Energy conversion in dc excited flux-switching machines

Citation for published version (APA):

Tang, Y., Paulides, J. J. H., & Lomonova, E. A. (2014). Energy conversion in dc excited flux-switching machines. *IEEE Transactions on Magnetics*, 50(11), 8105004-1/4. <https://doi.org/10.1109/TMAG.2014.2325405>

DOI:

[10.1109/TMAG.2014.2325405](https://doi.org/10.1109/TMAG.2014.2325405)

Document status and date:

Published: 01/01/2014

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Energy Conversion in DC Excited Flux-Switching Machines

Yang Tang, Johannes J. H. Paulides, and Elena A. Lomonova

Eindhoven University of Technology, Eindhoven 5612 AZ, The Netherlands

This paper initiates a study on energy conversion in dc excited flux-switching machines (DCEFSMs) to reveal the torque production mechanism of this type of machines. The flux linkage components and self- and mutual inductances of a single-phase two-rotor-tooth DCEFSM are investigated. Based on the understanding of the relation between these variables and the rotor position, two different switching strategies are implemented to the armature current of this machine. Current-flux linkage loops are sketched for each switching strategy, resulting in different torque expressions. These torque expressions, validated using finite element analysis, show that the DCEFSM is a reluctance machine in which torque is generated due to variation of self- and mutual inductances. In addition, the torque component related to the mutual inductance can be dominant with certain current commutation in the armature winding.

Index Terms—DC excitation, energy conversion, flux-switching machine, torque calculation.

I. INTRODUCTION

A DC EXCITED flux-switching machine (DCEFSM) is a type of double-salient structured brushless machine with two sets of windings in the stator: the armature winding and the field winding [1], [2], as shown in Fig. 1(a). It combines the advantages of switched reluctance machines (SRMs) and synchronous machines (SMs), which allows a robust rotor structure while preserving a reasonable torque density [3]. Furthermore, in DCEFSMs, the field weakening can be directly performed by reducing the field current, leading to an extendable speed range and an improved efficiency in the high-speed region with a constant power. Therefore, they are a strong candidate for applications where high ruggedness with a wide constant power speed range is required [3].

The design and control of DCEFSMs require a thorough understanding of the torque production mechanism of this machine. On the one hand, attempts have been made to analogize this type of machines to dc machines (DCMs) and SMs. In [2], the torque of a single-phase DCEFSM was calculated using a similar equation to that used for DCMs. In [4]–[6], three-phase flux-switching permanent magnet machine (FSPMM) was analyzed as SMs. In [6], the dq reference frame was adopted to calculate the torque of an FSPMM. However, the air-gap magnetic field of DCEFSMs shows a pulsating characteristic, which is completely different from that in DCMs or SMs and more similar to that in SRMs. On the other hand, DCEFSMs are usually confused with SRMs with dc-assisted excitation (SRDCMs) [7], which also employs two sets of windings in the stator and a simple rotor structure, as shown in Fig. 1(b). The difference between these two types of machines is generally understood as that the armature flux linkage of a DCEFSM is bipolar, similar to the case in an SM, while that of an SRDCM is unipolar, similar to an SRM. Thus, a question on the nature of DCEFSM is raised: is it a reluctance machine [Fig. 1(b)] or a wound-field SM [Fig. 1(c)]?

To be able to answer this question, this paper initiates a study on the energy conversion in DCEFSMs. Using the current-flux linkage loops, the factors that decide the torque

Fig. 1. Cross sections of (a) DCEFSM, (b) SRDCM, and (c) wound-field SM.

Fig. 2. Cross sections of a single-phase two-rotor-tooth DCEFSM with different rotor positions. (a) $\theta = 0^\circ$. (b) $\theta = 45^\circ$. (c) $\theta = 90^\circ$. (d) $\theta = 135^\circ$.

production of a DCEFSM are investigated. The nature of this machine is thus revealed in comparison with DCMs, SMs, and SRMs. To highlight this nature, this paper chooses the simplest topology of this type of machines, a single-phase two-rotor-tooth DCEFSM, as the example shown in Fig. 2. With this simplification, the mutual coupling in multi-phase machines between different phases of the armature winding is assumed negligible.

II. INDUCTANCES OF DCEFSMS

In a single-phase DCEFSM, the total flux linked by the armature winding consists of two components: the flux created by the armature current i_a through the self-inductance of the armature winding L_{aa} and the flux created by the field current i_f through the mutual inductance between the armature winding and the field winding M_{af} . Disregarding the magnetic saturation, the armature flux linkage can be expressed as

$$\lambda_a = \lambda_{aa} + \lambda_{af} = L_{aa}i_a + M_{af}i_f \quad (1)$$

in which L_{aa} and M_{af} are variant with respect to the rotor position.

Fig. 2(a)–(d) shows cross sections of the single-phase DCEFSM with different rotor positions in an electrical period.

Manuscript received March 7, 2014; revised April 16, 2014 and April 29, 2014; accepted May 15, 2014. Date of current version November 18, 2014. Corresponding author: Y. Tang (e-mail: y.tang1@tue.nl).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TMAG.2014.2325405

Fig. 3. Inductances of the DCEFSM.

TABLE I
MACHINE DIMENSIONS AND PARAMETERS

Description	Value
Stack length	120mm
Stator outer diameter	120mm
Rotor outer diameter	66mm
Stator back iron height	10mm
Airgap length	2mm
Number of turns / slot	20

In this machine, the maximum values of armature self-inductance L_{aa_max} and mutual inductance M_{af_max} are both reached when the rotor teeth are fully aligned with the stator teeth, i.e., $\theta = 45^\circ$ and 135° . In contrast, the minimum values L_{aa_min} and M_{af_min} are reached when the rotor teeth are fully unaligned with the stator teeth, i.e., $\theta = 0^\circ$ and 90° , where M_{af_min} decreases to zero as no flux created by the field current is linked by Coil A at these two positions. Furthermore, the polarity of the armature flux linkage resulting from the field current is inverted when $\theta > 90^\circ$, and therefore, the mutual inductance is presented as negative at these rotor positions. These analytical presumptions in the variation of inductances with respect to the rotor position are validated using finite element analysis (FEA), shown in Fig. 3. The dimensions used for the FEA are presented in Table I.

III. CURRENT-FLUX LINKAGE LOOPS OF DCEFSMS

Based on the analysis of flux components and inductances, the energy conversion of this single-phase DCEFSM with different switching strategies is investigated.

A. Energy Conversion With Quarter-Period Switching

The so-called quarter-period switching strategy is similar to that used for SRMs or SRDCMs. In this strategy, the armature current is conducted when the rotor rotates from an unaligned position toward the next aligned position and switched OFF before the rotor reaches that aligned position. However, due to the bipolar flux linkage created by the field current, the armature current should be reversely conducted when $\theta > 90^\circ$ so that the magnetic field is intensified instead of weakened.

Fig. 4(a) shows the idealized waveform of the armature current using this switching strategy. The process of

Fig. 4. Energy/coenergy of the single-phase DCEFSM with the quarter-switching strategy. (a) Idealized waveform of the armature current. (b) Energy/coenergy conversion process. (c) Current-flux linkage loop and with the half-period switching strategy. (d) Idealized waveform of the armature current. (e) Energy/coenergy conversion process. (f) Current-flux linkage loop.

energy/coenergy conversion is presented in Fig. 4(b). The red dashed lines indicate the armature flux linkage created by certain field current I_f , in which the slope of each line corresponds to the mutual inductance M_{af} at different rotor positions. Lines inside ABCD and EFGH show the additional flux linkage component created by the armature current, while the slope of each line corresponds to the self-inductance L_{aa} at different rotor positions. The current-flux linkage (i - λ) loop is thus derived, shown in Fig. 4(c).

When the rotor position changes from A: $\theta = 0^\circ$ to B: $\theta = 45^\circ$, the armature current is imposed at I_a , hence the armature flux linkage increases with the increasing self- and mutual inductances L_{aa} and M_{af} . When the rotor reaches the aligned position B, the armature current is switched OFF, thus the armature reaction disappears. From C to D, the armature flux linkage only contains the component created by the field current till a reversely conducted current is switched ON at E. Then, a similar procedure of energy conversion is repeated in the third quadrant. The part of energy that is converted

from the electromagnetic form to the mechanical form can be calculated as

$$W_m = W_e - (W_{fa} - W_{fu}) = S_{ABQP} - (S_{BQC} - S_{APD}) = S_{ABCD} \quad (2)$$

in which W_m is the converted mechanical energy, W_e is the input electromagnetic energy, and W_{fu} and W_{fa} are the field energy stored in the self-inductance of the armature winding for the unaligned and aligned rotor positions, respectively.

Apparently, this mechanical energy W_m is corresponding to the area enclosed in the i - λ loops ABCD and EFGH, which can be calculated as the change of coenergy $\Delta W'$ in one electrical period. From Fig. 4(c), it can be seen that the area of each loop can be divided into two parts: a parallelogram (AOCD) and a triangle (OBC). The length of the side AO indicates the difference in the armature flux linkage created by the field current, $\Delta \lambda_{af}$, between the aligned and unaligned rotor positions. While, the length of the side OB indicates that difference in the armature flux linkage created by the armature current $\Delta \lambda_{aa}$. Hence, the total area $\Delta W'$ can be calculated as

$$\Delta W' = 2(\Delta W'_1 + \Delta W'_2) = 2\Delta \lambda_{af} I_a + \Delta \lambda_{aa} I_a \quad (3)$$

in which

$$\Delta \lambda_{af} = (M_{af_max} - M_{af_min}) I_f \quad (4)$$

$$\Delta \lambda_{aa} = (L_{aa_max} - L_{aa_min}) I_a \quad (5)$$

while L_{aa_max} and M_{af_max} are the self- and mutual inductances when the rotor teeth are fully aligned with the stator teeth, L_{aa_min} and M_{af_min} are the self- and mutual inductance when the stator and rotor teeth are unaligned. From Fig. 4, it can be seen that $M_{af_min} = 0$. Therefore, with this switching strategy the average torque can be calculated as

$$\bar{T} = \frac{\Delta W'}{\pi} = \frac{2}{\pi} M_{af_max} I_a I_f + \frac{1}{\pi} (L_{aa_max} - L_{aa_min}) I_a^2 \quad (6)$$

in which π is the mechanical angle of one electrical period of this two-rotor-tooth DCEFSM.

Two torque components can be found in the torque expression in (6). The first torque component is proportional to each current of the armature winding and the field winding and the maximum mutual inductance between these two windings, which is similar to that of a wound-field DCM or SM. The second torque component is proportional to the square of armature current and the difference in the self-inductance of armature winding between the aligned and unaligned rotor positions, which is similar to that of an SRM.

The FEA results of the torque production in the DCEFSM specified in Table I using this quarter-period switching strategy are shown in Fig. 5(a) and (b). It can be seen in Fig. 5(a) that when the field current is constant, e.g., $I_f = 50$ A, the average torque shows a second-order relation with the peak value of the armature current I_a , while when the armature current is constant, the relation between the average torque and the field current is fairly linear. Hence, the relation between the average torque and the armature and field currents presented in (6) is validated.

However, this switching strategy is usually not optimal for the torque production. After the rotor crosses the aligned position, the field current is still creating flux despite of zero armature current. This continuous existence of field current generates a negative torque, as observed in Fig. 5(b), which lowers the average torque.

Fig. 5. FEA results of the torque production in the single-phase DCEFSM with the quarter-period switching strategy (S1) and the half-period switching strategy (S2). (a) S1: average torque versus armature current/field current. (b) S1: torque versus rotor position ($I_a = I_f = 50$ A). (c) S2: average torque versus armature current/field current. (d) S2: torque versus rotor position ($I_a = I_f = 50$ A).

B. Energy Conversion With Half-Period Switching

Under certain conditions, the negative torque can be reduced by reverting the armature current right after the rotor crosses the aligned position, thus increasing the average torque. The idealized waveform of the armature current using this switching strategy is shown in Fig. 4(d). The process of energy/coenergy conversion with this switching strategy is shown in Fig. 4(e). When the rotor reaches the aligned position B: $\theta = 45^\circ$, the armature current changes from I_a to $-I_a$, hence the total flux linkage of the armature winding decreases from λ_{a_max} to $-\lambda_{a_min}$, in which

$$\lambda_{a_max} = \lambda_{aa_max} + \lambda_{af_max} \quad (7)$$

$$\lambda_{a_min} = \lambda_{aa_max} - \lambda_{af_max}. \quad (8)$$

The armature current is then imposed at $-I_a$ till the rotor crosses the next aligned position E: $\theta = 135^\circ$, in the meantime the flux linkage of the armature winding increases toward the maximum value with an opposite polarity, i.e., $-\lambda_{a_max}$. After that, the armature current is again reverted to I_a . Consequently, the flux linkage changes to λ_{a_min} . Then, the armature current is imposed at I_a while the armature flux linkage increases till the rotor position reaches the aligned rotor position B again.

The i - λ loop of the single-phase DCEFSM with this switching strategy is thus derived, shown in Fig. 4(e). Similar to that explained in (2), the total area enclosed in this i - λ loop BCEF indicates the converted mechanical energy W_m , which is equal to the change of coenergy $\Delta W'$ in one electrical period using this switching strategy. From Fig. 4(f), it can be seen that the length of the side FB is the difference between λ_{a_max} and λ_{a_min}

$$\lambda_{a_max} - \lambda_{a_min} = 2\lambda_{af_max} = 2M_{af_max} I_f. \quad (9)$$

Hence, the total area $\Delta W'$ and the average torque using this switching strategy can be calculated as

$$\Delta W' = 2M_{af_max} I_f \cdot 2I_a = 4M_{af_max} I_a I_f \quad (10)$$

$$\bar{T} = \Delta W' / \pi = 4M_{af_max} I_a I_f / \pi. \quad (11)$$

Compared with (6), the item that is similar to the torque expression of an SRM disappears in (11). The torque expression of the single-phase DCEFSM with this half-period switching strategy becomes similar to that of a wound-field DCM or SM.

The FEA results of the average torque of the DCEFSM specified in Table I using this half-period switching strategy are shown in Fig. 5(c). It can be seen that the relation between the average torque and the peak value of the armature current I_a is identical to that between the torque and the field current I_f , both of which are linear. Thus, the torque expression presented in (11) is validated.

Fig. 5(d) shows the torque variation with respect to the rotor position when the field current equals the rms value of the armature current. In this case, the negative torque is eliminated. However, this does not mean that the half-period switching strategy always gives a higher torque than the quarter-period switching strategy. By comparing (6) and (11), it can be found the half-period switching strategy is advantageous only when

$$I_f > (L_{aa_max} - L_{aa_min}) I_a / 2M_{af_max}. \quad (12)$$

C. Characteristics of DCEFSMs

From (6) and (11), it can be observed that in the DCEFSM, the torque is generated due to variation of self- and mutual inductances. This is not a typical characteristic as the torque production in wound-field DCMs or SMs can also be understood as a result of the varying mutual inductance between the armature winding and the field winding. However, in DCEFSMs, the variation of both self- and mutual inductances is resulting from the variation of the air-gap reluctance, while in wound-field DCMs or SMs the air-gap reluctance does not necessarily change as the variation of mutual inductance is mainly due to the rotation of the winding placed in the rotor. The requirement of the air-gap reluctance variation for the torque production in DCEFSMs shows the characteristic of a reluctance machine.

Nevertheless, DCEFSMs are different from other types of reluctance machines, such as SRMs and SRDCMs, as in DCEFSMs, the variation of mutual inductance, instead of self-inductance, plays an important role in the torque production. It is worth mentioning that in SRDCMs, mutual inductances between each phase armature winding and the assisted dc field winding also contributes to the torque production. However, in this machine, the armature winding is fully coupled with the field winding, as observed in Fig. 1(b), which means their mutual inductance is always equal to the self-inductance of the armature winding [7]. Hence, for SRDCMs, the variation of the self-inductance of armature windings is still critical for the torque production. While for the DCEFSM, with certain switching strategy, the torque production can be almost independent on the self-inductance. In this case, the torque of the DCEFSM becomes approximately proportional to the product of armature and field currents, exhibiting a similarity to that of a wound-field DCM or SM.

IV. CONCLUSION

In this paper, a study on the energy conversion and the consequent torque production mechanism in DCEFSMs is presented. From the investigation on a single-phase DCEFSM, it is found that the armature flux linkage of this machine is created by both the armature current and the field current, through the self-inductance of the armature winding and the mutual inductance between this winding and the field winding, respectively. Both inductances vary with respect to the rotor position and reach their maximum and minimum values when the rotor teeth are fully aligned and unaligned with the stator teeth, respectively.

Based on these results, two switching strategies are implemented into the armature current. With the first strategy, the armature current is conducted only when the rotor rotates from an unaligned position toward the next aligned position, while with the second strategy the armature current is always conducted, however, the conducting direction is reverted at each aligned position. Using the current-flux linkage loops, the process of energy/coenergy conversion is studied, resulting in a torque expression for each switching strategy. From the derived torque expressions, it can be concluded that in DCEFSMs, the torque is produced due to the variation of inductances, including the self and mutual inductance. More importantly, the inductance variation is mainly resulting from the variation of the air-gap reluctance, thus the characteristic of a reluctance machine is observed. However, in DCEFSMs, the variation of the mutual inductance, instead of the self-inductance, is crucial to the torque production, which identifies this type of machines from SRMs. These characteristics observed from the single-phase DCEFSM can also apply to multi-phases DCEFSMs. In DCEFSMs with certain combination of stator segments and rotor teeth, e.g., the 6/5 DCEFSM in Fig. 1(a), the variation of the mutual inductance between each phase armature winding and the field winding becomes fairly sinusoidal, resulting in sinusoidal phase flux linkage, hence sinusoidal currents can be applied to the armature winding to lower the torque ripples. This research will thus be continued with investigating the energy conversion in multi-phase DCEFSMs.

REFERENCES

- [1] S. E. Rauch and L. J. Johnson, "Design principles of flux-switching alternators," *Trans. AIEE Power App. Syst., Part III*, vol. 74, no. 3, pp. 1261–1268, Jan. 1955.
- [2] C. Pollock and M. Wallace, "The flux switching motor, a dc motor without magnets or brushes," in *Proc. IEEE 34th IAS Annu. Meeting. Conf. Rec. Ind. Applicat. Conf.*, Phoenix, AZ, USA, vol. 3, Oct. 1999, pp. 1980–1988.
- [3] Y. Tang, J. J. H. Paulides, T. E. Motosca, and E. A. Lomonova, "Flux-switching machine with dc excitation," *IEEE Trans. Magn.*, vol. 48, no. 11, pp. 3583–3586, Nov. 2012.
- [4] E. Ilhan, M. F. J. Kremers, E. T. Motosca, J. J. H. Paulides, and E. A. Lomonova, "Sensitivity analysis for phase inductances in flux-switching PM machines," in *Proc. 20th ICEM*, Sep. 2012, pp. 763–768.
- [5] E. Ilhan, T. E. Motosca, J. J. H. Paulides, and E. Lomonova, "Energy conversion loops for flux-switching PM machine analysis," in *Proc. 15th ISEF Mechatron., Elect. Electron. Eng.*, Funchal, Portugal, Sep. 2011, pp. 1–8.
- [6] W. Hua, M. Cheng, Z. Q. Zhu, and D. Howe, "Design of flux-switching permanent magnet machine considering the limitation of inverter and flux-weakening capability," in *Proc. IEEE 41st IAS Annu. Meeting. Conf. Rec. Ind. Applicat. Conf.*, Tampa, FL, USA, Oct. 2006, pp. 2403–2410.
- [7] Y. Li, J. D. Lloyd, and G. E. Horst, "Switched reluctance motor with dc assisted excitation," in *Proc. IEEE 31st IAS Annu. Meeting. Conf. Rec. Ind. Applicat. Conf.*, vol. 2, 1996, pp. 801–807.