Analysis and Modeling of Tooth-Tip Leakage Fluxes in a Radial-Flux Dual-Stator Machine with Diametrically Magnetized CylindricalPermanentMagnets

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Abstract—Tooth-tip Leakage flux (TLF) has a major effect on the prediction of air-gap flux distribution and electromagnetic torque in the permanent magnet (PM) machines. Therefore, deriving a model for TLF is necessary for machine design and optimization. Accurate modeling of TLF can lead to fast and precise solutions, which ease the analysis of electromagnetic devices. It also provides the opportunity to increase torque density by more efficient utilization of PM’s volume and prevent saturation in machine optimization. This paper presents a method for modeling and analyzing TLFs in a radial-flux dual-stator permanent magnet (DSPM) machine with diametrically magnetized cylindrical permanent magnets (DMCPM) in series and parallel magnetic circuit structures. In this model, some expressions in terms of machine dimensions are derived for the TLF analysis. Finite element method (FEM) is applied to validate the proposed model. Results indicate that the maximum error between the proposed model and FEM is insignificant (less than 6%). Finally, by a prototyped machine the validity of the proposed model was investigated with the experimental tests.

Index Terms—Dual-stator permanent magnet (DSPM) machine, diametrically magnetized cylindrical permanent magnet (DMCPM), tooth-tip leakage fluxes (TLFs).

I. INTRODUCTION

Dual stator permanent magnet (DSPM) machines have recently attracted a lot of attention to wind power generation, electric vehicles, hybrid electric vehicles, and starter generators because of their advantages, such as high efficiency and high torque and power density [1]-[5]. From the structural point of view, DSPM machines are designed to provide more efficient utilization of the rotor’s space in conventional PM machines, which increases torque density [1]. DSPM machines are a combination of two conventional single stator PM machines, one with outer rotor structure and the other with inner rotor structure [3]. As shown in Fig.1, in series magnetic circuit (SMC) structure, stators have magnetic connection and fluxes pass through PMs and another stator, although, these stators in parallel magnetic circuit (PMC) structure have no magnetic connection. In other words, fluxes pass through the ferromagnetic rotor without passing another stator. In SMC structure, the rotor is made of non-ferromagnetic material to lead PM’s flux pass through stators and participate in torque production [6-8]. Due to the rotor’s material, DSPM in SMC structure has lower inertia in comparison to the PMC structure, which causes a faster dynamic of the machine. Also, in the PMC structure, the machine has higher torque density and cogging torque [6].

Although using two stators in the PM machine can increase the costs of fabrication, it can provide the optimum value of torque production. It is also important to mention that however, DSPM has other disadvantages such as higher cogging torque in comparison to single stator structure, recent studies proved that DSPM with diametrically magnetized cylindrical PM (DMCPM) has lower cogging torque compared to the PM machine with other conventional PM shapes [9].

Besides, Due to the effect of leakage fluxes on air-gap flux and electromagnetic torque in PM machines, investigation of these fluxes is necessary for analysis and optimum design of these machines [10]. The most important part of leakage fluxes is known as zigzag leakage fluxes that can be decomposed to three types of leakage fluxes; the first one is short-circuited by stator tooth; the second type only links pieces of the stator winding and the third type, which passes through the tooth to tooth, does not connect to any coil [11]. The first type has a significant value compared to other types. So, in this paper, the fluxes that are short-circuited by stator tooth, which is known

Fig. 1. DSPM machine with DMCPM. (a) SMC structure, (b) PMC structure.
as tooth-tip leakage fluxes (TLFs), are investigated. This type of leakage fluxes for SMC and PMC structure in the DSPM machine is depicted in Fig. 2.

Leakage fluxes in different types of PM machines with rectangular and arc shape PMs are modeled [12]-[18], although TLFs modeling is only described for surface mounted PM machines with rectangular PM [16]-[18]. In some of the aforementioned researches, TLFs are modeled by calculating the maximum value of TLFs and approximating variation trend [16]-[17]. In another research, TLFs are modeled by utilizing magnetic equivalent circuit with calculating permeance of TLF paths by neglecting pole shoes for simplification [18].

The purpose of this paper is to present a model for analyzing the TLFs in the DSPM machine with DMCPM by a new approach for approximating the maximum value of TLF and variation trend. In the following sections, the modeling process of TLF is described. Then, this model is validated by FEM and experimental results.

II. TLF MODELING IN SMC STRUCTURE

As shown in Fig. 3, the value of TLF depends on the rotor’s position and also because of the cylindrical shape of PMs, the air-gaps are asymmetric. Thus, modeling the TLFs by the magnetic equivalent circuit method is more complicated. In order to understand flux variations, the rotor position is considered relative to the stationary reference. The position of PM is known as \( x \), corresponding to the axis that is assumed to be in the middle of slot opening, shown by \( A \) axis in Fig. 3. By the increase of \( x \) from zero, the TLF increases and the maximum value of TLF occurs when two PMs have an equal distance from the axis that is assumed to be in the middle of the tooth, shown by \( B \) axis in the Fig.3. In this position, the TLF has a maximum value in both inner and outer stators. By continuing the increase of \( x \), the TLF decreases gradually and when two...
where \( \alpha \) is defined as

\[
\alpha = \frac{w_t - l_{PM}}{2}
\]

When \((W_t - l_{PM})/2 > r_{PM}\), the second part of (3) will be positive and when \((W_t - l_{PM})/2 < r_{PM}\), it will be negative.

In [16], the variation of TLF is approximated linearly from the minimum value to the maximum value for a rectangular PM. Here, this variation is approximated with a second-order equation because the PMs' cylindrical shape makes asymmetrical air-gap. The second-order variation of TLF, which is based on FEM investigations (discussed in the next sections), is well shown in Fig. 6. Therefore, the \( \varphi_{TLF} \) can be expressed as

\[
\varphi_{TLF}(x) = \begin{cases} 
\frac{\beta \varphi_{PM}}{(x_{max} - x_{min})^2} (x - x_{min})^2, & \text{for } x_{min} \leq x \leq x_{max}, \\
\frac{\beta \varphi_{PM}}{(x_{max} - x_{min})^2} (2x_{max} - x - x_{min})^2, & \text{for } x_{max} \leq x \leq 2x_{max} - x_{min}, 
\end{cases}
\]

where \( \beta = a_d/a_c \). Also, \( x_{max} \) and \( x_{min} \) can be expressed as

\[
x_{max} = \frac{w_t + w_{go} - l_{PM}}{2}
\]

\[
x_{min} = \frac{-l_{PM}}{2}
\]

Equation (5), (6), and (7) can be used for both stators by substituting their dimensions.

The total value of TLF from both sides of PM is (see Appendix)

\[
\varphi_{TLF, net}(x) = \varphi_{TLF}(x) + \varphi_{TLF}(2r_{PM} - x)
\]

The average of TLF from both sides of PM over one tooth pitch is given by the integral of the total value of TLF.

\[
\varphi_{TLF, ave} = \frac{1}{2(x_{max} - x_{min})} \int_{x_{min}}^{x_{max}} \varphi_{TLF, net}(x) \, dx
\]

The solution of the integral is

\[
\frac{\varphi_{TLF, ave}}{\varphi_{PM}} = \frac{\beta}{2(x_{max} - x_{min})} \left( \frac{2}{3} [8r_{PM}^3 - x_{max}^3] - (x_{min} - x_{max})^3 - (x_{max} + x_{min} - 2r_{PM})^3 \right) - 2r_{PM} (3x_{min} + x_{max}) - \frac{16}{3} (r_{PM} - x_{max})^3
\]

The factor for TLF in SMC structure can be defined as:

\[
K_{TLF} = \frac{\varphi_{PM} - \varphi_{TLF, ave}}{\varphi_{PM}}
\]

This coefficient can be used for both stators by substituting their dimensions in (5), (8), (9), and (10). \( K_{TLF} \) is the critical factor in machine design and optimization to predict air-gap flux density and electromagnetic torque accurately.

III. TLF MODELING IN PMC STRUCTURE

As shown in Fig. 5, in the DSPM machine with DMCPM in the PMC structure, stators have no magnetic connection. Therefore, TLFs return to the same PM after passing a tooth. In this structure, the amplitude of the TLF depends on the rotor’s position, similar to the SMC structure. Thus, the rotor’s position is considered relative to the stationary reference and \( x \) is defined as the distance between the center of the circular section of PM and the \( B \) axis.

The maximum value of TLF in the PMC structure occurs when \( x = 0 \). To be more specific, when the center of the circular section of PM is placed on the \( B \) axis, the PM’s flux has the maximum space of the pole shoe to pass through. When the rotor moves from this position, the value of TLF decreases gradually. Furthermore, while the center of the circular section of PM is placed on \( A \) axis, due to the present maximum space of slot opening in the TLF path, the value of TLF reaches the minimum. In this position, \( x \) is equal to \((W_t + W_{go})/2\).

Due to the ferromagnetic rotor in the PMC structure, the air-gap between both stators and rotor is almost symmetric. Therefore, when \( r_{PM} > W_t/2 \), the maximum value of TLF can be found by linear division over the tooth width as

\[
\varphi_{TLF, max} = \frac{w_t}{2r_{PM}} \varphi_{PM}
\]

Also, when \( r_{PM} < W_t/2 \), disregarding an insignificant air-gap leakage flux, the whole of PM’s flux pass through stator’s teeth and the value of TLF in each stator depends on stator tooth width.

\[
\frac{\beta' \varphi_{go}}{\beta' \varphi_{to}} = \frac{w_g}{w_t}
\]

where \( \beta' \varphi_{go} \) and \( \beta' \varphi_{to} \) are the ratio of the maximum value of TLF to PM’s Flux in the inner stator and outer stator, respectively.
In the PMC structure, the variation of TLF is approximated by a straight line from the maximum value to the minimum value because of symmetric air-gaps. During \((w_{t}+w_{g})/2 < x < (w_{t}+w_{g})/2\), TLF is almost negligible due to the slot opening present in the flux path [16]. Therefore, the TLF can be expressed as

\[
\phi_{TLF} (x) = \begin{cases} 
0 & \text{for} \ -\frac{w_{t}+w_{g}}{2} \leq x \leq x'_{\text{min}} \\
\frac{\beta'}{x'_{\text{min}}} (x + x'_{\text{min}}) & \text{for} \ -x'_{\text{min}} \leq x \leq 0 \\
\frac{\beta'}{x'_{\text{min}}} (x'_{\text{min}} - x) & \text{for} \ 0 \leq x \leq x'_{\text{min}} \\
0 & \text{for} \ x_{\text{min}} \leq x \leq \frac{w_{t}+w_{g}}{2} 
\end{cases}
\]

where \(x'_{\text{min}}\) can be expressed as

\[
x'_{\text{min}} = \frac{w_{t}+w_{g} - l_{PM}}{2}
\]

The total value of one PM’s TLF in the PMC structure is the sum of TLFs in both sides of the PM. When the right-hand side of PM is in \(x\) position relative to the \(B\) axis, another side is in \(-x\) position relative to the same \(B\) axis. Given that TLF in PMC structure is an even function, the total value of one PM’s TLF can be obtained by

\[
\phi_{TLF, ave} = \frac{4}{w_{t}+w_{g}} \int_{0}^{x'_{\text{min}}} \frac{\beta'}{x'_{\text{min}}} (x'_{\text{min}} - x) dx
\]

\[
= \frac{2\beta' x'_{\text{min}}}{w_{t}+w_{g}}
\]

(18)

The factor for the TLF in the PMC structure can be defined as

\[
K_{TLF} = \frac{\phi_{PM} - \phi_{TLF, ave}}{\phi_{PM}}
\]

(19)

This equation can be used for both stators by substituting their dimensions in (14), (15), (18), and (19).

### IV. FEM VERIFICATION OF TLF IN SMC AND PMC STRUCTURES

The FEM analysis is applied to the DSPM machine with DMCPM in ANSYS Maxwell to validate the analytical equations for TLF in both structures. The parameters that used for the simulation are \(g_{o}=1\ mm\), \(g_{i}=1\ mm\), \(r_{PM}=3\ mm\), \(l_{PM}=2.5\ mm\), \(w_{g=}=10\ mm\), \(w_{t}=7.7\ mm\), \(w_{g}=1\ mm\) and \(w_{g}=1\ mm\). The results of simulation in SMC structure for inner and outer stators are tabulated in Table I and Table II, respectively and the results of the PMC structure are tabulated in Table III and Table IV, respectively. Also, these results for SMC and PMC structures are presented in Fig. 6 and Fig. 7, respectively, where the differences between the existent model and the proposed model are well illustrated.

By evaluating (11) and (19), the TLF factor for both magnetic circuit structures is calculated. In Table V, the absolute errors between FEM and analytical results for SMC structure are 5.9% and 1.2% for the outer and inner stator, respectively, and in PMC structure are 5.3% and 4.4% for outer and inner stators, respectively.
PM’s flux line of DSPM machine with DMCPM for both magnetic circuit structures are shown in Fig. 8. In this figure, three rotor position cases for each magnetic circuit structure are considered; the maximum value of TLF, the minimum value of TLF, and one case between them.

V. COMPARISON AND APPLICATION IN THE PM MACHINE

As shown in Fig. 6, in the machine with variable PM thickness, the existent model could not predict TLF precisely while the proposed model could predict TLF more accurately in comparison to the previous model. Also, according to Table V, in the SMC structure, the TLF factor has a higher value. It shows that considering the same condition, the machine with SMC structure has lower TLF than a machine with the PMC structure.

The analytical models of the TLF were explained in the previous sections and comparison results between SMC and PMC structure were utilized to design a new PM machine based on SMC structure: dual-stator radial-flux machine with diametrically magnetized cylindrical permanent magnets [9, 19].

A 3-Phase 1714 r/min twenty eight-pole prototype machine was designed and built. Fig. 9 shows different parts of the test-setup to measure the efficiency and the torque angle characteristics of the proposed machine for the validation of the FEM and proposed analysis. It also demonstrates the different sections of the prototyped machine with the proposed PMs.

Fig. 10 compares the FEM and experimental torque-angle characteristics of the machine with the proposed PMs and Fig. 11 shows the measured and the FEM predicted efficiencies for 400 Hz frequency (speeds).
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Fig. 9. The test setup and the prototype of the proposed machine.

Fig. 10. The torque-angle characteristics.

Fig. 11. Machine efficiency.

The discrepancies between the measured and the FEM results maybe because of the windage losses and measurement errors that were not introduced in the simulations.

Unfortunately, due to practical limitations, it was not possible to test more specifically the leakage calculations. However, this broad agreement on torque and efficiency are a good indication of the validity of the model.

VI. CONCLUSION

In this paper, tooth-tip leakage flux (TLF) in dual-stator permanent magnet (DSPM) machine with diametrically magnetized cylindrical magnets in series and parallel magnetic circuit structures were modeled and validated by FEM analysis. In the series magnetic circuit (SMC) structure, the maximum value of TLF was modeled by a new approximation method which used the ratio of the air-gap area between stator tooth and PM to the air-gap area between the stator and PM.

Also, in the parallel magnetic circuit (PMC) structure, flux division over the teeth width in both stators was utilized. In SMC structure, TLF variation was modeled with a second-order equation to provide a more accurate approximation because of asymmetric air-gaps. But in PMC structure, TLF variation was modeled with a straight line due to symmetric air-gaps. This model would be beneficial for designing and optimizing a dual-stator PM machine to predict air-gap flux density and electromagnetic torque precisely. FEM results show that the proposed model has a 5.9% error in the worst case. Finally, by a prototyped machine the validity of the proposed model was investigated with the experimental tests.

In the future work, the author will consider the analytical modeling of air-gap leakage fluxes in both structures for DSPM machines with DMCPM to have another important leakage flux coefficient that has a key role in machine design and optimization.

APPENDIX

The total value of one PM’s TLF in the SMC structure is calculated by (8) because both sides of the PM have leakage fluxes that pass through different teeth. To be clear, when the right-hand side of PM is in \( x \) position relative to the \( A \) axis, another side is in \( 2r_{\text{PM}} - x \) position relative to the same \( A \) axis. Therefore, the total value of TLF is the sum of both sides TLFs. The calculation of the total value of TLF is illustrated in Fig. 12. In two points, the value of both sides of PM’s TLF is equal. In point 1, the center of the circular section of PM is placed on the \( A \) axis, and in point 2, it is placed on the \( B \) axis.

Based on (8) and Fig. 9, the total value of TLF can be obtained by

\[
\Phi_{\text{TLF, net}}(x) = \gamma \left( \frac{(x-x_{\text{min}})^2 + (x + 2(x_{\text{max}} - r_{\text{PM}}) - x_{\text{min}})^2}{(2r_{\text{PM}})^2}, \right.
\]

\[
\left. \text{for } x - x_{\text{min}} \leq x \leq 2r_{\text{PM}} - x_{\text{max}} \right),
\]

\[
\left( x - x_{\text{min}} ight)^2 + \left( x + 2r_{\text{PM}} - x_{\text{min}} - x \right)^2, \quad \text{for } 2r_{\text{PM}} - x_{\text{max}} \leq x \leq x_{\text{max}},
\]

\[
\left( 2x_{\text{max}} - x_{\text{min}} - x \right)^2 + \left( 2r_{\text{PM}} - x_{\text{min}} - x \right)^2, \quad \text{for } x_{\text{max}} \leq x \leq 2r_{\text{PM}} - x_{\text{min}},
\]

\[
\left( 2x_{\text{max}} - x_{\text{min}} - x \right)^2 + \left( x + x_{\text{max}} - 2r_{\text{PM}} \right)^2, \quad \text{for } 2r_{\text{PM}} - x_{\text{min}} \leq x \leq 2x_{\text{max}} - x_{\text{min}}.
\]

where \( \gamma \) is defined as

\[
\gamma = \frac{\beta \Phi_{\text{PM}}}{(x_{\text{max}} - x_{\text{min}})^2}
\]

The average of PM’s TLF over one tooth pitch can be computed by the integral of (20) during one period of TLF.

Fig. 12. Total TLF in the DSPM machine with DMCM in the SMC structure.
\[ \varphi_{TLP_{ave}} = \frac{\gamma}{x_{\text{max}} - x_{\text{min}}} \int_{r_{\text{min}}}^{2r_{PM} - r_{\text{max}}}(x - x_{\text{min}})^2 + (x + 2(x_{\text{max}} - r_{PM}) - x_{\text{min}})^2 \, dx + \int_{r_{\text{min}}}^{2r_{PM} - r_{\text{max}}}(x - x_{\text{min}})^2 + (2r_{PM} - x_{\text{min}} - x)^2 \, dx + \int_{r_{\text{min}}}^{2r_{PM} - r_{\text{max}}}(2x_{\text{max}} - x_{\text{min}} - x)^2 + (2r_{PM} - x_{\text{min}} - x)^2 \, dx + \int_{r_{\text{min}}}^{2r_{PM} - r_{\text{max}}}(2x_{\text{max}} - x_{\text{min}} - x)^2 + (x + x_{\text{max}} - 2r_{PM})^2 \, dx \]

(22)

The solution of the integral is

\[ \varphi_{TLP_{ave}} = \frac{\beta \varphi_{PM}}{2(x_{\text{max}} - x_{\text{min}})^3} \left\{ \frac{2}{3} \left[ 8(r_{PM} - x_{\text{max}})^3 - (x_{\text{min}} - x_{\text{max}})^3 - (x_{\text{max}} + x_{\text{min}} - 2r_{PM})^3 \right] \right\} - \frac{4}{3} (r_{PM} - x_{\text{max}}) (4r_{PM}^2 + 3x_{\text{min}}^2 + 3x_{\text{max}}^2 - 2r_{PM} (3x_{\text{min}} + x_{\text{max}})) - \frac{16}{3} (r_{PM} - x_{\text{max}})^3 \]

(23)

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