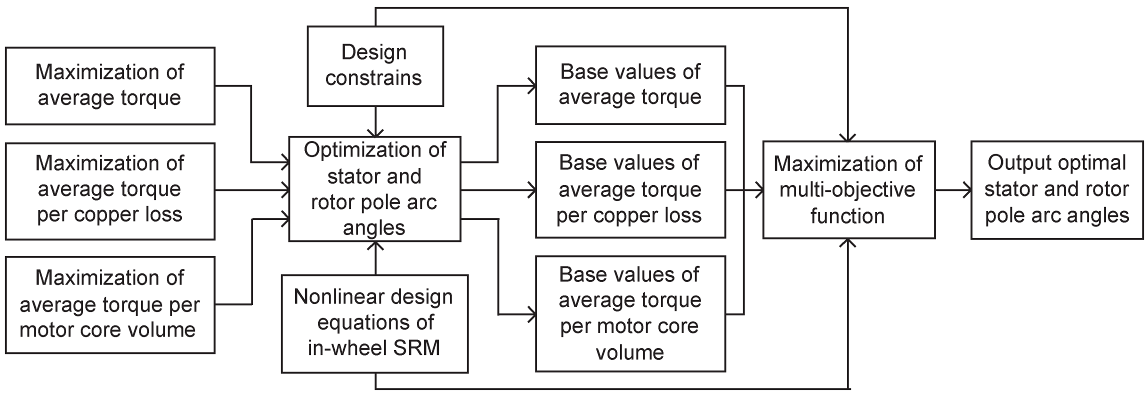

Fig. 2. Block diagram of the proposed multi-objective optimization.

Due to the requirement of self-starting, the minimum stator pole arc angle is determined as [17]

$$\beta_{\rm s} > \frac{720}{N_{\rm s} N_{\rm r}}. \tag{20}$$

In summary, the optimization of the stator and rotor pole arc angles must be constrained by (15)–(20).

F. Algorithm of Multi-Objective Optimization

The block diagram in Fig. 2 illustrates the algorithm of the proposed multi-objective optimization. At first, the stator and rotor pole arc angles are optimized to maximize three individual objective optimization functions, which are the average torque, the average torque per copper loss, and the average torque per motor core volume. Then, the base values of the average torque, the average torque per copper loss, and the average torque per motor core volume are computed. After that, the weight factors are selected and the multi-objective optimization function is established. Finally, the stator and rotor pole arc angles are optimized to maximize the multi-objective function.

III. Consideration of Design Requirements

A. Selection of Rated Power

In-wheel SRM drives are used to directly drive EV wheels. Thus, the rated power of an in-wheel SRM depends on the rated output power of an EV and the number of motors.

B. Selection of Numbers of Phases and Poles

For SRMs, the number of phases depends on the number of stator poles. In general, the number of phases is half the number of stator poles. For instance, the number of phases is four if the stator has eight poles and the rotor has six poles. On one hand, a smaller number of phases results in a simpler converter topology and hence reduces the converter cost, but increases the torque ripple. On the other hand, a larger number of poles will result in thinner stator and rotor yokes, and thus reduces the weight of the motor. An SRM with a large number of poles requires a smaller air gap for the same performance. However, the origin of acoustic noise in SRMs is the radial force, which increases inversely with the air gap. Furthermore, SRM drives with larger number of poles operate with higher electrical frequency at the same motor speed, which will increase the losses dependent on the electrical frequency. With all the above factors, three-phase and four-phase SRMs should be taken into account for EVs. Three-phase SRMs have the inherent problem of torque dips that will invariably cause higher torque ripple at low speed compared to four-phase SRMs. Four-phase SRM drives will produce smaller dc current ripple than three-phase SRM drives. Developed techniques of torque control have been applied to minimize torque ripple in the constant torque range for SRM drives. It should be noted that the torque ripple cannot be eliminated in the constant-power range for any type of SRM drives.

C. Selection of DC-Link Voltage Level

Considering safety in EVs, lower voltage level of SRM drives is desired. However, low voltage level will result in large current for the same output power. Thus, low voltage level will be difficult for the manufacturing of SRM drives. For in-wheel SRMs, furthermore, the motor's size is limited by the rims of the EVs. However, higher voltage level is not beneficial to personal safety. Thereby, a tradeoff between the high voltage level and the safety needs to be chosen.

D. Selection of Maximum Motor Speed

The maximum motor speed will be determined by the maximum EV velocity and the outer diameter of EV wheels. Suppose that the maximum motor speed is $\omega_{\max}$ (r/min), the outer diameter of the EV wheels is $d_{\rm ev}$ (m), and the maximum vehicle velocity is $v_{\max}$ (km/h). For EVs directly driven by in-wheel SRMs, the maximum motor speed is computed as

$$\omega_{\max} = \frac{50}{3\pi}\frac{v_{\max}}{d_{\rm ev}}. \tag{21}$$

E. Selection of Rated Motor Speed

On one hand, the output characteristics of EVs require that the rated motor speed is as low as possible and the maximum motor speed is as high as possible. On the other hand, the maximum motor speed is limited by the maximum vehicle

TABLE I
VALUES OF STATOR AND ROTOR POLE ARC ANGLES

β_s (degree)	β_r (degree)
19	20, 21, 22
20	21, 22, 23, 24
21	22, 23, 24, 25
22	23, 24, 25, 26

velocity and the outer diameter of wheels. Furthermore, it should be emphasized that the lower rated motor speed will result in a larger motor size and larger motor weight for the same rated power. Hence, the compromise between the good EV characteristics (low rated speed) and the limitation of motor size has to be chosen.

IV. APPLICATIONS

A. Design Requirements

In this paper, two 5-kW in-wheel SRMs are determined to directly drive EV wheels. From the discussion in the last section, the design requirements are proposed as follows:

$$\text{rated power} = 5\ \text{kW}$$
$$\text{number of phases} = 4$$
$$\text{number of stator poles} = 8$$
$$\text{number of rotor poles} = 6$$
$$\text{rated motor speed} = 1000\ \text{r/min}$$
$$\text{dc-link voltage} = 240\ \text{V}.$$

B. Optimized Parameters

Taking into account the constraints on the stator and rotor pole arc angles, which are given by (15)–(20), for the design requirements proposed in this paper, the stator pole arc angle has to be confined as

$$18 < \beta_s < 22.5. \tag{22}$$

Consequently, the rotor pole arc angle has to be selected in the range, given as

$$18 < \beta_r < 27. \tag{23}$$

Defining the stator and rotor pole arc angles in mechanical degree as the integer, the stator and rotor pole arc angles for the proposed design requirements must vary with the specified values, which are shown in Table I.

C. Results of Optimization Computation

Fig. 3 illustrates the distribution of the flux lines at the fully aligned and completely unaligned positions. It is obtained by the FEA computation.

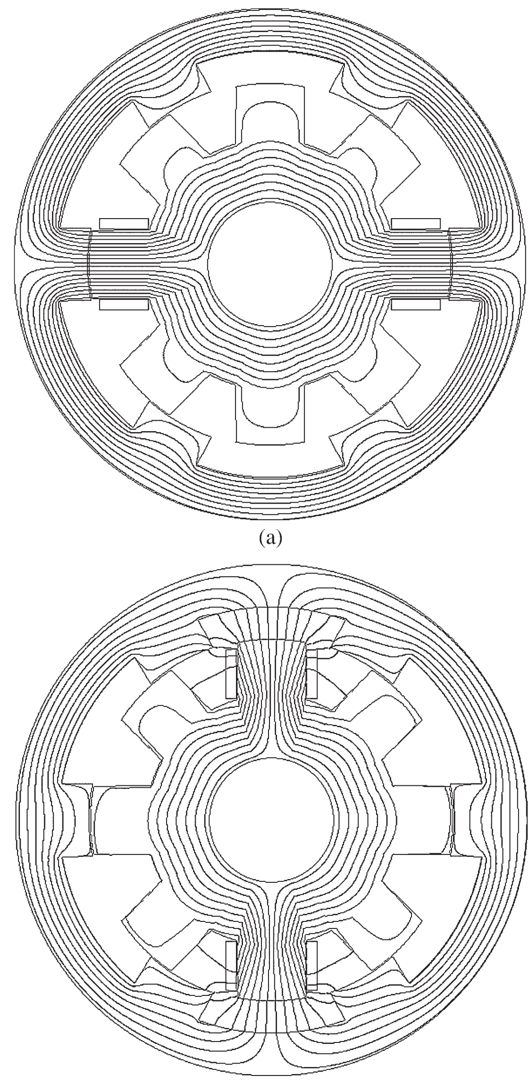

Fig. 3. Distribution of flux lines in the designed in-wheel SRM. (a) Fully aligned position. (b) Completely unaligned position.

TABLE II
COMBINATION OF STATOR AND ROTOR POLE ARC ANGLES

Number	1	2	3	4	5	6	7	8
β_s (degree)	19	19	19	20	20	20	20	21
β_r (degree)	20	21	22	21	22	23	24	22
Number	9	10	11	12	13	14	15	
β_s (degree)	21	21	21	22	22	22	22	
β_r (degree)	23	24	25	23	24	25	26	

The number can be used to describe the combination of the stator and rotor pole arc angles, as shown in Table II. Fig. 4 illustrates the change of the objective function only including the average torque. The distribution of the objective function only including average torque per copper loss can be seen in Fig. 5. If the objective function only includes the average torque per motor lamination volume, Fig. 6 shows the variation of the objective function versus the stator and rotor pole arc angles. The change of the objective function with the stator and rotor

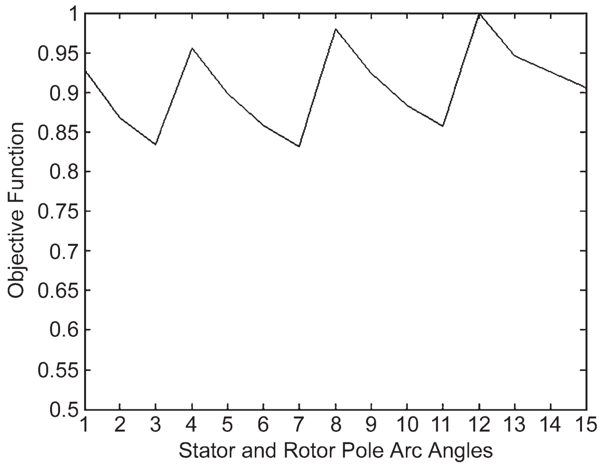

Fig. 4. Objective function only including average torque.

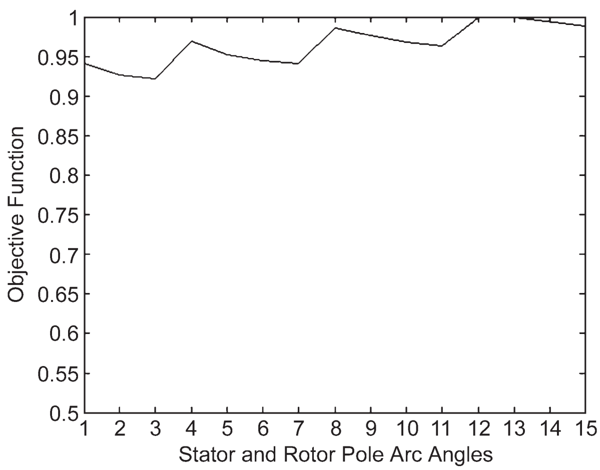

Fig. 5. Objective function only including average torque per copper loss.

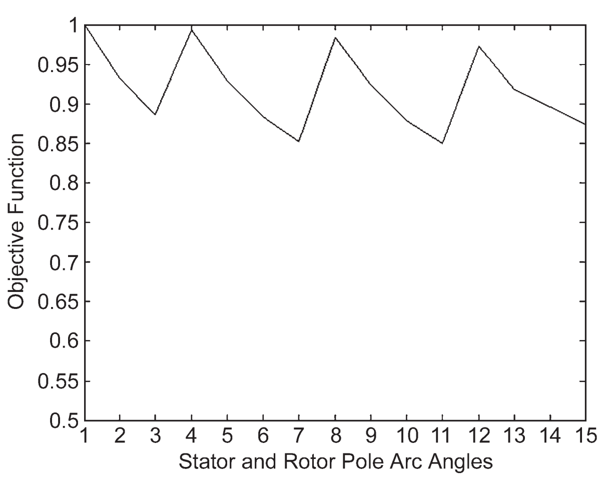

Fig. 6. Objective function only including average torque per motor lamination volume.

pole arc angles are shown in Fig. 7, if three weight factors are determined as $w_{\rm t} = w_{\rm tp} = w_{\rm tv} = 1/3$.

It can be observed from Figs. 4–7 that the maximum objective function values and optimal stator and rotor pole arc angles can be found for the given weight factors.

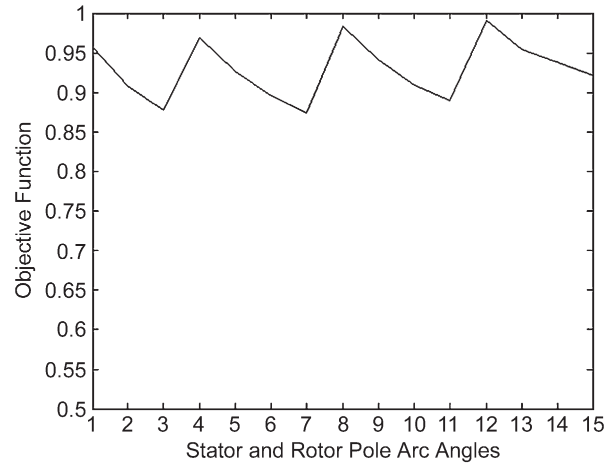

Fig. 7. Multi-objective function at given weight factors ($w_{\rm t} = w_{\rm tp} = w_{\rm tv} = 1/3$).

TABLE III
RESULTS OF MULTI-OBJECTIVE OPTIMIZATION

Weight factor	Objective function	Optimal β_s (degree)	Optimal β_r (degree)
$W_t = 1$, $W_{tp} = W_{tv} = 0$	1.0	22	23
$W_{tp} = 1$, $W_t = W_{tv} = 0$	1.0	22	23
$W_t = W_{tp} = 0$, $W_{tv} = 1$	1.0	19	20
$W_t = W_{tp} = W_{tv} = 1/3$	0.991149	22	23

Table III shows the optimization results with various weight factors. It can be seen that the optimal stator and rotor pole arc angles are 22 and 23°, respectively, if only the average torque is selected as the objective function. The optimal stator and rotor pole arc angles are also 22 and 23°, respectively, if only the average torque per copper loss is selected as the objective function. The optimal stator and rotor pole arc angles are 19 and 20°, respectively, if only the average torque per motor lamination volume is selected as the objective function. The optimal stator and rotor pole arc angles are 22 and 23°, respectively, if the average torque, the average torque per copper loss and the average torque per motor lamination volume are selected as the objective functions simultaneously and they have the same weight factor, which is equal to 1/3.

In this paper, the designed in-wheel SRMs will be applied to EVs. Thus, high torque, low copper loss, and high torque density are desired for the in-wheel SRM design. Consequently, the average torque, the average torque per copper loss, and the average torque per motor lamination volume should take up the same share in the optimization objective function. Therefore, the optimal stator and rotor pole arc angles are 22° and 23°, respectively.

Table IV shows the values of three criterions at different combinations of stator and rotor pole arc angles. It can be seen that the optimal stator pole arc angle (22°) and the optimal rotor pole arc angle (23°) result in the best design that means high torque, low copper loss, and high torque density.

TABLE IV
COMPARISONS BETWEEN VARIOUS DESIGNS

β_s (degree)	β_r (degree)	T_{ave}/T_b	TP/TP_b	TV/TV_b
22	23	1.0	1.0	0.973450
19	20	0.927223	0.941108	1.0
20	21	0.955214	0.958662	0.992916
21	22	0.979854	0.987391	0.984439
22	24	0.946465	0.999889	0.917623

TABLE V
DESIGNED DIMENSIONS OF IN-WHEEL SRM

Design parameter	Value
Outer diameter of rotor	382 mm
Length of air gap	0.5 mm
Stator pole arc angle	22 degree
Rotor pole arc angle	23 degree
Outer diameter of stator	266 mm
Length of stack	74 mm
Thickness of stator back iron	46 mm
Thickness of rotor back iron	32 mm
Number of turns per phase	136

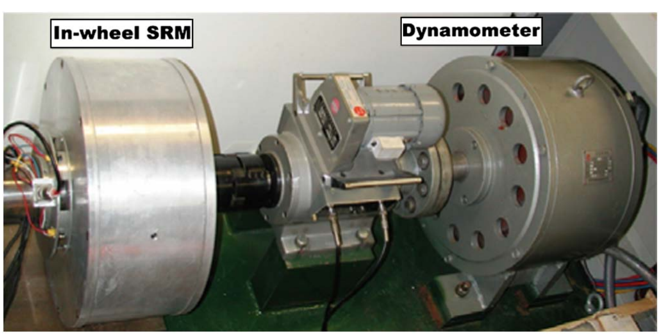

Fig. 8. Prototype of optimally designed in-wheel SRM.

D. Design Data of Optimized In-Wheel SRM

Table V shows the data of the optimal design of the in-wheel SRM. Using the data, the prototype of the four-phase in-wheel SRM has been manufactured. Fig. 8 shows the optimally designed in-wheel SRM, which is under test.

Table VI shows the comparisons between the computed and measured individual and weighted objective functions. It can be observed that the computed and measured results are satisfying. The errors between the designed and measured values are caused mainly by the following reasons: 1) T is the average electromagnetic torque in the computation and T is the average output torque in the operation; and 2) the phase current waveform in the design is regarded as the rectangular one in the half rotor period and the actual phase current waveform is the approximate trapezoid one generated by the hysteresis current controller.

TABLE VI
COMPARISONS BETWEEN DESIGNED AND MEASURED OBJECTIVE FUNCTIONS

Value	T/T_b	TP/TP_b	TV/TV_b	F_{obj}
Design	1.0	1.0	0.973450	0.991149
Measurement	0.944106	0.935407	0.919039	0.932850

Fig. 9. Engineering model of the in-wheel SRM.

V. CONCLUSION

From the requirements of EVs on electric motors, three criterions to evaluate the design of in-wheel SRMs for EVs have been presented. The optimization function is proposed to be the correct compromise between the maximum average torque, the maximum average torque per copper loss, and the maximum average torque per motor lamination volume, by using three weight factors and three base values. The optimized parameters are selected as the stator and rotor pole arc angles. Thus, the proposed optimization design indicates that the stator and rotor pole arc angles are optimized to obtain the in-wheel SRM with high torque, high efficiency, and high torque density. The constraints on the stator and rotor pole arc angles, furthermore, and the consideration of the design requirements have been discussed.

The optimization results of the four-phase 5-kW in-wheel SRM have shown the following: 1) the optimal stator pole arc angle is equal to 22° and the optimal rotor pole arc angle is equal to 23° to have the maximum average torque; 2) the optimal stator and rotor pole arc angles are also 22 and 23°, respectively, to obtain the minimum copper loss; 3) the optimal stator pole arc angle is 19° and the optimal rotor pole arc angles is 20°, to have the maximum torque density; and 4) the optimal stator and rotor pole arc angles are 22 and 23°, respectively, to obtain the optimal design with high average torque, low copper loss, and high torque density. The design results have demonstrated the developed optimization design method. The proposed method can include multi-objectives and multi-variables. Hence, this paper has provided a valuable method to fulfill the optimal design of in-wheel SRMs for EVs. Finally, the in-wheel SRM has been prototyped and is shown in Fig. 9.

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REFERENCES

[1] X. D. Xue, K. W. E. Cheng, and N. Cheung, "Selection of electric motor drives for electric vehicles," in *Proc. AUPEC*, Sydney, Australia, 2008, pp. 1–6.

[2] I. Husain and M. S. Lslam, "Design, modeling and simulation of an electric vehicle system," in *Advance in Electric Vehicle Technology*. Warrendale, PA: SAE, Inc., 1999, pp. 9–16.

[3] K. M. Rahman, B. Fahimi, G. Suresh, A. V. Rajarathnam, and M. Ehsani, "Advantages of switched reluctance motor applications to EV and HEV: Design and control issues," *IEEE Trans. Ind. Appl.*, vol. 36, no. 1, pp. 111–121, Jan./Feb. 2000.

[4] K. M. Rahman and S. E. Schulz, "Design of high efficiency and high density switched reluctance motor for vehicle propulsion," *IEEE Trans. Ind. Appl.*, vol. 38, no. 6, pp. 1500–1507, Nov./Dec. 2002.

[5] C. C. Chan, "Low-cost electronic-controlled variable-speed reluctance motors," *IEEE Trans. Ind. Electron.*, vol. IE-34, no. 1, pp. 95–100, Feb. 1987.

[6] R. Krishnan, A. S. Bharadwaj, and P. N. Materu, "Computer-aided design of electrical machines for variable speed applications," *IEEE Trans. Ind. Electron.*, vol. 35, no. 4, pp. 560–571, Nov. 1988.

[7] R. M. Davis, "Variable reluctance rotor structures—Their influence on torque production," *IEEE Trans. Ind. Electron.*, vol. 39, no. 2, pp. 168–174, Apr. 1992.

[8] T. J. E. Miller, "Optimal design of switched reluctance motors," *IEEE Trans. Ind. Electron.*, vol. 49, no. 1, pp. 15–27, Feb. 2002.

[9] R. B. Inderka, M. Menne, and R. W. A. A. De Doncker, "Control of switched reluctance drives for electric vehicle applications," *IEEE Trans. Ind. Electron.*, vol. 49, no. 1, pp. 48–53, Feb. 2002.

[10] I. Husain and S. A. Hossain, "Modeling, simulation, and control of switched reluctance motor drives," *IEEE Trans. Ind. Electron.*, vol. 52, no. 6, pp. 1625–1634, Dec. 2005.

[11] A. K. Jain and N. Mohan, "Dynamic modeling, experimental characterization, and verification for SRM operation with simultaneous two-phase excitation," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1238–1249, Jun. 2006.

[12] C. S. Edrington, B. Fahimi, and M. Krishnamurthy, "An autocalibrating inductance model for switched reluctance motor drives," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 2165–2173, Aug. 2007.

[13] X. D. Xue, K. W. E. Cheng, and S. L. Ho, "A position stepping method for predicting performances of switched reluctance motor drives," *IEEE Trans. Energy Convers.*, vol. 22, no. 4, pp. 839–847, Dec. 2007.

[14] H. S. Lim, R. Krishnan, and N. S. Lobo, "Design and control of a linear propulsion system for an elevator using linear switched reluctance motor drives," *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 534–542, Feb. 2008.

[15] A. Tenconi, F. Profumo, S. E. Bauer, and M. D. Hennen, "Temperatures evaluation in an integrated motor drive for traction applications," *IEEE Trans. Ind. Electron.*, vol. 55, no. 10, pp. 3619–3626, Oct. 2008.

[16] J. G. Amoros and P. Andrada, "Sensitivity analysis of geometrical parameters on a double-sided linear switched reluctance motor," *IEEE Trans. Ind. Electron.*, vol. 57, no. 1, pp. 311–319, Jan. 2010.

[17] R. Krishnan, *Switched Reluctance Motor Drives—Modeling, Simulation, Analysis, Design, and Applications*. Boca Raton, FL: CRC Press, 2001.

X. D. Xue (M'10) received the B.Eng. degree from Hefei University of Technology, Hefei, China, in 1984, the M.Eng. degree from Tianjin University, Tianjin, China, in 1987, and the Ph.D. degree from The Hong Kong Polytechnic University, Hong Kong, in 2004, all in electrical engineering.

He was engaged in teaching and research in the Department of Electrical Engineering, Tianjin University, Tianjin, China, from 1987 to 2001, as a Lecturer and Associate Professor. He is currently a Research Fellow in the Department of Electrical Engineering, The Hong Kong Polytechnic University. He has published over 70 papers. His current research is focused on electric machines and drives applied to electric vehicles and wind power generation. His research interests are in the areas of electrical machines, electrical drives, and power electronics.

K. W. E. Cheng (M'90–SM'06) received the B.Sc. and Ph.D. degrees from the University of Bath, Bath, U.K., in 1987 and 1990, respectively.

Prior to joining The Hong Kong Polytechnic University, Hong Kong, in 1997, he was a Principal Engineer with Lucas Aerospace, U.K., and led a number of power electronics projects. He has published over 250 papers and seven books. He is currently a Professor and Director of the Power Electronics Research Centre at the university. His research interests are all aspects of power electronics, motor drives, EMI, electric vehicles, and energy saving.

Dr. Cheng received the IEE Sebastian Z. De Ferranti Premium Award (1995), Outstanding Consultancy Award (2000), Faculty Merit Award for best teaching (2003) from The Hong Kong Polytechnic University, Faculty Engineering Industrial and Engineering Services Grant Achievement Award (2006), the Brussels Innova Energy Gold Medal with Mention (2007), Consumer Product Design Award (2008), and the Electric Vehicle Team Merit Award of the Faculty (2009).

T. W. Ng is a Research Associate in the Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong. His research interest is power electronics.

N. C. Cheung (S'85–M'91–SM'05) received the B.Sc. degree from the University of London, London, U.K., in 1981, the M.Sc. degree from The University of Hong Kong, Hong Kong, in 1987, and the Ph.D. degree from the University of New South Wales, Kensington, Australia, in 1996.

He worked for two years as a Technical Manager with ASM Assembly Automation Ltd., Hong Kong, in the areas of intelligent motion control and robotics systems. He has been with The Hong Kong Polytechnic University, Hong Kong, since 1997, where he is currently in the Department of Electrical Engineering.

Dr. Cheung is a Chartered Engineer in the U.K., and a member of the Institution of Engineering and Technology, U.K.