

A new design of a double excitation synchronous machine with L-shaped end-shields

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Abstract. This article proposes a new design for a double excitation synchronous machine. The end-shields with an L-shaped core are introduced to lower the magnetic resistance. The analyses are accomplished by using a three-dimensional finite element method, required by the truly three-dimensional flux paths of the machine. The length of the end shield was varied from 1 mm to 23 mm, and the resulting flux control curves were compared to those of the base model. The design with an end-shield length of 17 mm was chosen as the best compromise. Compared to the base model, this design widens the flux control range from 3.569 mWb to 3.883 mWb (+8.8 %) and increases the slope of the curve in the linear region from 0.367 mWb/A to 0.565 mWb/A (+53.9 %), at the cost of a mass increase from 17.36 kg to 18.16 kg (+4.6 %). The minimum flux achieved was 0.65 mWb at a field current of 4.3 A, instead of 7 A, indicating a significant 62% reduction in field winding copper losses.

Keywords: double excitation, flux control, L-shaped core.

Classification numbers: 5.5.1, 5.6.2.

1. INTRODUCTION

The Double Excitation Synchronous Machine (DESM) class is recognized for its advantageous ability to control the magnetic flux density in the air gap. The air-gap magnetic flux density, denoted as B_{a-PM} , is produced by permanent magnets (PMs). This density can be flexibly increased or decreased by adjusting the magnitude and direction of the excitation currents in the additional field windings [1–8] as (1):

$$B_a = B_{a-PM} + B_{a-Field} \quad (1)$$

where B_a is the resultant air-gap magnetic density and $B_{a-Field}$ is the air-gap magnetic density created by field windings.

For conventional permanent magnet synchronous machines, regulating the air-gap flux density involves injecting d-axis current into the armature winding [9–11]. This method requires a complex control algorithm, which limits the flexibility of the control system. However, by incorporating the concept of double excitation, various DESM configurations can be developed. The classification of these machines depends on how the two flux sources are combined; they

can be categorized as either parallel or series types. Additionally, the placement of the excitation sources plays a role in their classification: both sources can be located in the stator, the rotor, or a combination of both (one in the stator and the other in the rotor). Based on the trajectories of the magnetic flux, DESMs can also be divided into two-dimensional (2-D) or three-dimensional (3-D) types. Analyzing 3-D DESM machines is considerably more complex and typically requires the use of three-dimensional finite element method (FEM) analysis to achieve highly accurate results [12].

As the key feature of introducing the additional field windings is to control the air-gap flux density at the expense of copper losses associated with these windings, the effectiveness of the flux control is of importance. In other words, with the same amount of field current, i.e., the same copper losses, it is desirable to lower or increase the air-gap flux density. In [8], a parallel DESM in which both the PMs and the field windings are housed in the stator was proposed; this arrangement removes the need for slip rings and brushes and prevents the field flux from crossing the magnets, thereby limiting the demagnetization risk. The machine was analyzed by a 3-D FEM model, and the analysis was supported by experimental results obtained on a prototype. Flux regulation of various DESM structures were compared in that work, and the proposed design obtained a zero air-gap flux density, i.e., the magnetic flux from the PMs is completely canceled by the flux created by the field windings, demonstrating a true field regulation capability. The authors of [8] also compared the advantages of parallel and series DESMs regarding the no-load flux control capability. The flux control range, i.e., the distance between the minimum and the maximum air-gap flux attainable at the admissible field current, was explicitly targeted in [13]. The studied DESM was modeled by a nodal-based generalized equivalent magnetic circuit, and a structural multi-objective optimization was performed to maximize this range while monitoring the electromagnetic torque. The results indicated that the achievable range is essentially bounded by the magnetic saturation of the iron sections shared by the PM and the field-winding fluxes, together with the thermal limit of the field windings; this observation directly motivates design measures that lower the magnetic resistance seen by the field flux. The same machine family was investigated in [14] by means of a lumped-parameter equivalent magnetic circuit (reluctance network), the accuracy of which was verified against both 3-D FEM computations and experimental results. Two improvements were reported in that study: the flux control range was broadened, and the torque ripple was minimized by adjusting the air-gap flux according to the instantaneous torque profile, leading to an almost constant resultant torque for the considered case study. Nevertheless, in both [13] and [14], the improvements were obtained by re-dimensioning the existing active parts rather than by modifying the path along which the field flux closes. The work [15] investigated a flux–torque regulation hybrid excitation machine whose field flux closes through an axial–radial magnetic circuit containing two air gaps (a radial main air gap and an axial additional air gap). Equivalent magnetic network models were established to quantify the influence of the air-gap reluctances, showing that the dual air gaps are the dominant reluctance components of the axial–radial circuit and therefore the key structural parameters governing the flux control. By reducing the axial air-gap length from 0.95 mm to 0.35 mm, the flux regulation capability improved from 15.44 % to 26.51 %, and the additional torque increased by 40.77 %. In [16], the flux regulation range of an axial–radial flux hybrid excitation machine was addressed through a global structural parameter: the length–diameter ratio (LDR). Machines with different the LDRs were then compared in terms of air-gap flux density and no-load back-EMF, quantifying how the flux regulation capability and the utilization of the permanent magnets vary with the LDR.

This article explores the effectiveness of air-gap flux control by introducing a new configuration based on an existing model (base model) of a DESM. The innovation of this research lies in reducing the magnetic resistance along the flux path created by the field windings. Since the flux paths within the machine are inherently 3-D, a non-linear 3-D FEM package, specifically ANSYS Electronics, will be utilized to achieve accurate results. The comparison between the new design and the base model will focus on the slope of the fluxcontrol curve and the saturation regions. The structure of the article is organized as follows: Section 2 presents a detailed analysis of the base model using the 3-D FEM approach, discussing the flux paths and magnetic resistance to highlight potential improvements. Section 3 proposes the new design, addressing the critical aspects of the base model, followed by an analysis of the new design in comparison to the base model, and concluding remarks.

2. BASE MODEL DESM AND THE FLUX CONTROL CURVE CHARACTERISTIC

2.1. Base model DESM

The base model of the DESM [7] is presented in Figure 1. This model belongs to the homopolar configuration, which was proven to have better control of excitation flux [7]. That explains why it is chosen as the base model in this research for further improvement. Two toroidal field windings are utilized, conducting DC currents in opposite directions; they are placed in the stator to avoid sliding contacts. Ferrite PMs are used in the rotor with the flux-concentrating principle to increase the air-gap flux density. The reason to use ferrite PMs is the acceptable cost in comparison with that of the rare earth ones. This configuration not only has a complex structure but also produces truly 3-D flux paths. The model uses a conventional stator with three-phase distributed windings, as displayed in Figure 2, and the 2-D schematic of the machine is presented in Figure 3. This model belongs to the series type as the flux created by the excitation winding passes through the PMs [17, 18]. This complexity leads to a challenging analysis with a requirement for 3-D FEM software to get accurate results. Moreover, the complex flux paths result in potential improvement of the machine's performance by providing structural changes. The main flux paths due to the excitation sources (PMs and field windings) are demonstrated in Figure 4. While the field windings generate homopolar flux paths, i.e., creating only one type of pole, either north or south, PMs produce both homopolar and bipolar flux paths. Bipolar flux paths mean both north and south poles are created under the active part.

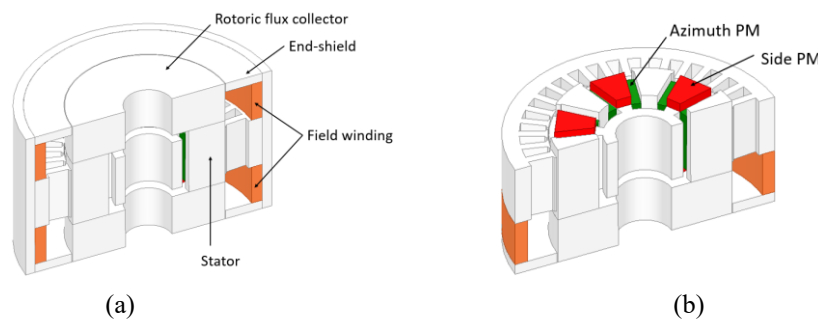


Figure 1. Base model DESM. (a) Half model. (b) PMs arrangement.

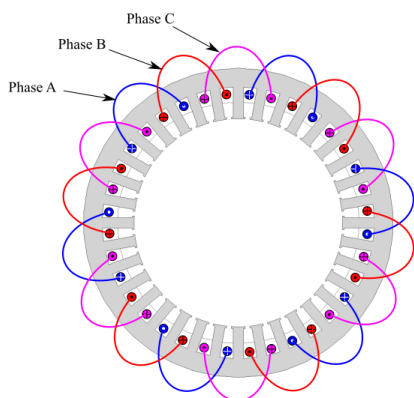


Figure 2. Diagram of distributed armature windings of the machine.

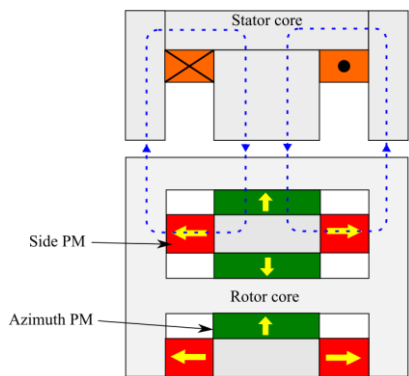


Figure 3. 2-D schematic of the machine.

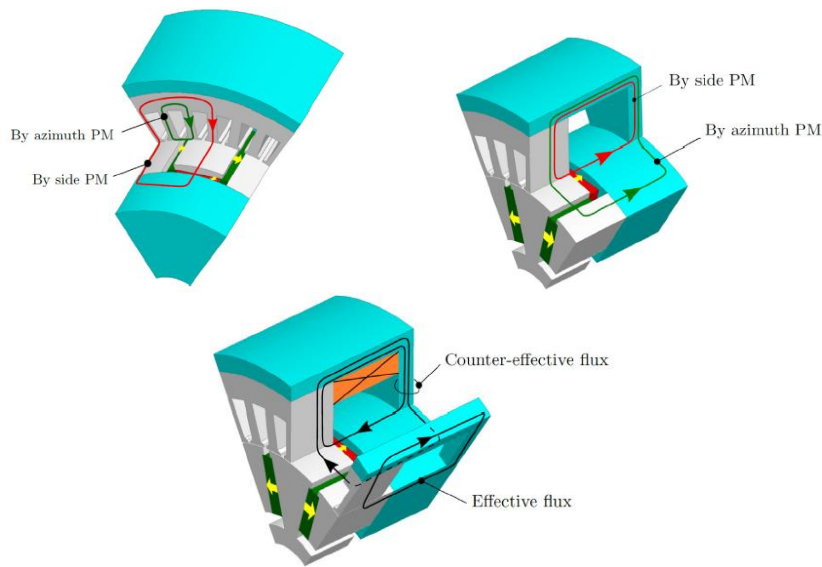


Figure 4. Various flux paths created by PMs and field windings.

Figure 4 illustrates two important types of magnetic flux: effective and counter-effective. The effective flux is crucial for regulating the air-gap flux, which can be adjusted by either increasing or decreasing this effective flux. In contrast, the counter-effective flux produces opposite flux trajectories, diminishing the effectiveness of the effective flux. The impact of the counter-effective flux becomes particularly significant in saturated regions, where the effective flux is close to its maximum level. Figures 5 and 6 depict the flux density during saturation—one figure shows conditions with highly positive field currents, while the other illustrates conditions with highly negative field currents. Key parameters of the machine are summarized in Table 1. Additionally, Figure 7 displays the B-H curve characteristic of the iron core material in both the stator and rotor. More detailed information about the working principle of the DESM and this base model can be found in [7].

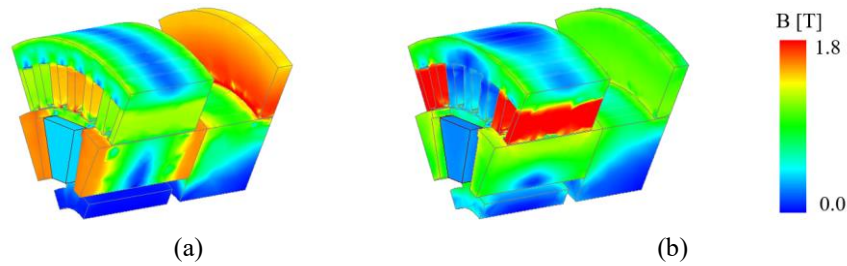


Figure 5. Flux density distribution of the machine. (a) Field current of -7 A. (b) Field current of 7 A.

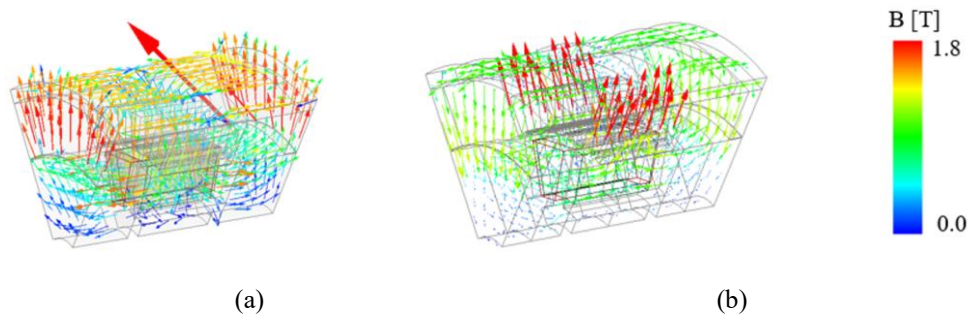


Figure 6. Flux density vector of the machine. (a) Field current of -7 A. (b) Field current of 7 A.

Table 1. Specifications of the base model.

Parameters	Value
Number of phases	3
Number of turns per phase	33
Number of turns per field winding	150
Number of pole pairs	6
Machine length	115 mm
Outer stator diameter	184 mm
Air-gap diameter	114.5 mm
Number of stator slots	36
Air-gap length	0.5 mm
PM residual flux density	0.4 T (ferrite PM)
Rated power	3 kW

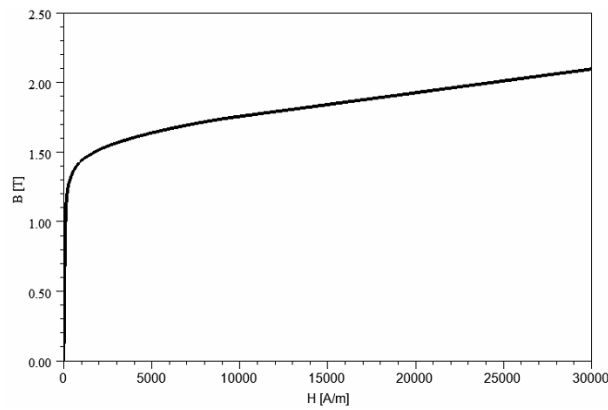


Figure 7. B-H curve of the ferromagnetic core materials.

2.2. Flux control curve characteristic

A key feature of a DESM is its ability to control air-gap flux by adjusting the field current. This capability is particularly important for applications such as electric vehicles [19]. Therefore, assessing this characteristic is a critical factor in evaluating the machine's performance. To explore this feature, the field current will be varied within a specific range, and the corresponding air-gap flux will be calculated. Figure 8 illustrates the flux control curve, which represents the maximum flux per phase per armature turn of the base model, with the field current varied from -7 A to 7 A. The calculations are performed using ANSYS Electronics with a 3-D FEM. It is important to note that this range of field current is chosen to ensure that the current density in the field winding remains below 6 A/mm².

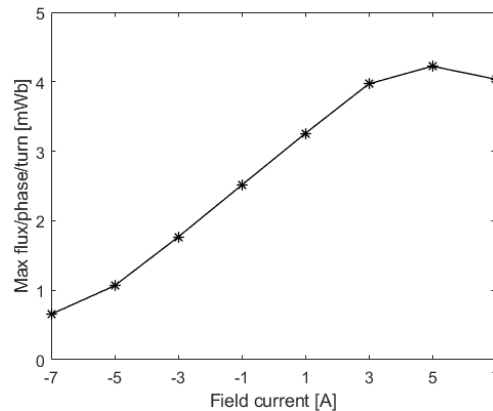


Figure 8. Flux control curve of base model.

In Figure 8, the flux control curve is defined by two main factors: the range of control, which is the difference between the maximum and minimum peak flux, and the slope of the curve, which indicates the efficiency of the field windings. A wider range is desirable because it allows the machine to adjust more air-gap flux, and a steeper slope reduces the copper losses associated with the field windings. Figure 8 illustrates two saturation regions on the curve. The first region, located at the upper part of the curve, corresponds to a highly positive field current. In this area, the flux actually decreases as the field current increases further. This behavior is due to strong saturation in the stator teeth (as shown in Figure 5b), which leads to an increased

influence of the counter-effective flux. The second saturation region, found at the lower part of the curve, results from saturation in the end-shields (illustrated in Figure 5a). These end-shields are unable to conduct more flux produced by the field windings. To improve the slope of the curve and enhance the effectiveness of the field current, it is necessary to reduce the magnetic resistance along the flux paths created by the field windings. One proposed solution to address this issue is the introduction of L-shaped end-shields, which will be discussed in the following sections.

3. L-SHAPED END-SHIELD INTRODUCTION

3.1. Concept of the L-shaped end-shield

The end-shield components are designed to conduct the magnetic flux generated by the field windings. Figure 9, which illustrates an one-pole-pair model, shows a typical flux path that travels through the air gap between the rotoric flux collector and the end-shield. From there, the path continues through the end-shield and is closed via the stator yoke, stator teeth, and back to the rotoric flux collector. To effectively increase or decrease the magnetic flux with the same amount of field current, it is essential to reduce the magnetic resistance along this path. The magnetic resistance of the air gaps - specifically, the one between the rotor's flux collector and the end-shield, and the other between the stator teeth and the rotor - constitutes the majority of the total resistance in this path. The magnetic resistance R of the air gap can be calculated using equation (2).

$$R = \frac{L}{\mu_0 A} \quad (2)$$

where L is the air-gap length, μ_0 is the permeability of the air, and A is the cross section of the air-gap. In this case, A is the lower surface of the end-shield (or the stator teeth).

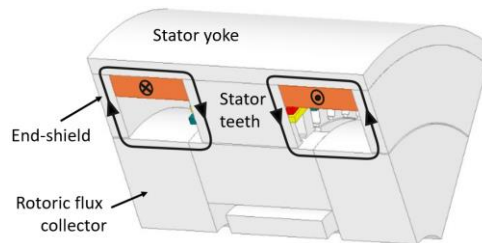


Figure 9. A typical flux path produced by field windings.

To reduce magnetic resistance, it is essential to either decrease the air-gap length or increase the surface area, as shown in (2). In this configuration, the air gap remains constant and equal to the air gap between the stator and rotor. Increasing the surface area motivates the introduction of L-shaped end-shields, as illustrated in Figure 10. These end-shields consist of an additional section made of the same material and thickness (7 mm) as the existing end-shield, creating L-shaped structures. Both end-shields are identical on either side of the machine. It is important to note that introducing this new form of end-shield will not affect the area of the field windings or their resistance. This is because the field windings are positioned above the armature winding.

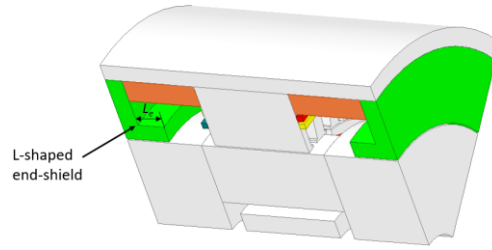


Figure 10. L-shaped end-shield concept.

3.2. Flux curve characteristics of the new design

To examine the flux control capability of the new design with a new end-shield shape, the flux curve characteristics are computed. In addition, the L_e (marked in Figure 10) of the additional part will be varied to analyze its impact. Figure 11 presents various flux curves at different values of L_e .

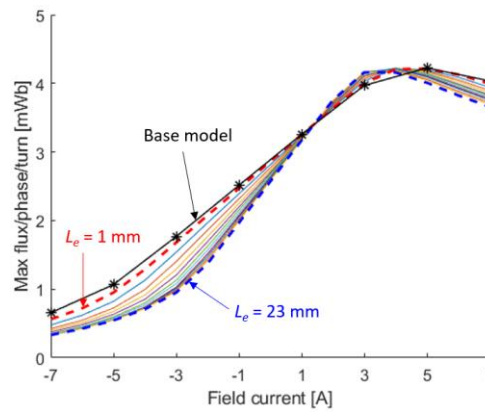


Figure 11. Flux curves of the new design at various L_e of the additional part.

The data presented in Figure 11 show that the L-shaped design enhances the performance of the field windings in two significant ways: it increases the slope of the curve in the linear region and widens the gap between the maximum and minimum flux values across the same range of field current, from -7 A to 7 A. It is important to note that while the L-shaped concept improves the flux curve, it does require the use of more materials. Additionally, this new design exhibits stronger saturation in both the negative and positive field current regions. This is explained by the fact that the L-shaped form helps conduct more flux in the end-shield, implying a more effective field current. Although saturation in the end-shields increases, there is no additional core loss because the magnetic field in these areas remains nearly constant as the rotor moves. The highly nonlinear area associated with the high positive field current is not utilized, as the flux begins to decrease. Figure 12 illustrates the magnetic density distribution for two cases where L_e equals 1 mm and 23 mm. The case with a 23 mm length of L_e reveals much more saturation in the end-shields. Table 2 provides a summary of the performance comparison between the original model and the new model. The new model incorporates a range of values for L_e , from 1 mm to 23 mm. The linear region for the base model corresponds to the field current range of -3 A to 3 A. In contrast, the linear region for the new designs is calculated for field currents ranging from -2 A to 2 A. The slopes and flux control ranges for various values of L_e are presented in Figures 13a and Figure 13b, respectively. Figure 13b illustrates a slight

decrease in the flux gap when L_e exceeds 17 mm, a phenomenon attributed to significant saturation occurring in the end-shields.

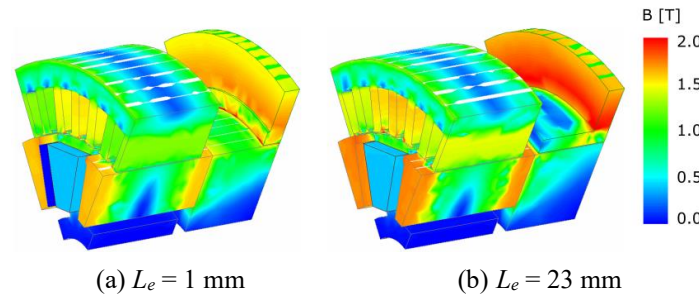


Figure 12. Magnetic density distributions at field current of -7 A. (a) $L_e = 1$ mm, (b) $L_e = 23$ mm.

Based on this analysis, the design with L_e of 17 mm has been selected due to the highest flux gap of 3.883 mWb and a slope of 0.565 mWb/A, which is only 5 % lower than the best result observed for the design with L_e of 23 mm. A detailed comparison between the new design and the base model is presented in Table 3. To achieve a minimum flux of 0.65 mWb, the base model requires a negative field current of 7 A, whereas the new design only needs 4.3 A, resulting in significant savings on copper losses in the field windings. It is important to note that there is no need to operate in the highly saturated region, where the flux begins to decrease (as shown in Figure 11).

Table 2. Performance comparison between the base and new design.

	Machine's mass [kg]	Slope in the linear region [mWb/A]	Flux gap [mWb]
Base model	17.36	0.367	3.569
$L_e = 1$ mm	17.41	0.389	3.654
$L_e = 3$ mm	17.51	0.420	3.739
$L_e = 5$ mm	17.60	0.452	3.798
$L_e = 7$ mm	17.69	0.478	3.830
$L_e = 9$ mm	17.79	0.499	3.846
$L_e = 11$ mm	17.88	0.521	3.785
$L_e = 13$ mm	17.98	0.538	3.878
$L_e = 15$ mm	18.07	0.554	3.882
$L_e = 17$ mm	18.16	0.565	3.883
$L_e = 19$ mm	18.26	0.575	3.860
$L_e = 21$ mm	18.35	0.586	3.849
$L_e = 23$ mm	18.45	0.596	3.829

Table 3. Comparison between the base model and the new design.

	L_e [mm]	Flux gap [mWb]	Linear slope [mWb/A]	Machine's mass [kg]	Required field current [A]	
					For flux of 0.65 mWb	For flux of 4.20 mWb
Base model	0	3.569	0.367	17.36	-7.0	4
New design	17	3.883	0.565	18.16	4.3	3

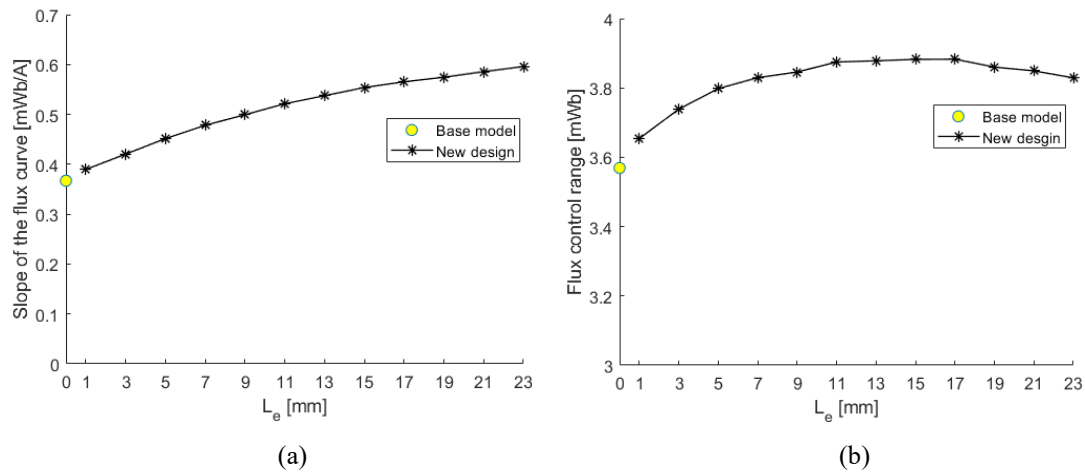


Figure 13. Key indicators of flux control curves for different L_e .
(a) Slope in the linear regions; (b) Control range.

4. CONCLUSION

A new design for a double excitation synchronous machine featuring an L-shaped end-shield has been presented. The primary purpose of this new end-shield design is to increase its surface area, which in turn reduces the magnetic resistance in the flux paths created by the field windings. This new design enhances the slope and flux gap of the flux control curves. Compared to the base model, the updated design can increase the flux gap by approximately 8.8 % and improve the slope by about 53.9 %. However, it is important to note that this design will add more weight to the machine. Additionally, the saturation in the end-shield will increase, resulting in a more non-linear flux control curve. The introduction of the L-shape also impacts the area allocated for the end-windings of the armature coils. To mitigate this issue, it is recommended to increase the size of the rotor flux collector to optimize the effectiveness of the L-shaped design.

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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