A Novel Structure of High Thrust Force Spoke-Type Linear Permanent Magnet Vernier Machine with Reduced Thrust Force Ripple

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***Abstract*—Linear permanent magnet vernier machines (LPMVMs) have become prevalent in direct-drive applications, such as wave energy harvesting systems and traction applications, owing to their distinctive merit of providing high thrust force at low speeds. In this paper, a novel structure of a double-sided spoke-type linear PM vernier machine is proposed, which takes advantage of the magnetic gearing effect. The proposed double-sided linear machine exploits spoke-type permanent magnets (PMs) and one of the stators is displaced as half of the stator tooth pitch to obtain the flux-focusing effect. The thrust force ripple of the proposed spoke-type LPMVM can be decreased by adjusting the stator end-teeth and mitigating the detrimental impact of the longitudinal effect, leading to a novel structure of LPMVM, which offers high thrust force density, higher power factor, and lower thrust force ripple. The proposed LPMVM with adjusted end-teeth is a suitable candidate for different direct-drive applications. The presented spoke-type linear PM vernier machine is compared with a conventional surface-mounted LPMVM in order to validate the superiority of the new structure. Also, transient and steady-state thermal analyses of the proposed LPMVM are performed to verify the thermal stability of the new machine. A two-dimensional finite element analysis (2D-FEA) is adopted to confirm the outstanding characteristics of the proposed double-sided spoke-type linear vernier structure.**

***Index Terms*—Direct-drive, Finite element analysis, Linear permanent magnet vernier machine, Magnetic gearing effect, Thermal analysis, Wave energy harvesting**

I. Introduction

Linear machines are extensively employed for applications with the requirement of linear motion [1]. Therefore, different kinds of direct-drive linear permanent magnet (PM) machines attracted much attention in recent years [2]. Although the conventional PM synchronous machines can be driven directly, a high number of poles and windings are obliged to generate high torque/force at low speeds [3]. Linear PM vernier machines (LPMVMs) are excellent candidates for direct-drive applications, which provide high thrust force density at low speeds [4].

In recent years, different configurations and solutions have been introduced to improve the performance of LPMVMs, and various methods have been presented to survey the operation principle of linear PM vernier structures [5]. The electromagnetic performance of a linear PM vernier machine was studied in [6] by adopting a nonlinear equivalent magnetic network (NEMN) method, in which the longitudinal effect was considered into account. A novel structure of linear PM vernier was surveyed in [7], adopting the appropriate magnetization direction of magnets. The proposed machine offered a thrust force density of 150 kN/m^3.

To improve the thrust force capability of a conventional LPMVM, the multi-harmonics structure of a linear vernier machine with non-uniformly distributed PMs was presented in [8]. Even though thrust force density is increased, the proposed linear machine suffers from a low power factor of 0.2. The low power factor of linear vernier configurations, which arises from their high leakage flux, is a significant challenge that must be taken into account during their design process and operation [9]. A single-sided LPMVM adopting spoke-type PMs was proposed in [10], employing a non-magnetic space between the stator and PMs in order to decrease the leakage flux. However, the proposed spoke-type structure offers a power factor of 0.28, which is regarded as a crucial concern for linear vernier structures. To advance the low power factor of linear PM vernier machines, auxiliary DC field excitation can be implemented as an additional field winding [11], [12]. Although the power factor is developed by utilizing additional DC field excitation, the copper losses increase. Accordingly, a reduction in efficiency is inevitable, which adversely affects the performance of the whole system. Also, the temperature rise was resulted from the additional DC field winding, which causes the system to require cooling equipment [13].

In this paper, a novel high thrust force double-sided spoke-type LPMVM is proposed, providing a high power factor and decreased thrust force ripple. The configuration and design characteristics of the proposed LPMVM are investigated using 2D-FEA analysis and evaluations. The electromagnetic and thermal behaviors are analyzed, in which the results confirm the excellence of the new structure in terms of high thrust force density, high power factor, and decreased thrust force ripple. The configuration and operation principles of a surface-mounted LPMVM and a spoke-type counterpart will be analyzed in Section II. FEA is exploited in Section III to make a comparison between surface-mounted and spoke-type LPMVMs. Also, a novel LPMVM with decreased thrust force ripple will be proposed to mitigate the detrimental impact of the longitudinal end effect. The thermal analysis of the proposed LPMVM with adjusted end-teeth will be surveyed in IV based on its loss calculations. Finally, the conclusion will be provided in V.

II. Configuration and operation principles

Direct-drive LPMVMs are widely employed to provide linear force. Owing to their adherence to the principles of magnetic gearing [14], the capability to offer a high power/force is feasible for vernier structures.

A. Magnetic gearing effect

To utilize the magnetic gearing effect, LPMVMs must possess a combination of slots and poles based on the following relationship:

$$p_r = z \pm p_s \tag{1}$$

where p_r is the number of pole pairs of the moving part, which is also called the translator, z is the stator slots number, and p_s is the number of pole pairs of the stationary part. The slot/pole combination of the proposed LPMVM must be selected delicately to achieve a high thrust force density. In this study, the proposed LPMVM adopts 24 stator slots, 2 stator armature pole pairs, and 22 translator pole pairs. The ratio of the number of translator pole pairs to the number of stator pole pairs is expressed as the gear ratio (GR):

$$GR = \frac{p_r}{p_s} \tag{2}$$

The gear ratio of the studied machine is 11, which provides a high thrust force density, and a suitable value of power factor can be obtained simultaneously [15]. Also, the ratio between the speed of the translator (v) and the speed of the PM magnetic field (v_{PM}) is dependent upon the gear ratio:

$$v = v_{PM} \times (1/GR) \tag{3}$$

B. Configuration of linear PM vernier machines

The configurations of conventional surface-mounted and spoke-type LPMVMs are studied in this section. The LPMVMs presented in this paper take advantage of the double-sided structure to eliminate the disadvantageous attraction

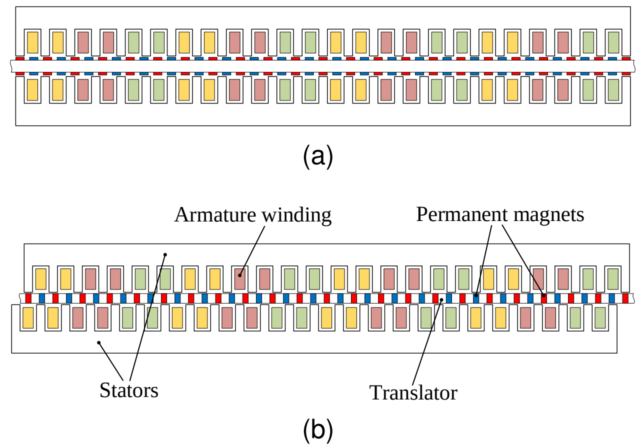

Fig. 1: Configuration of double-sided (a) surface-mounted LPMVM, and (b) spoke-type LPMVM

force in the vertical direction of the linear motion. The double-sided linear machines possess two wound stators and a long PM translator, in which the translator is sandwiched between two stators. The configurations of surface-mounted and spoke-type machines are shown in Fig. 1. The magnets of the surface-mounted LPMVM are located on both sides of the translator. Segmented spoke-type magnets are preferred for the spoke-type LPMVM. Hence, the leakage flux can be decreased owing to the eradication of iron bridges [16]. Also, one of the stators is shifted as half of the stator tooth pitch to realize the flux-focusing effect; consequently, a higher thrust force can be provided for the proposed linear structure.

III. Finite element analysis of double-sided LPMVMs

A two-dimensional (2D) model of the linear machine is presented based on the operation principles and the initial design. To improve the performance of LPMVM, the parameters should be optimized by defining an objective function [17]. In this work, a single-objective function of improving thrust force is adopted. Utilizing an optimization method, such as the Genetic Algorithm (GA), can be a practical approach for developing the thrust force capability of the linear structure by optimizing the machine parameters. The parameters that have the most significant impact on the objective function should be selected as the variables. Although the GA has been widely used in various problems, the results are not reliable due to ignoring some essential factors that directly affect the performance of the LPMVM, such as the leakage flux, the interference of adjacent PMs, and the saturation effect. Above all, this paper aims to reduce the thrust force ripple resulting from the longitudinal effect, which is computationally expensive to consider all these parameters in the GA optimization method. Therefore, the study of the performance of LPMVM based on a fast and realistic optimization procedure and considering all the affecting factors require further investigation, which can be surveyed in future studies. The Global Sensitivity Analysis (GSA) using Monte Carlo simulations is combined

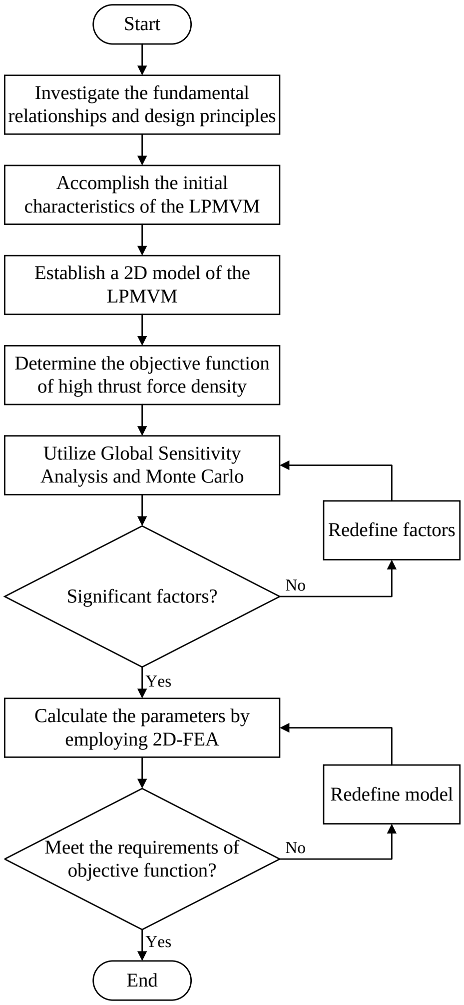

Fig. 2: Flowchart of the design process of the double-sided LPMVM

with FEA to model the probability of all aspects that influence the whole system. Random samples are generated by using Latin Hypercube Sampling (LHS). Despite allocating a longer time, the reliability of this approach outweighs the merit of evaluating the linear machine by using the GA. The process is summarised in Fig. 2.

The design characteristics of the spoke-type and conventional surface-mounted LPMVMs are tabulated in Table I. To make a fair comparison, the key parameters of both linear machines are decided to have the same values. The stators of both linear machines have the same dimensions and the same configuration of windings, and equal volumes of PMs are used for the translators.

Fig. 3 illustrates the flux linkage waveforms of the surface-mounted and spoke-type LPMVMs under the no-load condition. Compared to the surface-mounted LPMVM, the maximum values of flux linkage in phase A, phase B, and phase C for the spoke-type LPMVM with the same volume of PMs are improved by 73.8%, 72.7%, and 71.1% respectively. This development is accomplished by decreasing the leakage

TABLE I: Key parameters of surface-mounted and spoke-type LPMVMs

	surface-mounted LPMVM	spoke-type LPMVM
Number of phases	3	
Rated frequency	50 Hz	
Air gap length	1 mm	
Rated translator speed	1 m/s	
Number of stator slots	24	
Number of armature pole pairs	2	
Number of translator pole pairs	22	
Stator tooth width	6.2 mm	
Stator slot width	11.8 mm	
Stator slot height	20.7 mm	
Stator yoke length	15.6 mm	
Stack length	60 mm	
Translator height	8.6 mm	7 mm
PM remanence	1.2 T	
PM material	NdFeB	
PM dimensions	7*2 mm	4*7 mm
Slot filling factor	0.5	
Current density	3.1 A/mm^2	
Armature windings per coil	85	

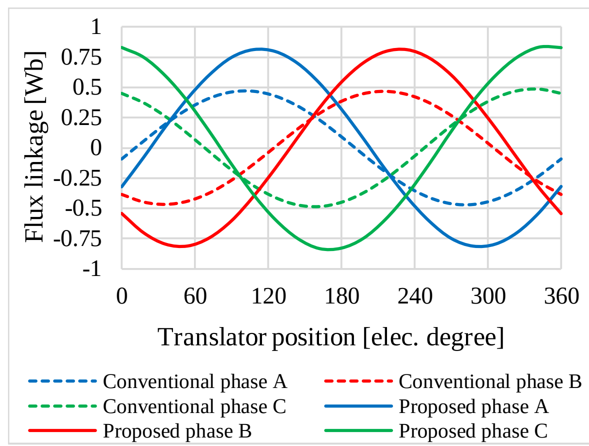

Fig. 3: Flux linkage waveforms of surface-mounted and spoke-type LPMVMs

flux and obtaining the beneficial effect of focusing the flux, resulting from the unique structure of spoke-type PMs and displacement of the lower stator as half of the stator tooth pitch. However, there is a difference between the maximum amplitudes of the phases and a slight shift between phases. Even though there is no discrepancy between the maximum values of flux linkage in phases A and B, the difference between the maximum values of phases A and C is 22 mWb. Also, the phase difference between phases A and B is 114.5 degrees, and between phases A and C is 122.4 degrees. The adverse impact of phase shift mainly stems from the linear configuration of the proposed LPMVM and the unwanted effect of end-teeth, which leads to a high thrust force ripple.

Fig. 4 shows the thrust force for surface-mounted and spoke-type LPMVMs. Even though the average force is increased by 58% for the latter structure, their thrust force ripple is 21.3%

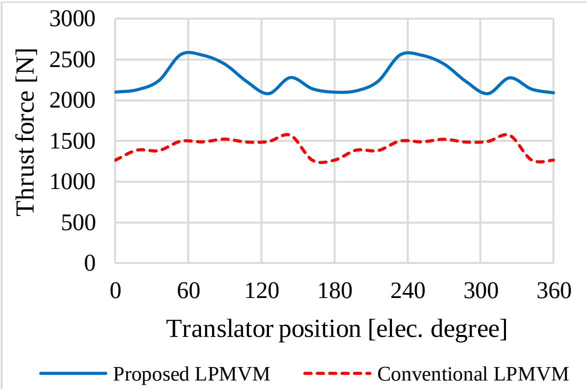

Fig. 4: Thrust force of surface-mounted and spoke-type LPMVMs

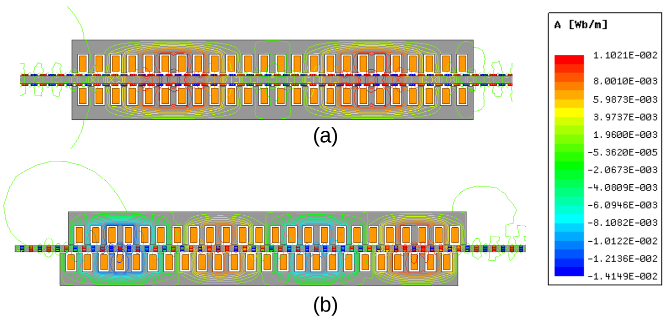

Fig. 5: Longitudinal effect of (a) surface-mounted LPMVM, and (b) spoke-type LPMVM

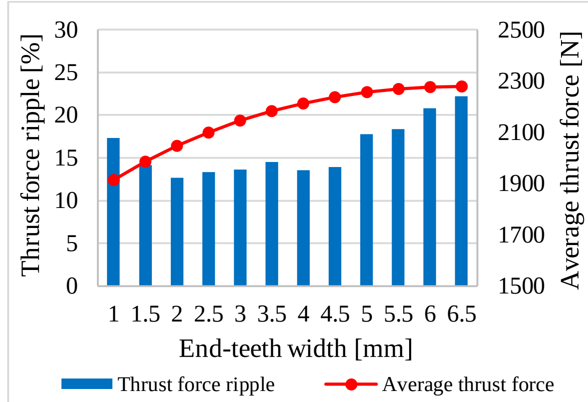

Fig. 7: Average thrust force and thrust force ripple in terms of the width of stator end-teeth

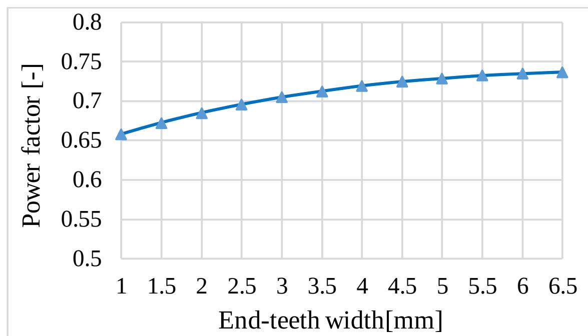

Fig. 8: Power factor in terms of the width of stator end-teeth

for surface-mounted and 21.1% for spoke-type machines, arising from their destructive longitudinal effect.

The impact of the longitudinal effect on the surface-mounted and spoke-type LPMVMs are shown in Fig. 5. The longitudinal effect can be mitigated by adopting the innovative approach of adjusting the stator end-teeth for the spoke-type LPMVM. Therefore, as illustrated in Fig. 6, by adjusting the stator end-teeth of the spoke-type machine, the longitudinal effect can be attenuated, and the thrust force ripple can be decreased.

The width of the end-teeth, excluding the other stator teeth, is changed and the values of thrust force ripple and average thrust force are reported in Fig. 7. The thrust force ripple can be reduced by adjusting the width of the stator end-teeth, in which the average thrust force is affected slightly. However, a trade-off is taken into account to realize a low thrust force ripple and maximum thrust force simultaneously. The stator end-teeth width is designed to be 4.5mm, in which the thrust force ripple of 13.9%, and the average thrust force of 2.23kN is achieved. The thrust force ripple is decreased by 7.2% and 7.4% in comparison with the surface-mounted and spoke-type LPMVMs, respectively. The average thrust force of the proposed LPMVM with adjusted end-teeth is reduced by 1.7% compared to the spoke-type LPMVM without adjusted end-teeth by a negligible decrease. By comparing the conventional surface-mounted LPMVM and the proposed spoke-type LPMVM, the average thrust force is improved remarkably by 55.9%. The power factor is influenced by changing the width of stator end teeth, as shown in Fig. 8. The power factor of the proposed LPMVM is 0.72, which has undergone a trivial reduction compared to the spoke-type LPMVM without adjusted end-teeth, still higher than the surface-mounted structure.

By comparing the three linear vernier structures investigated in this paper, the proposed spoke-type LPMVM with adjusted stator end-teeth can be an excellent candidate for direct-drive applications owing to the merits of high thrust force capabil-

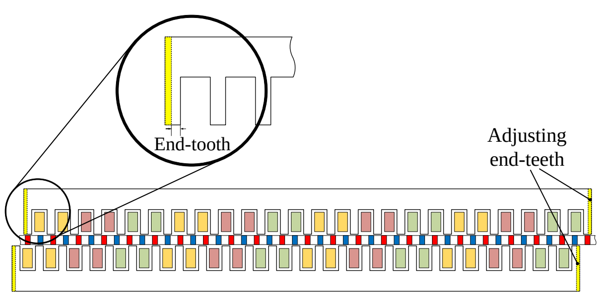

Fig. 6: Design optimization outcome to adjust the stator end-teeth

TABLE II: Characteristics comparison of the conventional LPMVM, spoke-type LPMVM, proposed LPMVM with adjusted end-teeth, a LPMVM [18], and a HTS LPMVM [19]

	Unit	Conventional LPMVM	Spoke-type LPMVM	Proposed LPMVM	LPMVM [18]	HTS LPMVM [19]
Average thrust force	kN	1.43	2.27	2.23	1	3.05
Thrust force ripple	$\%$	21.3	21.1	13.9	31	9
Thrust force density	kN/m^3	624	1058	1039	855	601
Gear ratio (GR)		11	11	11	5	17
PM volume	cm^3	73.92	73.92	73.92	51.3	-
Average force per PM volume	N/cm^3	19.3	30.7	30.1	19.5	-
Power factor		0.68	0.73	0.2	0.71	0.6

ity, high power factor, and reduced thrust force ripple. The main characteristics of the conventional and proposed linear machines with and without adjusted end-teeth are presented in Table II. To show the superiority of the proposed LPMVM, a comparison with two other double-sided LPMVMs possessing similar geometry and the same operation principles is conducted in Table II, i.e. a 6-slot/10-poles spoke-type LPMVM [18] and a high-temperature superconductor (HTS) LPMVM [19]. The 6-slot/10-pole LPMVM utilizes the conventional stator teeth similar to the proposed LPMVM with adjusted end-teeth. Although the 6-slot/10-poles LPMVM offers the same power factor as the proposed LPMVM, it suffers from a considerable thrust force ripple of 31% and has a lower thrust force density. Furthermore, a novel HTS LPMVM was proposed in [19], employing the double-sided structure and spoke-type PMs similar to the proposed LPMVM. The HTS LPMVM exploits the flux modulation poles (FMPs), and the HTS bulks are inserted inside the space of FMPs in order to decrease the leakage flux. Even though the HTS LPMVM offers a lower thrust force ripple, thrust force density and power factor are also lower. Moreover, employing HTS bulks imposes drawbacks and difficulties for a linear machine, such as the complexity of the structure, the increased weight, and the higher cost. Consequently, the proposed LPMVM with adjusted end-teeth is a suitable choice for direct-drive applications due to providing high thrust force density, higher power factor, and reduced thrust force ripple.

IV. Thermal analysis of the proposed LPMVM with adjusted end-teeth

The temperature rise of different parts of the linear vernier structure affects its performance and lifetime, indicating the significance of thermal analysis in addition to electromagnetic analysis. The study of the thermal behavior of the proposed LPMVM is considered one of the principal steps during its performance evaluation. In order to thermally analyze the proposed machine, a broad range of approaches can be adopted, including numerical and analytical methods. To offer an accurate and reliable investigation, the proposed LPMVM is evaluated using 2D-FEA-based thermal modeling. Firstly, the iron and copper losses are needed to be carefully computed under different loads. Next, the temperature rise can be predicted based on the heat sources. Bertotti model is used to calculate the core losses for the magnetic steel domain, and resistive heating is employed to model copper losses. The reference temperature is 293.15 $[K]$ and the material properties are tabulated in Table III [4].

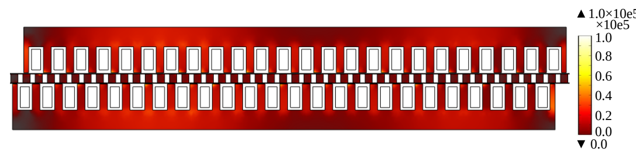

Fig. 9: Volumetric loss density $[W/m3]$ of the proposed LPMVM

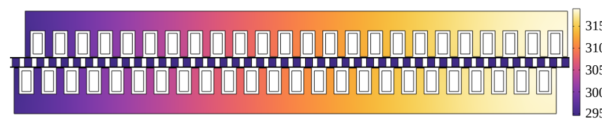

Fig. 10: Steady-state thermal analysis of the proposed LPMVM with adjusted end-teeth

The copper losses are 83.8 W for the conventional surface-mounted LPMVM and the proposed LPMVM with adjusted end-teeth. The core losses are 11.3 W and 22.3 W for surface-mounted and proposed LPMVMs, respectively. The volumetric loss density $[W/m3]$ of the proposed LPMVM with adjusted end-teeth is depicted in Fig. 9.

Conduction and convection mechanisms are defined as heat transfer mechanisms to analyze the thermal behavior of the LPMVMs. 2D FEA is used to anticipate the temperature rise of the double-sided linear vernier machine under the external forced convection, while air with a speed of 1 m/s is regarded as fluid. The steady-state thermal behavior of the proposed LPMVM with adjusted end-teeth is demonstrated in Fig. 10.

The transient thermal analysis is investigated to make sure that the temperature does not exceed the maximum allowed limit. The average temperature rise of the stators of the surface-mounted and proposed LPMVMs are compared in Fig. 11. The proposed structure has a higher temperature rise owing to higher losses. The maximum temperature of the stator of the surface-mounted LPMVM is 309.3 K, while the same value for the proposed machine increases to 311.5 K and stabilizes after approximately 1 hour. The analysis confirms the reliable performance of the proposed LPMVM, while the windings are safe and magnets are not at risk of demagnetization.

TABLE III: Material properties of the proposed LPMVM [4], [20]

Material	Thermal conductivity $[W/(m.K)]$	Specific Heat Capacity $[J/(kg.K)]$	Density $[kg/m^3]$
Steel	30	460	7650
Magnet	7.6	460	7500
Copper	401	385	8933

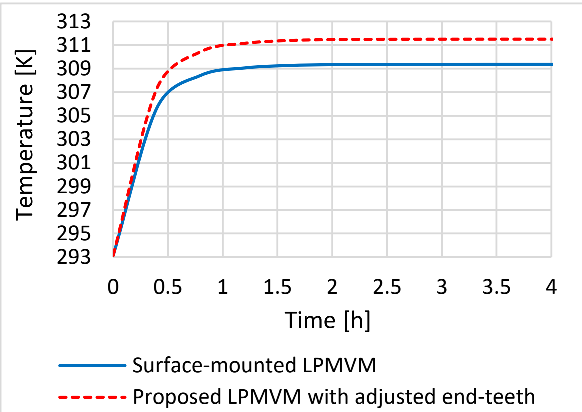

Fig. 11: Temperature rise of the stator of the proposed LPMVM with adjusted end-teeth

V. Conclusion

In this paper, a structure of a double-sided linear PM vernier machine is proposed, which employs spoke-type PMs, and one of the stators is displaced as half of the tooth pitch to adopt the flux-focusing effect. Furthermore, the stator end-teeth of the proposed LPMVM are adjusted to attenuate the longitudinal end effect and decrease the thrust force ripple. The proposed LPMVM with adjusted end-teeth is compared with conventional surface-mounted and spoke-type LPMVMs. Results show that the proposed machine has the unique benefits of high thrust force at low speeds and improved power factor. By adopting an innovative design approach for adjusting the stator end-teeth, the thrust force ripple is reduced from 21.1% to 13.9% for the proposed spoke-type LPMVM using the adjusted stator end-teeth. Moreover, the power factor and thrust force density of the proposed linear vernier structure with adjusted end-teeth is higher than the conventional surface-mounted LPMVM. The steady-state and transient thermal analyses of the proposed machine are performed based on its power loss models. In summary, the proposed LPMVM offers a high thrust force density, power factor, and lower thrust force ripple.

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