Computation of Iron Losses in Permanent Magnet Machines by Multi-Domain Simulations

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Keywords

«Iron Losses», «Permanent Magnet Synchronous Machines», «PWM voltages», «Multi-Domain Simulations»

Abstract

Nowadays the majority of electric drives work at variable speeds. In this kind of drives the electrical machines are supplied by inverters which generate modulated voltages. It is widely known that these non sinusoidal voltages cause additional current harmonics dealing to higher iron losses than with sinusoidal voltages. The iron losses affect to several design constraints as the efficiency and the thermal behavior of electrical machine. Hence, the accurate computation of the iron losses under different supply voltage conditions is very important in order to optimize the machine design as much as possible.

This work deals with multi-domain simulations in order to calculate the iron losses in permanent magnet synchronous machines (PMSM) under Pulse Width Modulated (PWM) voltages. The current supplies are implemented in the simulation system MATLAB-SIMULINK®. Whereas the electrical machine is simulated using the Finite Element Method (FEM). The iron losses are computed by a post-processing analysis carried out using the tool so called Loss Surface Model (LSM) which is integrated in the FEM software FLUX® of Cedrat. Finally, experimental tests are performed in order to validate the proposed methodology.

Introduction

It is widely known that the performances of electric machines depend strongly on the losses. The efficiency, the thermal behavior or the compactness are some of the design constrains which are strongly influenced by the losses. So it is very important to predict these losses accurately if an optimum design of the electric machine is required. The losses in electric machines can be divided in three main components: Joule losses, iron losses and additional or stray losses (mechanical losses, induced Eddy current losses in frames, etc). The Joule losses are relatively easy to compute from the armature resistance and current values. However, the other two components are rather more complicated to estimate. This work is focused on the calculation of iron losses which can be relevant in some cases depending on the machine topology, speed, saturation levels, etc.

Nowadays the majority of the electric machines are integrated in variable speed drives. That means that the motors are supplied by modulated voltages such as Pulse Width Modulated (PWM) voltages. It is well known that the additional current harmonics introduced by PWM voltages increase the iron losses. So it is necessary to consider the voltage characteristic in the computation process in order to achieve accurate results in loss computation.

The most extended way to define the iron losses is by the widely known loss separation method in which they are divided in three main components: hysteresis losses, classical Eddy losses and excess losses [1;2]. In case of non sinusoidal voltages, the high order harmonics of currents can accentuate the presence of some phenomena such as the skin effect or the minor loops which are not directly taken into account by theses classical methods. Many efforts have been dedicated to the adaptation of the initial definition of the iron losses given by *Bertotti* in [1] to consider all these phenomena. For instance, in [3] *Boglietti et al.* complete the expression of the classical Eddy losses component with the aim of taking into account also the skin effect. In [4] *Toda et al.* propose a modification of the hysteresis losses formula in order to consider the minor loops. It is also possible to find in the literature some papers that deals with the iron losses computation under arbitrary supply voltages, mainly focused on pulse width modulated (PWM) voltages [3;5-8].

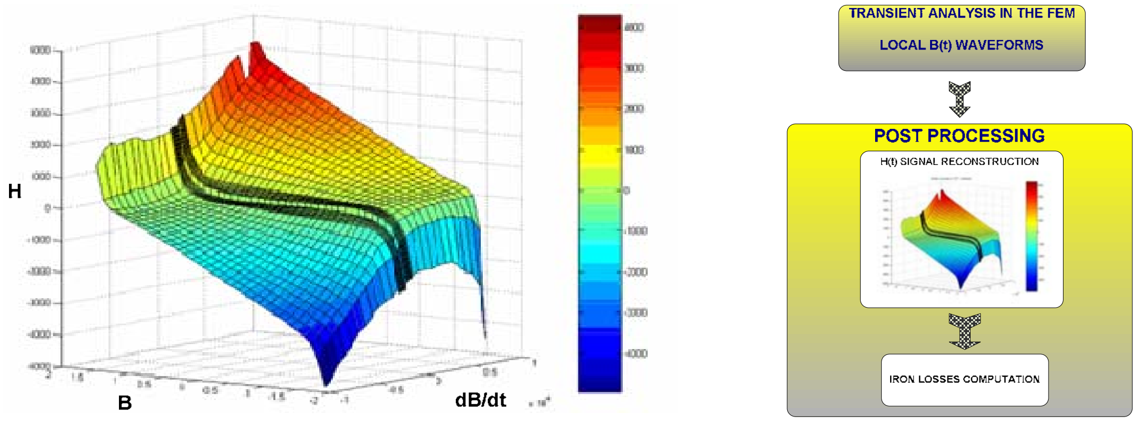
In this work a novel method for iron losses computation under non-sinusoidal supply voltages is proposed. The method consists in coupling the FEM software FLUX® from CEDRAT Company with the system simulator software MATLAB-SIMULINK®. The iron losses are computed by a post-processing analysis separating the computation of the Eddy current losses in the permanent magnets (PM) and the iron losses in electrical sheets. The simulation results have been compared with experimental results in order to validate the proposed method.

Iron Losses Computation by the FEM

The total iron losses in permanent magnet synchronous machines (PMSM) can be separated in two components: The Eddy current losses in permanent magnets and the iron losses in electrical sheets. Hence, the computation of these losses components in FEM is carried out in two different ways. The Eddy current losses in permanent magnets are calculated as the active power dissipated in these regions considering the magnets as solid conductors. Meanwhile the losses in electrical sheets are computed by the tool so called Loss Surface Model (LSM) which is integrated in the FEM software FLUX® for that purpose.

Loss Surface Model (LSM) for Iron Losses Computation in Electrical Sheets

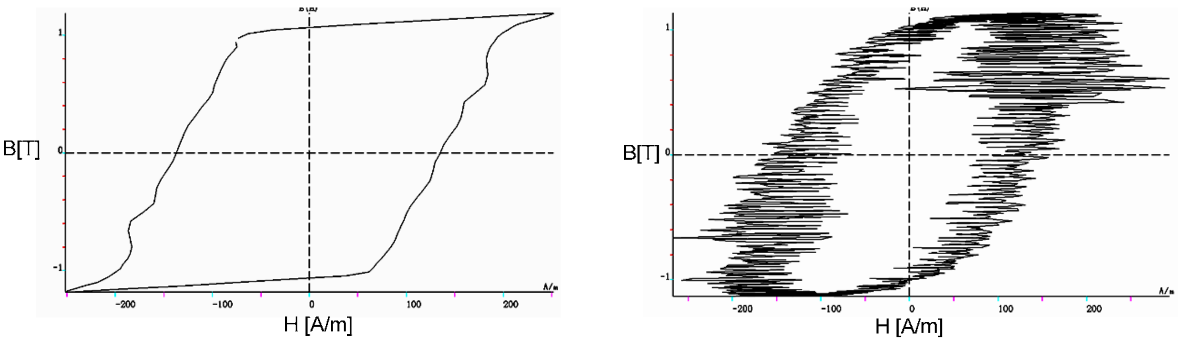
Normally FEM software do not consider the magnetic hysteresis cycle of electrical sheets in the solving process, but an approximated so called normal magnetization curve is taken into account. As the iron losses depend on the area enclosed by the hysteresis loop, these losses are not computed in the solving process and their calculation is addressed typically as a post processing task.



A) One of the characteristic surface H(B,dB/dt) curves saved in the data base of the Loss Surface Model

B) Block Diagram of the loss calculation by the FEM and the LSM

Fig. 1: Electric sheet losses computation methodology based on the LSM tool



a)Sinusoidal voltages *b) PWM voltages with switching frequency of fs=4KHz*

Fig. 2: Local hysteresis loops reconstructed by the Loss Surface Model with sinusoidal and PWM voltages

One calculation option consists in the local computation of the iron losses using the loss separation method and considering local induction waveforms calculated in the solving process. As main disadvantages, the accuracy of this computation method depends on some coefficients, and additional phenomenon as skin effect and minor loops are not normally considered.

The FEM software FLUX® presents an alternative tool so called Loss Surface Model for iron losses computation. This tool is supposed to be more accurate than the method based on the losses separation theory, because it does not depend on empirical coefficients and it considers additional phenomena such as the skin effect or the minor loops [9]. Due to this fact, in this case the LSM has been used as post processing tool for the calculation of the losses in electrical sheets.

In Fig1-B the iron losses computation process using the LSM is explained. First of all the electromagnetic problem is solved in the FEM calculating the temporal waveform of induction at each node of the mesh. In the post processing analysis the temporal waveforms of the magnetic field strength are reconstructed from the induction waveforms obtaining in this way local hysteresis loops. This reconstruction of the magnetic field strength is performed using a model based on one H(B,dB/dt) surface curve which is characteristic to each material. This curve must be obtained by experimental characterization of the material. In Fig1-A the surface curve of a given material is shown. The model that reconstructs the magnetic field strength can be described by the following expression.

$$H(B,dB/dt) = H_{static}(B) + H_{dynamic}(B,dB/dt) \tag{1}$$

In Fig 2 two different hysteresis loops reconstructed by the LSM tool at the same local point are shown. Resulting hysteresis loops with sinusoidal and PWM voltages are plotted. In this way the minor loops caused by the PWM voltages can be appreciated.

Once the local hysteresis loops are obtained, the specific iron losses are computed integrating the area enclosed by each hysteresis loop.

$$P = \frac{1}{T}\int_T \int_B H \cdot dB \quad \left[W\big/ m^3 \right] \tag{2}$$

Eddy Current Losses in the Permanent Magnets

In case of non-fractional machines normally the Eddy current losses in permanent magnets can be neglected. While in fractional machines these losses are more significant due to the high harmonic content of the armature field, so they cannot be neglected [10]. In order to make the proposed method usable to both non-fractional and fractional machines, the calculation of the permanent magnet losses is also addressed. Eddy current losses are due to the asynchronous harmonics of the magnetic field induced by the armature winding in the air-gap. The induced Eddy current density in the magnets can be expressed as in the following equation.

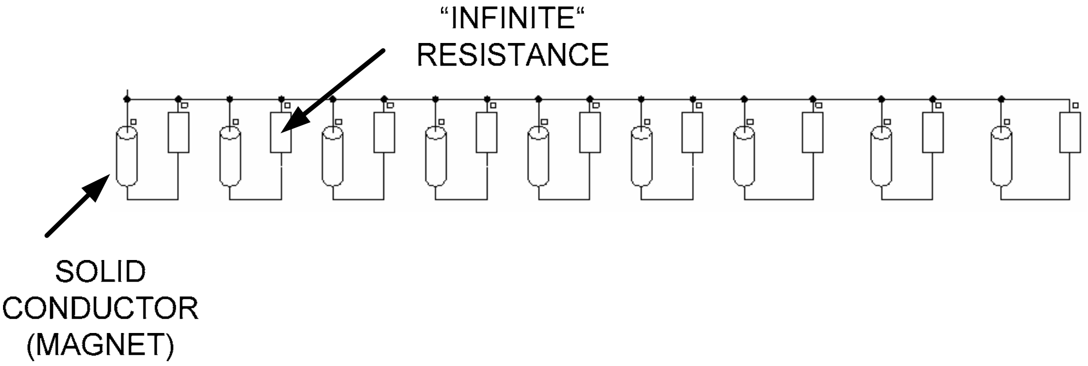


Fig. 3: Associated electrical circuit to the permanent magnets

$$J_{eddy} = -\frac{1}{\rho} \cdot \int \frac{\partial B}{\delta t} \cdot r \cdot dt + C \tag{3}$$

Where J_{eddy} is the induced Eddy current density in the magnets, ρ is the electrical resistivity of the magnets, B is the armature magnetic field and r is the radius of the point in which the current density is represented. The Eddy current losses are computed using the following formula.

$$P_{eddy} = \frac{2p}{T} \cdot \int_{0}^{T} \int_{-\frac{\alpha}{2}}^{\frac{\alpha}{2}} \int_{R_1}^{R_2} J_{eddy}{}^{2} \, \rho \cdot r \cdot dr \, d\theta \, dt \tag{4}$$

Where R_1 and R_2 are the inner and the outer radius of the magnets respectively, T is the period of the fundamental component of the armature field and α is the magnets spam in mechanical degrees [11]. It is necessary to consider in the formula the constant C in order to assure that the induced Eddy currents are limited to one pole piece. That means that the different magnet poles are supposed to be electrically isolated.

Regarding to the computation of the magnetic field induced by the armature winding in the air-gap, there are two options for that purpose depending if the Eddy current reaction field is neglected or not. In case this reaction field is neglected, the Eddy currents are considered resistance limited and this way they can be calculated performing magneto static simulations. However, in case the Eddy current reaction field has to be considered, it is necessary to perform time step simulations. In the proposed method, as the machine is co-simulated with SIMULINK®, the simulations are time stepped so the Eddy current reaction field is taken into account.

As far as the FEM simulation is concerned, magnets have to be defined as solid conductors. As the permanent magnets are electrically isolated, each one has to be associated to one solid conductor. In Fig 3 the electrical circuit associated to the permanent magnets is represented. It can be seen how each solid conductor has connected in parallel one resistor. It is because in the FEM software all the electrical components have to be connected in close circuit. These parallel resistances are set to very high values in order not to have influence on the losses computation.

Iron Losses Computation by Co-Simulations

In the proposed methodology the steady state iron losses are computed by a co-simulation between the FEM software and the system simulator software. The power system comprising a two-level converter is simulated in SIMULINK®, whereas the electrical machine is modelled in the FEM software. This way it is possible to evaluate the performance of the electrical machine under the functioning conditions imposed by the converter, in a relatively short and rather accurate way.

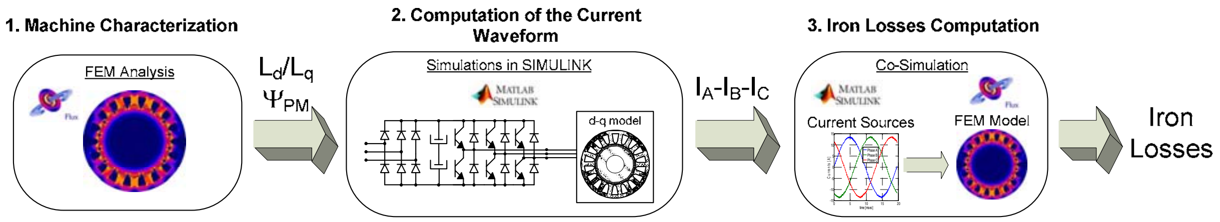


Fig. 4: Proposed methodology for iron losses computation under non-sinusoidal voltages

The FEM software permits the coupling of electric circuits for transient analysis. Generally these circuits comprise passive elements such as resistances and inductances along with sinusoidal voltage and current sources. Nevertheless, if more sophisticated circuits are required to consider, for example a power converter, it is necessary to couple the FEM software with the circuit simulator software.

When the machine is supplied by a converter, it is driven by voltage. In these cases there is an inevitable transient period which takes several electrical cycles before the motor reaches the steady state. It is considered that at least a resolution of 10 samples per switching period is necessary to achieve accurate results. The simulation of several electric periods with so small step size would lead to such an amount of samples and such long time consumption that current driven simulations are chosen instead of voltage driven simulations. In current driven simulations it is enough considering only one electric period to compute the iron losses, which enables to decrease significantly the time consumption of the simulation. For example, taking 10 samples per switching period, one co-simulation characterized by a switching frequency of $fs=4KHz$ and a period of $T=25.82$ *sec,* is carried out with a time step of $\Delta T=25\mu sec$ and it takes approximately 30 minutes.

The proposed method for iron losses computation is structured in three stages as it is shown in Fig 4. First of all the lumped parameters of the equivalent electrical circuit of the machine are calculated by the FEM. From these previous simulation the machine can be modeled with lumped parameters such as d-q axis inductances *Ld* and *Lq*, and the permanent magnet flux Ψpm. In the second stage the transient model of the machine in d-q axes is implemented in SIMULINK$^{®}$ using the lumped parameters previously estimated and a two level inverter is implemented as power supply. In this simulation the current waveforms in steady state are obtained for PWM voltages. Finally the co-simulation between the FEM software and SIMULINK$^{®}$ is carried out driving the FEM model of the electrical machine by current waveforms obtained in the previous stage. In this third stage the total iron losses are computed as the sum of the Eddy current losses in permanent magnets and the iron losses in electrical sheets.

In Fig 5 the total iron losses estimated by co-simulations for sinusoidal and PWM voltages are compared. It can be observed that the iron losses with PWM voltages are higher. Meanwhile in Fig 6 the resulting currents and electromagnetic torque are plotted for sinusoidal and PWM voltages. It can be noticed a significant difference in the ripples because of the PWM voltages.

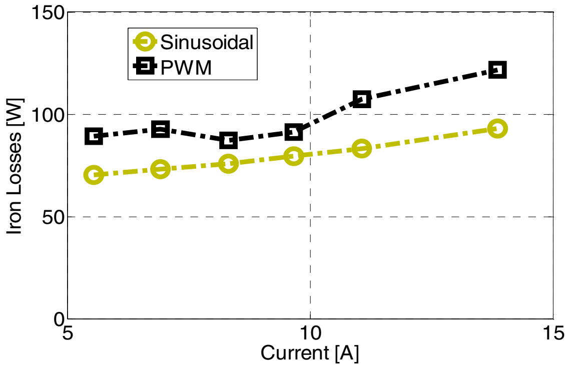
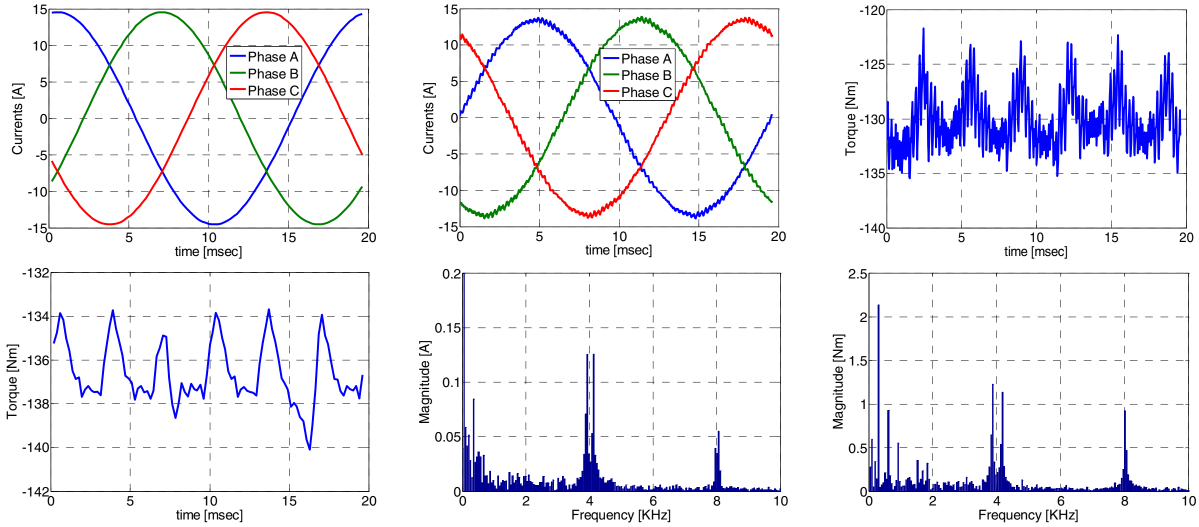


Fig 5. Iron losses computed with sinusoidal and PWM voltages with $fs=4KHz$



A) Current and Torque under sinusoidal voltages

B) Current under PWM voltages

C) Torque under PWM voltages

Fig 6. Co-simulation results obtained under sinusoidal and PWM voltages with $fs=4KHz$

Experimental Results

In this section the experimental test are described and the results are compared with that obtained by co-simulations in order to validate the proposed methodology.

Descriptions of the Experimental Test

In Fig 7 the test bench layout is shown. It consists of two machines, the one under test and the load motor, one torque sensor, one commercial controller for each machine and one power analyzer. During the test the controlled variables are the speed in case of the load machine and the torque in case of the machine under test. The test has been carried out controlling the d-axis current to zero avoiding in this way the functioning of the machine in the flux weakening operation mode. To calculate the losses, the loss segregation method has been implemented.

$$P_{in} - P_{cu} - P_{loss} - P_{mec} = 0 \tag{5}$$

Where P_{in} is the active power consumed by the machine, P_{cu} are the Joule losses, P_{mec} is the mechanic power in the motor axis and P_{loss} is the sum of the iron losses and the mechanical losses. The value of P_{in} is calculated by the power analyzer which is connected to the input of the machine. To calculate the Joule losses, a high accuracy ohmmeter has been used due to the fact that the power balance is very sensitive to the errors in the resistance measurement. The mechanical power is calculated from the torque and speed measurements. As the test is carried out at constant speed , the mechanical power can be calculated as the following.

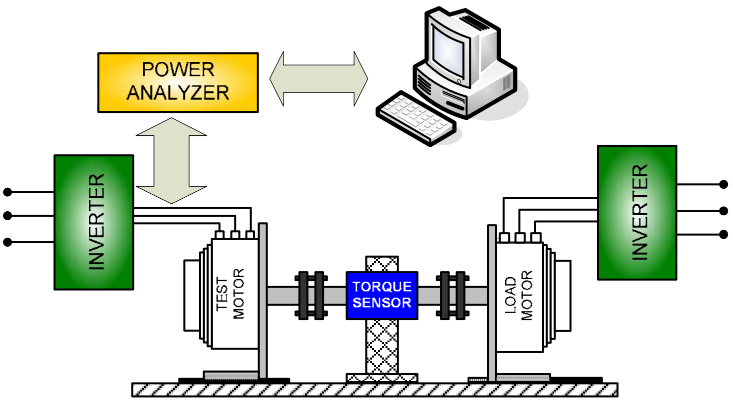
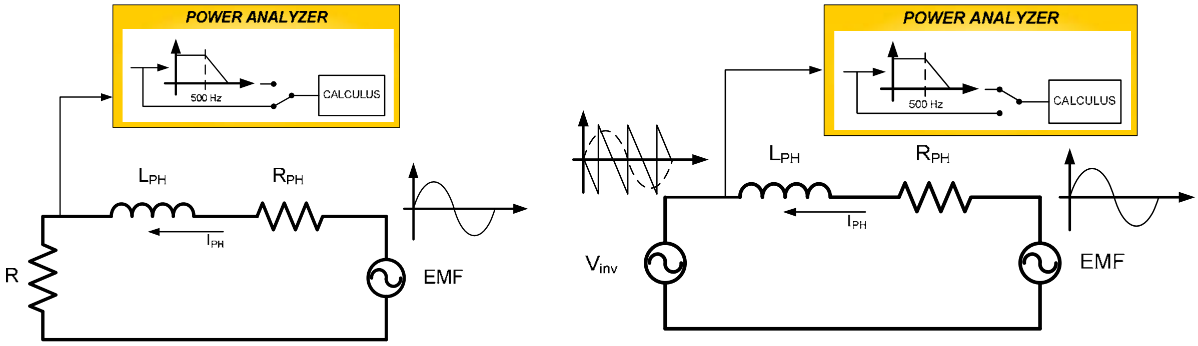


Fig. 7: Test bench configuration



a)Generator test with a resistive load *b)Motor test with an inverter*

Fig. 8: Description of the performed tests in order to validate the sinusoidal losses computation method

$$P_{mec} = T \cdot \Omega_m \tag{6}$$

Where T is the torque provided by the torque sensor and Ω_m is the mechanical speed measured by the encoder. In the power balance the only unknown variable is P_{loss} which involves two loss components, the iron losses and the mechanical losses. As the tests are performed at relatively low speeds (290 rpm) and the machine has been heated previously, the mechanical losses can be considered negligible in comparison with the iron losses. In addition all the tests have been carried out at constant speed in order to maintain the mechanical losses constant.

The configuration of the test bench does not allow supplying the machine with sinusoidal voltages. The possible solution would be to add RLC filters between the inverter and the machine or to use sinusoidal voltage supplies instead of the inverters. However in this case it has not been possible to implement neither of these solutions so finally it has been necessary to implement an alternative solution. The power analyzer comprises low pass band filters for the measured currents and voltage, which has been set to 500Hz. This way only the fundamental components of voltages and currents are considered for the computation of the power. The calculated power in this way is considered to be the power for sinusoidal voltages. However, before implementing this method, it has been validated performing two different tests which are described in Fig 8.

First of all the so called generator test is carried out. In this test a resistive load is connected to the terminals of the machine under test, which operates as a generator, and it is accelerate by the load motor. This way the currents are sinusoidal and so the computed iron losses correspond to the sinusoidal voltages. After that the second test is performed using the inverter and with the machine working exactly at the same operation conditions that in the previous test. In this case the input filters of the power analyzer are configured to 500Hz. In both cases the resulting P_{loss} are very similar, with a difference less than 5%. Hence it is considered that the losses calculated with the filter are equivalent to the sinusoidal losses.

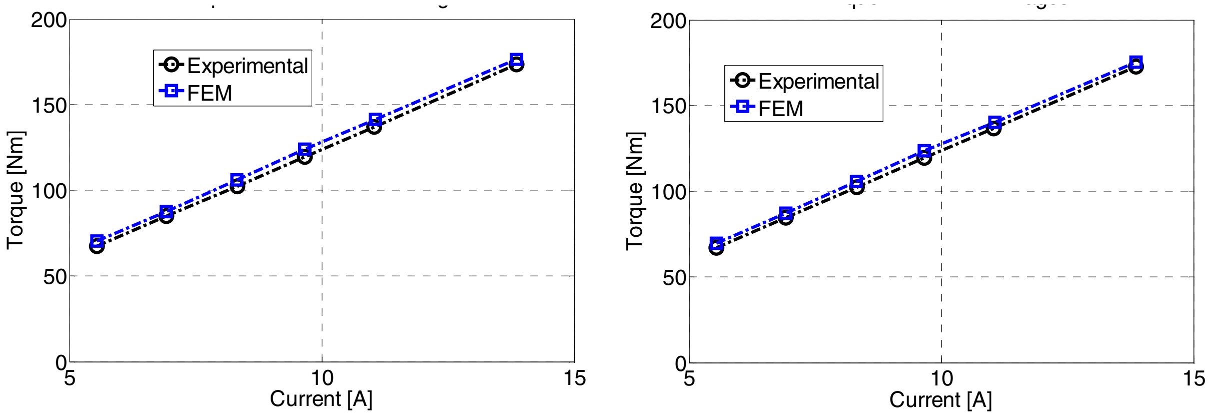
Validation of the Simulation Results

The proposed method to calculate the iron losses has been validated with experimental results. As the machine iron losses are closely related to the stator current density, the simulations and the tests have been done at the same of the phase current. The switching frequency of the PWM voltage is fixed to $fs=4KHz$ during all the tests.

In Fig 9 the simulated torque and the experimental torque at different current values are shown for both cases, sinusoidal and PWM voltages. It can be notice how the simulated and the experimentally measured torques are very similar.

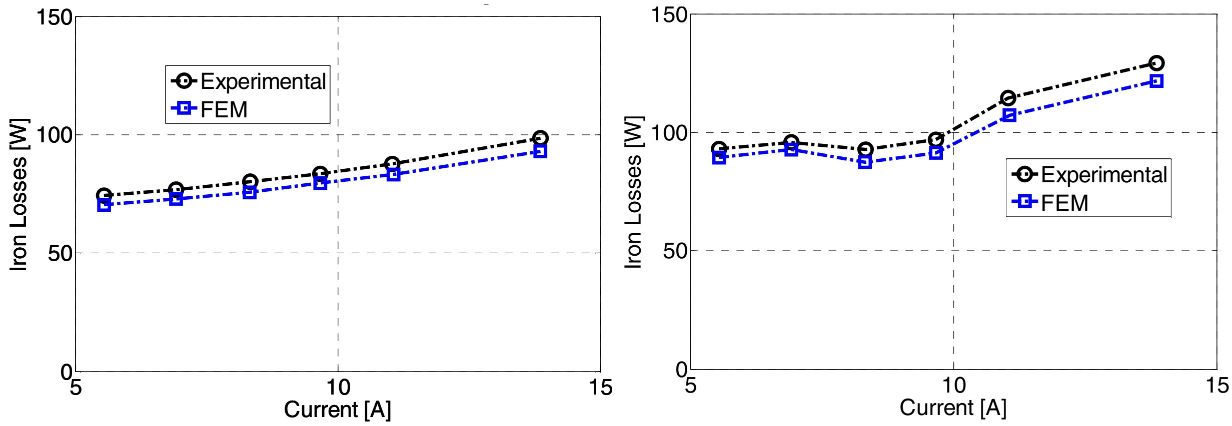
In Fig 10 the computed iron losses with sinusoidal and PWM voltages are shown. It is remarkable that certain difference arises between the co-simulation and the experimental results either with sinusoidal or PWM voltages. These differences are considered to be because of the mechanical losses which are not taken into account by the co-simulations. This difference is rather constant respect to the current and very similar in both cases with sinusoidal and PWM voltages. This behavior of the difference between simulations and test fits perfectly with the supposition that the difference is due to the mechanical losses.

Although there is a slight error in the prediction of the iron losses, an important point of this work is that the proposed methodology enables to calculate rather accurately the increase of the iron losses due to PWM voltages. In Fig 11 (a) the comparison between sinusoidal and PWM iron losses is shown. A coefficient can be defined to represent the increase of the losses due to the PWM modulation. This coefficient is defined as PWM losses factor K_{pwm} and it is calculated as following.



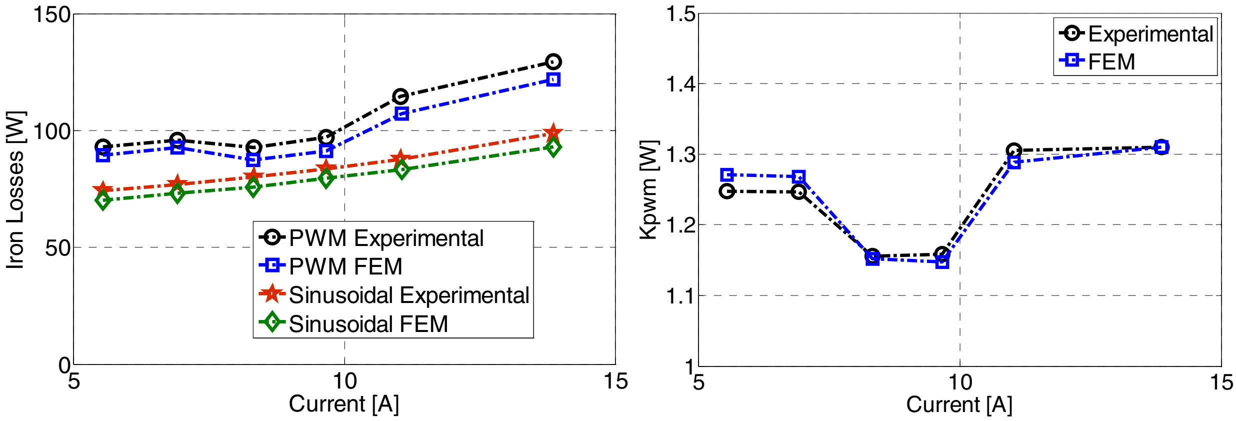
a)Sinusoidal Voltages *b)PWM Voltages (fs=4KHz)*

Fig. 9: Torque with Sinusoidal and PWM voltages



a)Sinusoidal Voltages *b)PWM Voltages (fs=4KHz)*

Fig. 10: Iron Losses with Sinusoidal and PWM voltages



a)Iron Losses *b)PWM Losses Factor*

Fig. 11: Iron Losses and PWM losses factor K_{pwm}

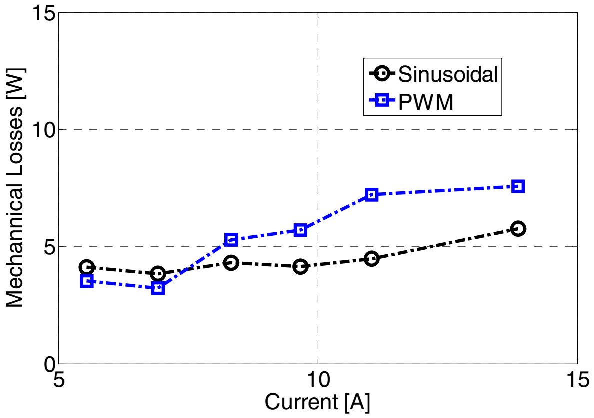


Fig. 12: Estimated Mechanical Losses

$$K_{pwm} = \frac{P_{PWM}}{P_{sen}} \qquad (7)$$

As it is shown in Fig 11 (b) the PWM loss factor is approximately constant for every load conditions. So it can be concluded that the losses increase due to PWM voltages hardly depends on the current value. In the procedure presented in this work, the loss terms which are not taken into account are independent from the modulation which enables us to calculate very accurately the loss increase in spite of making a slight error in the loss estimation.

Conclusions

In this work a new method for iron losses calculation in electrical machines is proposed. Co-simulations between the system simulator software and the FEM software are presented for the iron losses calculation under arbitrary voltages. A particular procedure is described to carry out current driven co-simulations in order to reduce as much as possible the computation load and the time consumption of the calculus.

The proposed method is validated by experimental tests. The estimated iron losses under sinusoidal and PWM voltages have a good agreement with the iron losses measured experimentally. So it can be stated that using this method is possible to estimate the iron losses under arbitrary voltages without the need of prototyping, which could lead to less expensive and more flexible design processes.

Regarding to the results, it can be conclude that the iron losses increase due to PWM voltages does not depend on the current value. As future work it would be interesting to study the influence of some characteristic parameters of PWM voltages such as switching frequency or modulation index on the iron losses.

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