Study of Copper Losses in the Stator Windings and PM Eddy-Current Losses for PM Synchronous Machines Taking Into Account Influence of PWM Harmonics

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Abstract — An accurate estimation of losses becomes more and more important in the design process of permanent-magnet (PM) synchronous machines (PMSM). This estimation is also a key issue of thermal design. Therefore, the study of losses (in particular non-conventional losses) is of great importance. In this paper, the authors present a calculation of the stator windings and PMs losses for different types of fed (i.e., sinusoidal and no sinusoidal current supply). The authors investigate using 2-D finite-element method (FEM): the effect of conductors' segmentation on the copper losses.

Index terms — Copper losses, PM losses, PWM harmonics, proximity effect, skin effect, synchronous machines.

I. Introduction

Different types of losses exist in the electrical machines. These losses are related to the waveform of supply current, the speed of rotation…, and we can classify these losses in three types [1]-[4]:

- The losses in the electrical circuit (i.e., the copper losses) are localized in the stator windings [2]. At low frequency, the normal and additional losses are due respectively to the circulation of the sinusoidal and non-sinusoidal supply current in the stator windings. At high frequency, the losses are due to the skin effect and the time harmonics. For high rotating speed the supplying frequency is higher than classical 50 Hz or 60 Hz; then, eddy-current in the stator windings causes more copper losses due to the skin and proximity effects [5]-[6].
- The losses in the magnetic circuit (i.e., the iron losses): the eddy-current losses and the hysteresis losses (in the PMs, these ones are negligible). At no-load, the iron losses are due to PMs spatial harmonics. At load, there are the PMs spatial harmonics and the magnetomotive force (MMF) harmonics due to the winding types (i.e., overlapping, non-overlapping…) and to the waveform of the supply current (time harmonics). In the PMs, at no-load, the eddy-current losses are caused by the reluctance variation due to the stator slot-openings, while on load these rotor losses result from both stator slotting permeance harmonics and MMF harmonics [7].
- The mechanical and ventilation losses consist of friction losses due to speed of rotation.

The purpose of this paper is to study the losses in the stator windings and in the PMs. We propose to highlight the impact of some parameters on the losses: **i)** the effect of conductors segmentation on the copper losses, and **ii)** the Pulse-Width-Modulation (PWM) harmonics on the copper losses and PM eddy-current losses. These different cases are analyzed by the way of 2-D FEM simulations.

II. Studied Machines

In this paper, the studied machine is a PMSM having 48 slots/8 poles with distributed windings, used for railway applications. The Fig. 1 shows the conductors in the stator windings. There are two layers in each slot.

III. Simulation Results

The results of simulation for different cases (at no-load and at load with sinusoidal current-supply and with harmonic current-supply) are ported in the below figures. At first we started with the no-load simulation.

A. Different types of losses at no-load

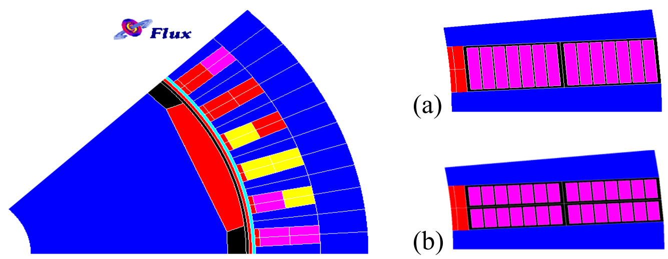

Fig. 1. The studied PMSM: (a) without and (b) with segmentation of conductors.

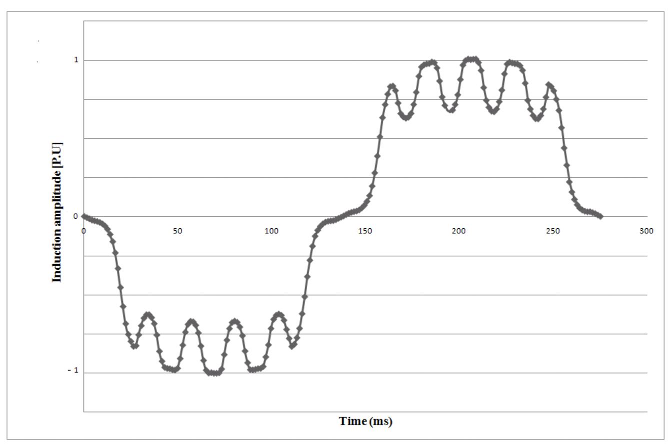

Fig. 2. The variation of the flux density amplitude of the study machines.

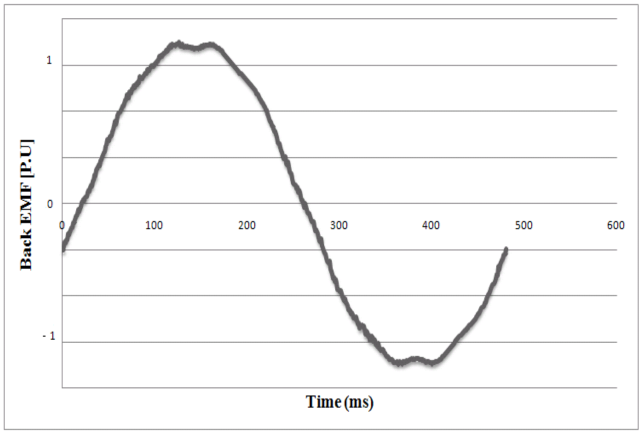

Fig. 3. The back EMF amplitude of the study machines.

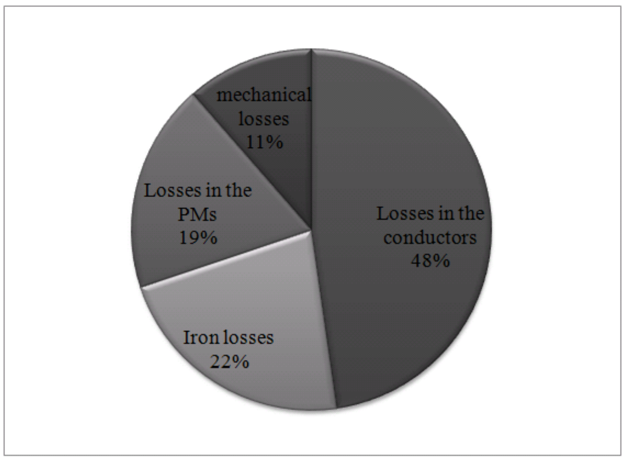

Fig. 4. The losses in the configuration N°1 (without the conductors segmentation effect).

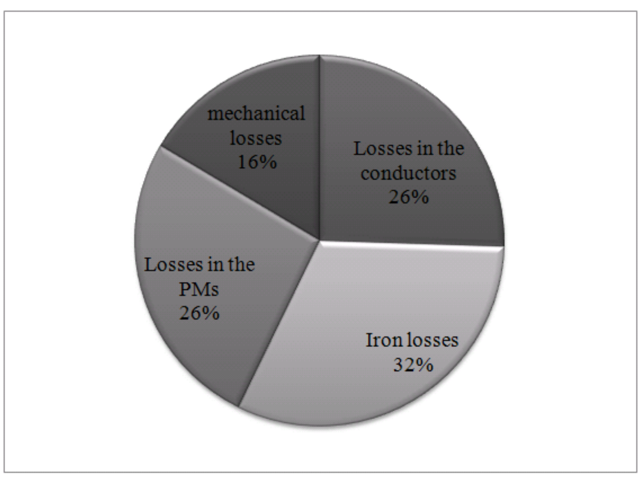

Fig. 5. The losses in the configuration N°2 (with the conductors segmentation effect).

The Fig. 2 shows the variation of the flux density of the study machines in the air gap. We see that the flux density has undulations which are due to the slot effect.

The Fig. 3 gives the back electromotive force (EMF) amplitude for the study machines.

The different types of losses in the two configurations (with and without the conductors segmentation effect) [See Fig. 1] resulting from the 2-D FEM simulations are given in the Figs. 4-6. In those simulations, the same magnetic sheet is used for the two types of machines.

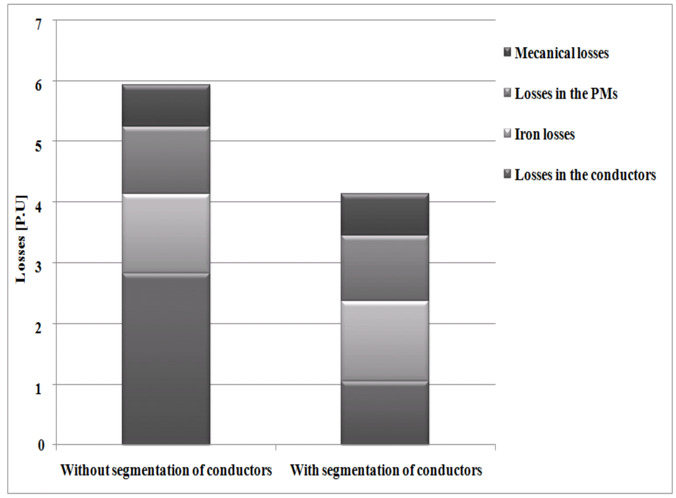

Fig. 6. Comparison between different types of losses for the two types of configuration.

The Fig. 4 illustrates the comparison between different types of losses in the configuration N°1 (i.e., without the conductors segmentation effect). As we can see, the conductors copper losses present the highest percentage compared with another types of losses (48%). In the second place the iron losses in the stator with 22%. The losses in the permanents magnets and mechanical losses present 19% and 11%. The Fig. 5 shows the comparison between the different losses in the configuration N°2 (i.e., with the conductors segmentation effect). First we can observe that the conductors' segmentation leads to decrease the losses in the conductors' (48% to 26%). As we can see in this case, the iron losses in the stator present the highest percentage compared with another types of losses (32%). In the second place the conductors copper losses with 26%. The losses in the permanents magnets and mechanical losses present 26% and 16%. In the Figs. 6 show a comparison between different losses for the types of configuration: with and without segmentation of conductors'. We can observe that the conductors' segmentation leads to decrease the total losses in the machine, even if the use of segmentation has no effect on both iron losses and mechanical losses. The main effect of segmentation concerns the copper losses reduction: the conductors segmentation enables to decrease the losses created by the eddy-current in the conductors. As a conclusion of this section, the conductor's segmentation enables to decrease the conductors' no-load losses and has no effect in the other losses (iron losses, losses in the PMs and mechanical losses).

A. Different types of losses at load

In this section, we calculate the losses at load for the two cases: the first case with sinusoidal current-supply and the second case with harmonic current-supply (with PWM harmonics). Usually there are several sources of losses inside the conductors; more precisely, we can find:

- ❖ Copper losses,
- ❖ Eddy-current losses,
- ❖ Proximity and skin effect losses,
- ❖ Additional losses.

The eddy-current losses, the proximity effect losses and the additional losses are of magnetic origin.
In this section of this study, we consider two cases: the first with sinusoidal current-supply, which is to study the effect of currents and its frequency on the conductors' losses; and the second part, with harmonic current supply, which is to study the effect of harmonics in the conductors' losses.

1) With sinusoidal current-supply

The Fig. 7 shows the waveform of the supply currents, which is perfectly sinusoidal in this part. The aim of these simulations is to study the influence of the stator currents on the different losses, particularly the conductors copper losses. Figs. 8-10 show the different types of losses for the different configurations (with and without the conductors' segmentation).

Firstly, we can remark the increase of the total losses in the machine particularly the losses inside the conductors, whatever the configuration: with and without the conductors' segmentation effect.

As said above, with sinusoidal stator currents, there are additional copper losses due to skin and proximity effects and these last lead to increase the conductors copper losses and thus the total losses in the machine.

In Figs. 8-9, shows the comparison between the different types of losses for the types of configurations. They shows that the conductors' losses are always greater compared with another types of losses. Similar conclusions come from Fig. 11 when the conductors are segmented. The comparison between the losses for the two types of machine configurations (with and without the conductors' segmentation) is shown in Fig. 10. We notice that the total losses decrease when the slots conductors are segmented.

As a conclusion of this section, when the stator is fed with sinusoidal currents, the conductors' segmentation enables to decrease the conductors copper losses enables to decrease the total losses.

2) With harmonic current-supply

In this section, we consider stator currents with time harmonics as shown in the Fig. 15. The aim is now to study the effect of the current harmonics on the different types of losses in the machine, particularly the copper losses and PM eddy-current losses. Figs. 16-20 show the different types of losses for the different considered configurations (with and without the conductors' segmentation effect).

First, we can notice the increase of the total losses in both machines. In Fig. 12, corresponding to the first case without segmentation of conductors': **i)** the conductors losses increase by 2.3%, **ii)** the PM eddy-current losses increase by 24.5 % , **iii)** the mechanical losses and iron losses slightly increase. The total losses in this case increase by 6 % in comparison with the losses obtained with sinusoidal current by 33%, **iii)** the mechanical losses and iron losses slightly increase.

In the second case with segmentation of conductors' : **i)** the conductors losses increase by 2%, **ii)** the PM eddy-current losses increase by 33%, **iii)** the mechanical losses and iron losses slightly increase. The total losses increase by 6.7% and iron losses slightly increase in comparison with the losses obtained with sinusoidal current.

Fig. 14 shows comparisons between the losses for the two types of configurations.

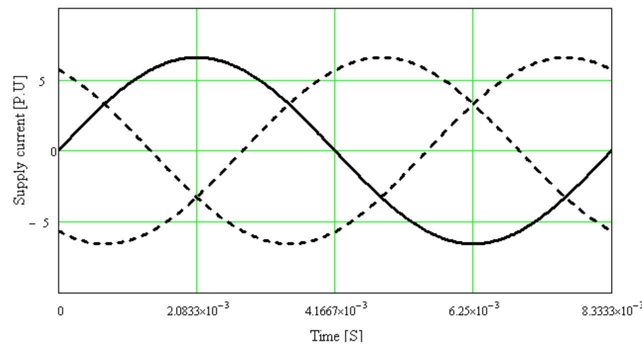

Fig. 7. The wave form of supply current.

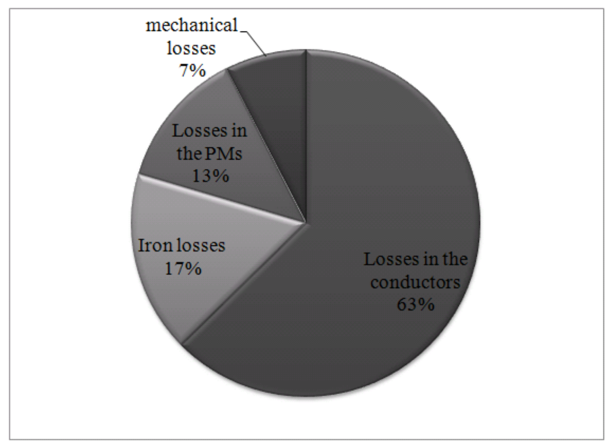

Fig. 8. The losses in the configuration N°1 (without the conductors' segmentation effect).

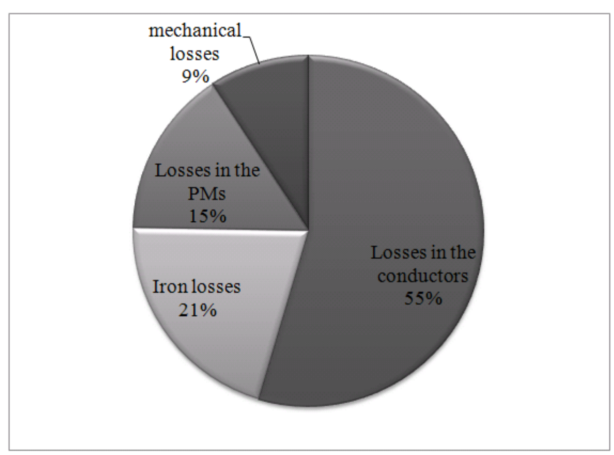

Fig. 9. The losses in the configuration N°2 (with the conductor's segmentation effect).

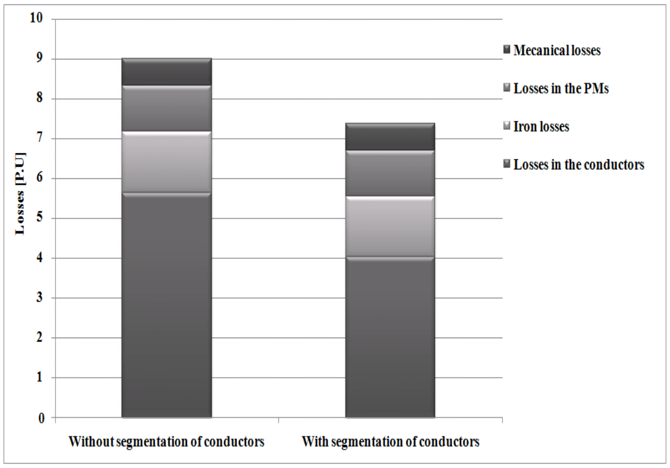

Fig. 10. Comparison between different types of losses for the two types of configuration.

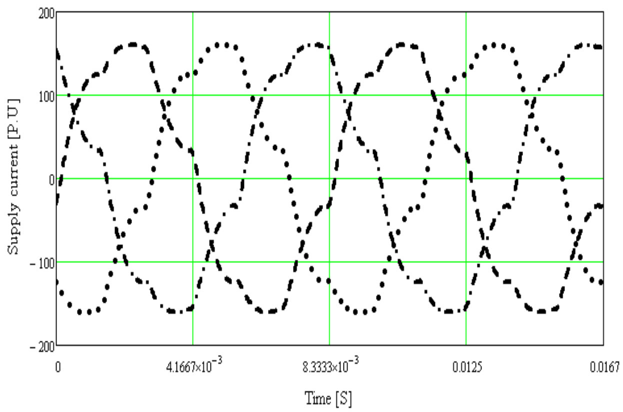

Fig. 11. The wave form of supply current.

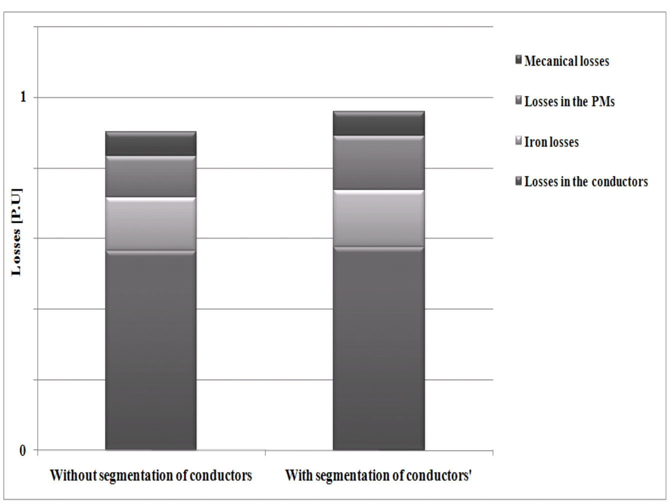

Fig. 12. Comparison of the losses in the configuration N°1 (without the conductors' segmentation effect) for the two cases of alimentation.

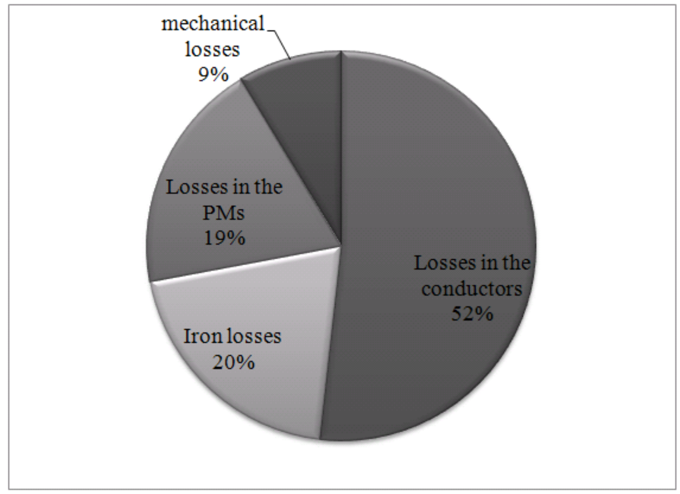

Fig. 13. Comparison of the losses in the configuration N°2 (without the conductors' segmentation effect) for the two cases of alimentation.

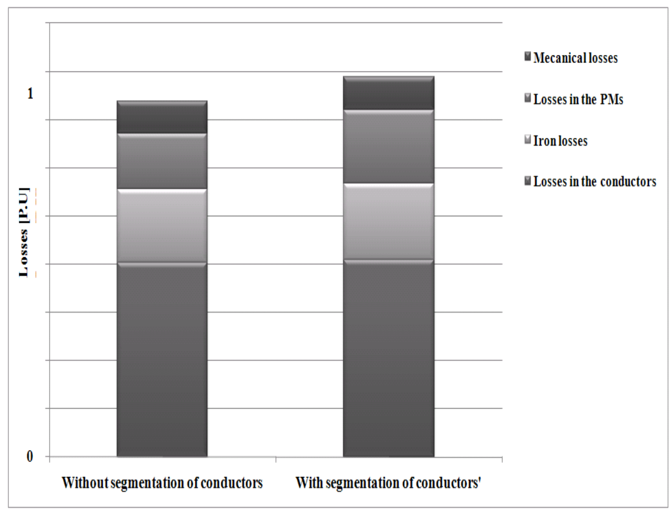

Fig. 14. Comparison between different types of losses for the two types of configuration.

IV. Conclusion

2D FEM simulations have been realized to estimate the losses in PM synchronous machine used for railway application. In particular, the authors have studied the effect of conductors' segmentation on both conductors copper losses and PM eddy-current losses. The following conclusions have been deduced from the simulations:

- The no-load conductor losses are very important in comparison with iron losses and we have to be decreased,
- To reduce the conductor losses, segmenting conductors has been studied,

A first interesting outlook is to calculate the losses in the conductors (with and without segmentation) analytically, in particular to make the choice of conductor segmentation number easier. A second outlook is also to achieve an experimental test in order to validate the study realized by using 2D FEM simulations.

V. REFERENCES

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