Accounting for AC Winding Losses in the Electric Machine Design Process

White Paper

The efficiency and power output capability of an electric machine is defined by the losses generated during the machine operation. Taking machine losses into account early on in the design process is, therefore, crucial to ensure that the design requirements are met.

This paper will discuss a Hybrid FEA approach to calculating frequency-dependent winding losses, which combines the speed of analytical methods with the accuracy of finite element analysis (FEA). This Hybrid FEA approach enables motor designers to easily and accurately model losses as part of the design process. Within this paper, the advantages and disadvantages of different methods of calculating AC losses will be discussed and we will demonstrate how using the Hybrid FEA approach can give accurate results in different electric machine types, whilst also saving time.

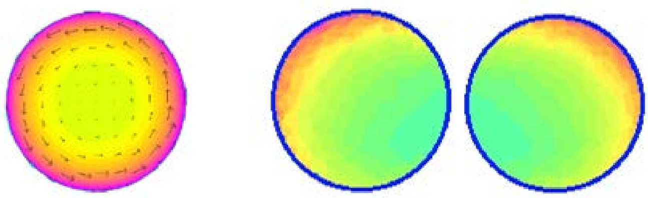
The importance of calculating AC losses early in the design process

The output capability of an electric machine is strictly related to its power dissipation and, as a result, special attention needs to be paid to machine losses during the design process. Losses that are generated in the machine cause heating, which fundamentally limits performance and defines the maximum torque and power capability of a design.

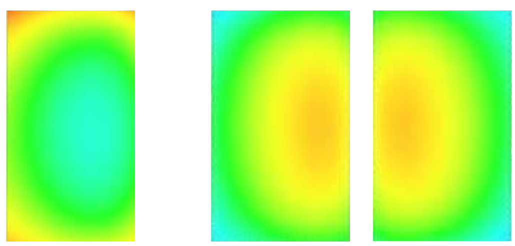
Conduction losses in the stator winding are usually the main loss component in a brushless permanent magnet machine (BPM). The size of the loss is dependent on the input current value and the winding resistance, and is closely related to the machine's temperature. The winding resistance does not have a fixed and constant value and increases as the input current frequency rises. This means that alternating current effects can lead to large effective resistance increases that are often not accurately treated and can result in a less efficient, suboptimal machine.

Large AC winding losses are often discovered at a late stage in the development process and this can result in significant additional costs, delays and a failure to meet the design requirements. Skin and proximity effects (due to self-induced eddy currents and externally-induced eddy currents respectively) are often simply ignored in the initial stage of the design process. Instead, motor designers typically consider a uniform current density distribution in the winding domain. There are, however, a number of cases—such as when designing high speed and high frequency machines—where these effects can significantly modify the performance of a machine and need to be taken into account at even the earliest stages of design.

Accurate prediction of the AC power losses generated by the combination of these effects is, therefore, highly desirable and essential to fully understand the thermal behaviour and overall efficiency of the machine.



Dominant skin effect in a circular conductor (left). Proximity effects in two circular conductors carrying current in the same direction (right). Images produced in Motor-CAD.



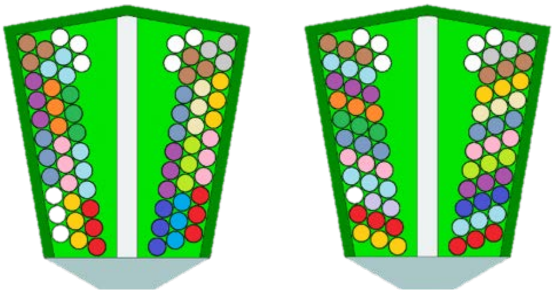
Skin effect in a single rectangular conductor (left). Proximity effect in two rectangular conductors carrying current in opposite directions (right). Images produced in Motor-CAD.

Comparison of AC loss modelling methods

A number of different methods have been proposed for evaluating AC losses. The main modelling approaches, and the advantages and disadvantages of each, are reported below.

The first approach is based on analytical calculations. With this approach, Maxwell's laws are processed and integrated over the conductive area domain and an easy formulation is obtained. Whilst this method has some benefits—it is easy to set up and computationally efficient—it can also be inaccurate and is unable to take into account complex winding distributions, higher order harmonics or non-linear behaviour.

The second approach is based on finite element analysis (FEA). With this method, Maxwell's equations are solved and integrated in mesh subdomains. Unlike the analytical approach described above, FEA is highly accurate and can be used to study more complex geometry with complex winding distributions. However, there are disadvantages to this approach to calculating AC losses: it can be time-consuming, take a long time to set up and have high memory requirements.



The position of conductors for windings with multiple parallel strands per turn can have a significant influence on the generation of AC losses. Motor-CAD enables users to control the orientation of the strands in winding from vertical (left) to horizontal (right) positions.

	Analytical	FEA
Speed	↑	↓
Accuracy	↓	↑
Complex Geometry	↓	↑
Set-up Time	↑	↓
Memory Requirements	↑	↓

Respective merits of Analytical and FEA Methods.

On one hand we have a fast but often inaccurate method and, on the other, an accurate method that is highly time-consuming. Thus, there was a need for a new approach to enable motor designers to calculate AC losses quickly and easily as part of the design process, whilst not sacrificing levels of accuracy.

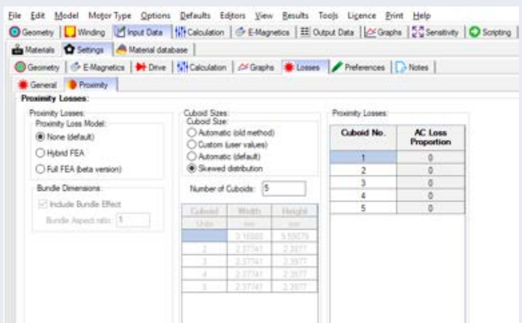
The Hybrid FEA approach was born from these considerations and combines elements of both methods described above: analytical equations for fast calculations and finite element calculation for accuracy.

Analytical formulations are used, but instead of making analytical assumptions regarding flux density values in the slot, flux density values are obtained using FEA. The flux density distribution in the slot cross section is measured at different layers in the slot. The speed by which accurate calculations can be performed means that AC losses can be taken into account early in the design process, and the quality of the design does not have to be traded-off against time and budget constraints.

Accounting for AC losses using Motor-CAD

FEA functionality has been significantly improved in the latest Motor-CAD release (version 11).

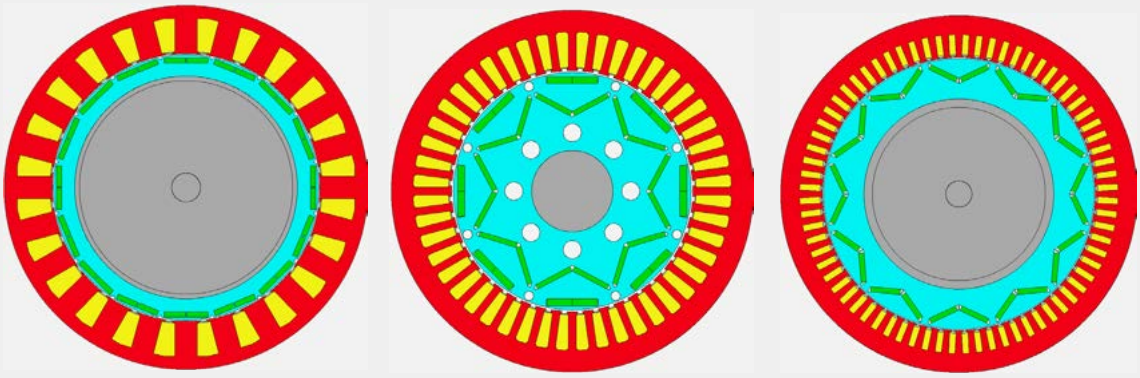
When selecting Full FEA analysis from the AC losses interface tab, Motor-CAD automatically places all the conductors in the slot, defines the bundles and chooses the optimal mesh for the problem analysis. The number of conductors and their size are input parameters, and they are placed in the slot from the slot bottom to the slot opening in order to fill the slot as much as possible. After they are placed in position they are bundled together based on the Number of Strands in Hand (NSH) and on the Bundle Aspect Ratio, entered by the user. Machine symmetry is utilised to minimise computation time. AC losses results are presented in the Output Data and the FEA plots.



Motor-CAD AC losses interface.

Comparing the Full FEA and Hybrid FEA approach using Motor-CAD

The Motor-CAD EMag module offers users a choice between calculating losses with Full FEA or using the Hybrid FEA approach. To demonstrate how the Full FEA and Hybrid FEA approaches compare in terms of speed of calculation and accuracy, Motor-CAD was used to model losses for three machine types with different winding configurations: a single strand winding, a multiple strand winding and a hairpin winding.



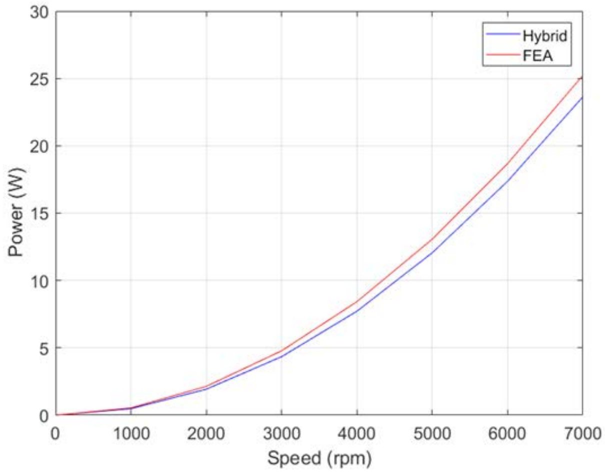
Single Strand Winding | Multiple Strand Winding | Hairpin Winding

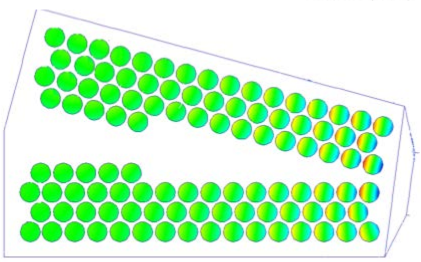
Radial view of the 24s16p IPM machine model (left), 48s8p IPM distributed winding model (centre) and 72s12p IPM hairpin winding machine (right). Images produced in Motor-CAD.

Single Strand Winding

The first comparison is based on a 24 slot 16 pole interior permanent magnet motor (24s16p IPM), for a hybrid electric vehicle P2 application. The winding consists of a concentrated bobbin wound winding, with a single conductor or strand per turn. The maximum speed of the machine is 6000rpm, resulting in a fundamental frequency of 800Hz. The winding is concentrated with 52 turns per coil and 1.55mm copper wires.

The AC losses of this model were initially calculated using Motor-CAD's Full FEA functionality and solved in approximately 15-20 minutes for a single operating point. By comparison, the same analysis using the Hybrid FEA approach in Motor-CAD was solved in only 30 seconds. The Hybrid FEA results closely align to those calculated using the highly accurate Full FEA method (with a maximum error of less than 10%). Therefore, the Hybrid FEA method was found to be 30-40 times quicker than conventional FEA, whilst still maintaining good levels of accuracy.





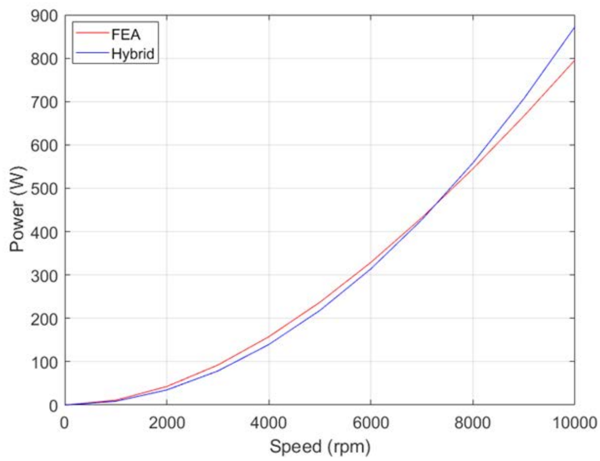
Graph showing a comparison of the AC losses calculated using the Full FEA and Hybrid FEA approach for the single strand winding (top). Eddy current density distribution in the slot for the 24s16p IPM machine model (bottom).

Multiple Strand Winding

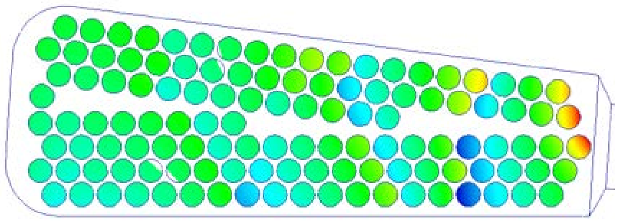
The second analysis is based upon a 48 slot 8 pole (48s8p) IPM machine with a multiple strand winding. It is for a P4 electric vehicle traction application and has a maximum speed of 10000rpm. This machine has a distributed winding and each turn is made up of multiple parallel conductors or strands (this group of parallel wires are typically referred to as 'bundles').

As stated earlier in this paper, the positioning of the conductors that make up the bundle has a significant influence on the AC loss. Using the Full FEA method, engineers can precisely define the position of each conductor in the slot and the turn each conductor is associated with. Controlling the positioning of the conductors and shape of the bundle is also possible with the Hybrid FEA method, using a 'bundle aspect ratio' parameter.

Once again, AC losses were first calculated using the Full FEA method in Motor-CAD, followed by the Hybrid FEA approach. The AC losses were solved within 12 minutes using the Full FEA method and in just 30 seconds using the Hybrid FEA approach. The Hybrid FEA results closely align to those calculated using the highly accurate Full FEA method, with a maximum error of less than 10%.



Graph showing a comparison of the AC losses calculated using the Full FEA and Hybrid FEA approach for the multiple strand winding.



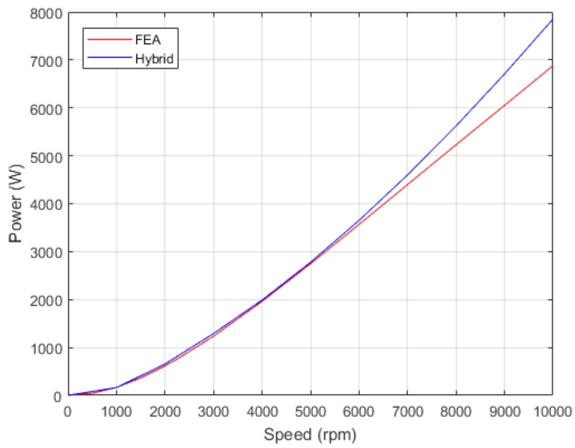
Eddy current density distribution in the slot for the 48s8p IPM machine model.

Hairpin Winding

The final machine type that this paper will discuss are hairpin wound machines. This machine type is becoming popular for its numerous advantages over conventional windings: hairpin winding machines are easier to manufacture and able to handle higher current density than conventional windings, and it is possible to get a higher slot copper fill.

However, the large conductive bars that characterise hairpin windings also generate significant AC losses. In certain hairpin windings the skin effect can start to dominate as the frequency increases and this can be challenging to model with analytical methods. The Hybrid FEA method developed by MDL detects the frequency at which the eddy currents become inductance limited and adjusts the scaling of the AC losses with frequency to account for this effect.

To model this final winding type, an example 72 slot 12 pole interior permanent magnet motor design (72s12p IPM) for a parallel hybrid automotive application is used. The winding is a distributed type with 4 square conductors in each slot and a single strand in hand per turn. The maximum operating speed is 10000rpm with a maximum fundamental frequency of 1000Hz.



Graph showing a comparison of the AC losses calculated using the Full FEA and Hybrid FEA approach for the hairpin wound machine (top).

A comparison between the Full FEA method and the Hybrid approach shows that the Full FEA method takes approximately 3 minutes for a single operating point, whereas the Hybrid FEA method is solved in 18 seconds. The hybrid method shows a good correlation across the operating speed range, including the higher frequencies where the skin depth is smaller than the conductor height.

Conclusion

This paper has shown how it is necessary to account for AC winding losses early in the design process to ensure an optimised machine design that meets the efficiency and thermally constrained performance requirements. Using Motor-CAD it is possible to accurately model AC losses in electric machines using two different modelling approaches. These validated loss calculations are easily set up and either method can be used to enable the electric machine design engineer to account for AC winding losses at an early stage in the design process.

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About MDL

Motor Design Limited

Motor Design Ltd (**MDL**) is a world leader in developing advanced software and tools for electric machine design. We have been developing electric motor design software since 1998.

Our software, Motor-CAD, is recognised worldwide as class-leading motor design **software**. We use our expert knowledge of designing electric motors to provide software support to electric machine designers at some of the most prestigious aerospace, automotive and industrial companies worldwide.

The design **consulting** services we offer cover all aspects of motor design from concept, performance optimisation, through to test and prototype development. Our customers benefit from our years of experience in designing electric motors and in-depth knowledge of simulation techniques.

Research and **innovation** is at the heart of what we do. We are active on several international research funded projects and have developed advanced motor solutions for the automotive and aerospace markets.

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