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Boulder WindPower

Effect of Skewing on Eddy Current Losses and Efficiency

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07-May-2013	[DY-MON-YEAR]	[DY-MON-YEAR]

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1 Scope

The purpose of this document is to describe the impact of skewing on eddy current loss and efficiency in BWP's axial-flux, coreless PM machine topology.

2 Model Description

The axial-flux, coreless PM generator is modeled in 2D EM-FEA as a single pole of a radial flux machine as shown in Fig. 2.1. This standard model has previously been validated against 3D EM-FEA results and was shown to calculate pertinent parameters (i.e. torque, voltage, etc.) to within 2-3%.

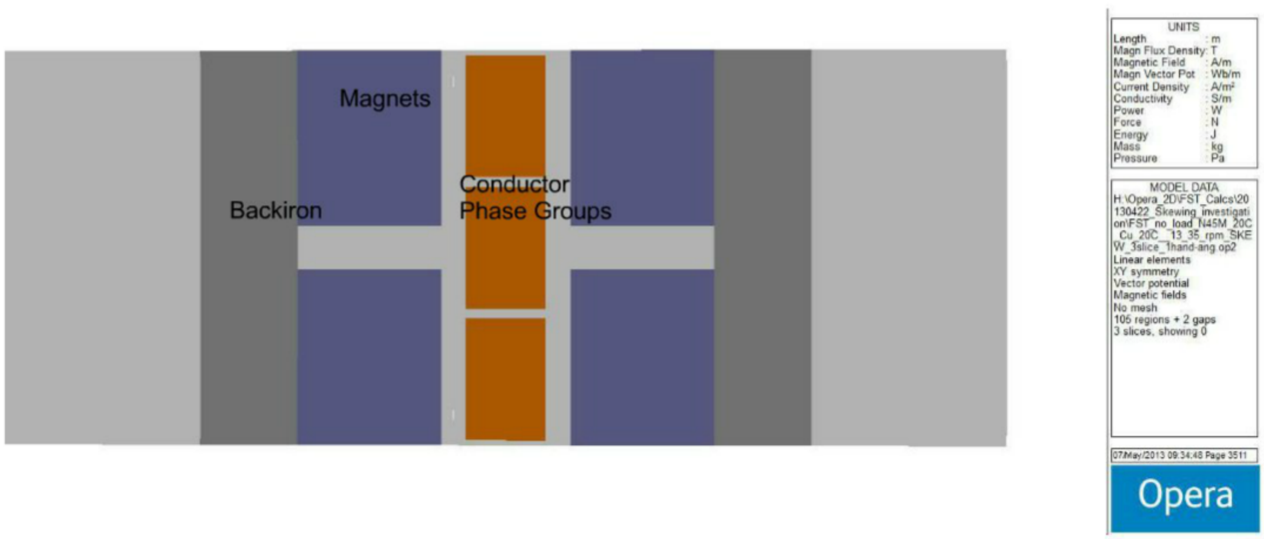
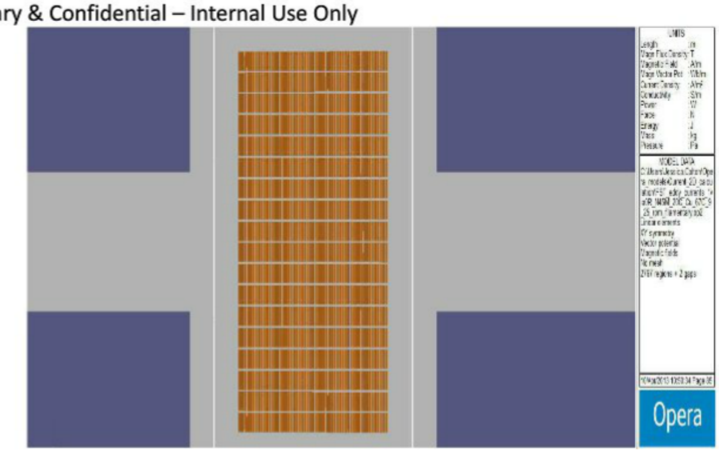


Fig. 2.1. 2D EM-FEA model of BWP's axial-flux, coreless PM generator.

The eddy current loss in the machine is considered to be the summation of all open-circuit conductor losses. This includes eddy currents contained within an individual conductor strand, circulating currents due to voltage imbalances between strands and current density distortion due to strand proximity effect. Therefore, the individual strands within a phase group (rust-colored regions in Fig. 2.1) must be modeled and attached to a circuit that is representative of the PCB connections. In order to simplify calculations, only a single bundle (axial direction) of strands is modeled and all strands have the same dimensions with uniform spacing. The FST parameters were used for the calculations (model inputs shown in Table 2.1) and the conductor strand geometry details for this machine are shown in Fig. 2.3.



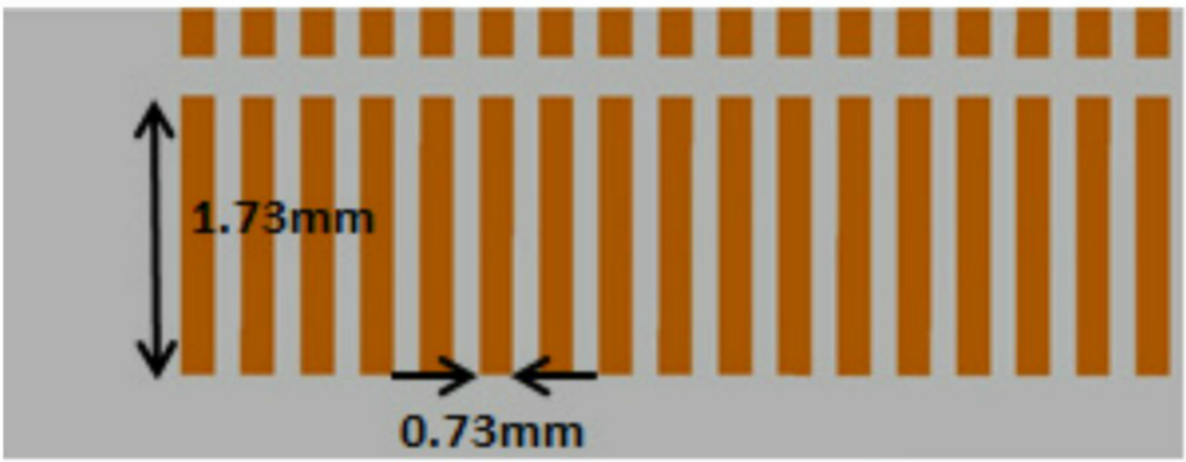


Fig. 2.3. Conductor (strand) geometry used in the model.

The FST board stackup consists of 16 working layers per board with 4 boards through the axial-thickness of the stator. The circuit used to model the via connections through the PCBs is shown in Fig. 2.4. Each strand is connected to a separate winding in the circuit. Resistors are included to model the via connection, however, the value of these resistors is set nearly to zero so that a perfect connection between layers is assumed.

TABLE 2.1. Model input parameters for the FST

Parameter	Value	Parameter	Value
Magnet outer radius	5.555 m	Copper fill factor	0.48
Magnet inner radius	5.000 m	# axial conductor divisions	64
# of poles	288	# of segments	18
Stator thickness	23 mm	# boards per segment	4
Airgap thickness (physical)	7.5 mm	Via resistance (per layer)	0 mΩ
Magnet thickness	42 mm	Speed	13.35 rpm

Backiron thickness	28.4 mm	# electrical cycles simulated	1
Magnet spacing (inner radius)	7 mm	# steps per electrical cycle	360
% magnet axially magnetized	33 %	Magnet material	N45M
Flux focusing angle	45 deg.	Magnet temperature	20 C
# turns per coil	6	Copper conductivity at 20 C	5.8E+07 S/m
# in hand conductors	3	Copper temperature	20 C
		Phase resistance at 20 C	40 mΩ

The model is divided into 3 slices (radially, into the page) with skewing applied to the magnet regions. The base angle for skewing corresponds to the pitch of one in-hand conductor and multiples of this angle (up to 18) were investigated. Two simulations were done for each skewing angle: (1) eddy current loss calculation to determine the effect of skewing on loss and (2) open circuit voltage calculation to determine how much increase in current would be needed to compensate for the drop in back EMF.

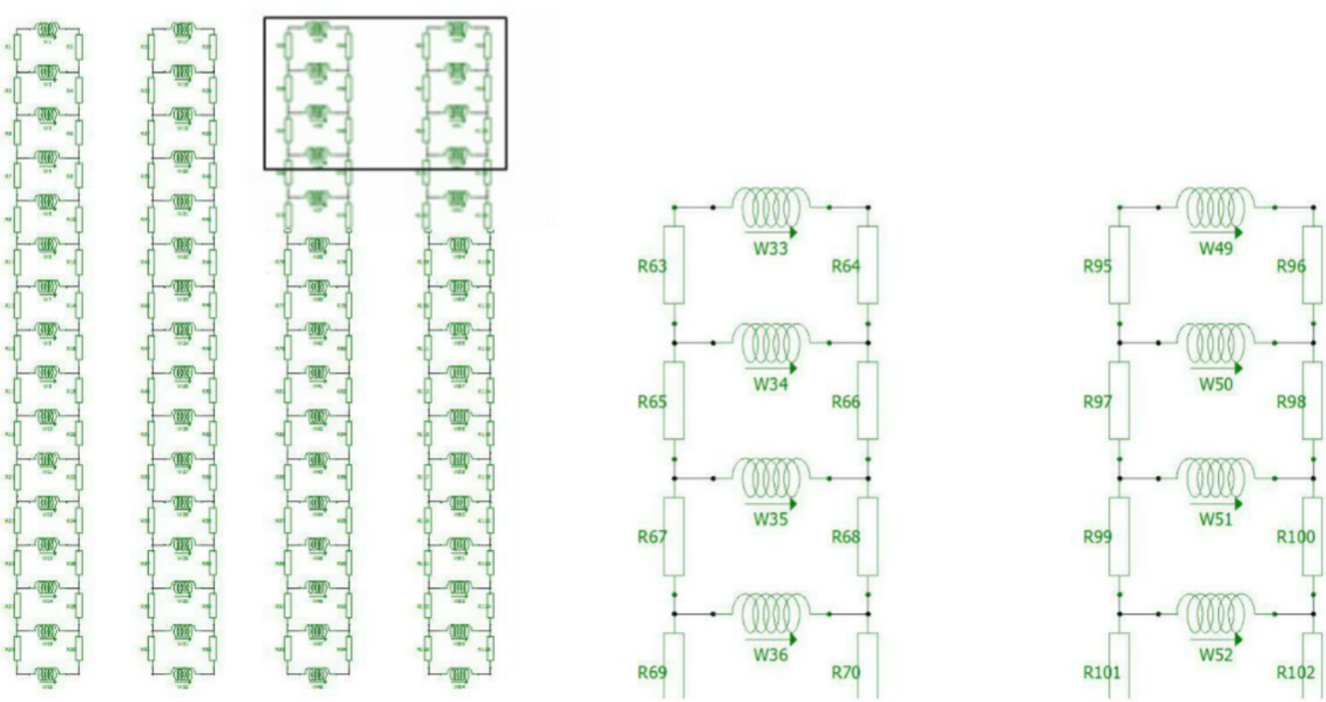


Fig. 2.4. Conductor (strand) geometry used in the model.

3 Results

A plot of eddy current loss and open circuit voltage versus skewing angle (given in multiples of the angle spanned by one in-hand conductor) is shown below in Fig. 3.1.

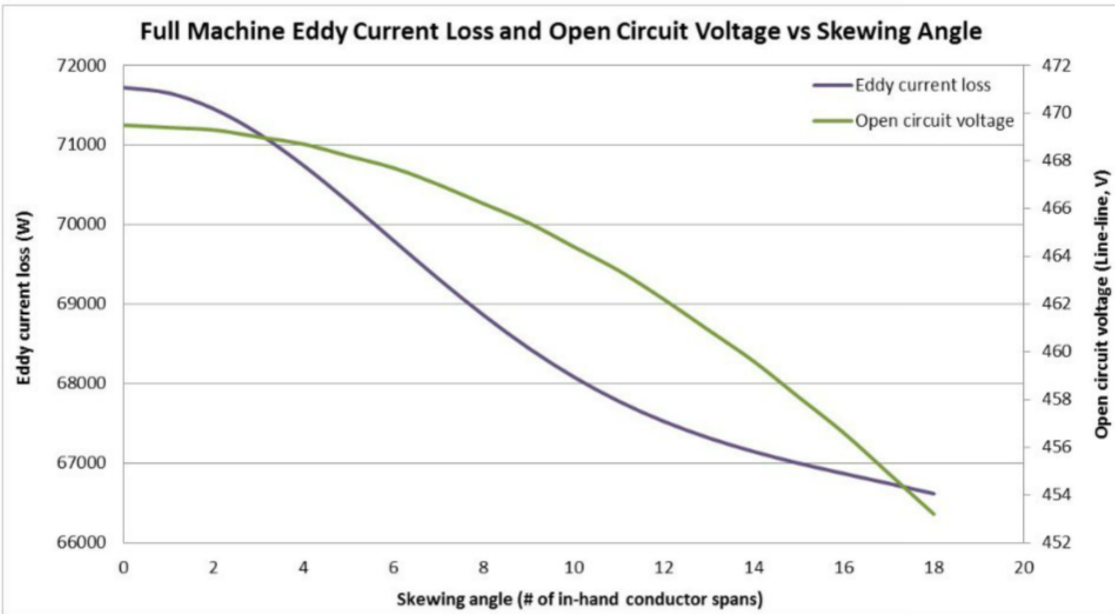


Fig. 3.1. Eddy current loss and open circuit voltage vs skewing angle for the FST machine at full speed.

The eddy current loss is calculated by integrating the square of the current density in all strands contained in the bundle, multiplying by the conductivity and the model depth as shown in Eq. 1. The loss is taken as an average over a complete electrical cycle. This is done for each slice of the model and the results are added, where the model depth is considered to be the difference between the outer and inner magnet radii divided by 3 (because the skewing is applied in 3 slices). The average loss over an electrical cycle is assumed to be the same in all bundles and is therefore translated to a "full machine" loss as given in Eq. 2.

$$P_{eddy\_bundle} = \frac{1}{T}\int_0^T \left(\frac{1}{\sigma}\iint J^2 dA * model\_depth\right) dt \qquad (1)$$

$$P_{eddy\_machine} = P_{eddy\_bundle} * \frac{\#\,bundles}{turn} * \frac{\#\,turns}{coil\ side} * \frac{2\ coil\ sides}{coil} * \frac{2\ coils}{board} * \frac{\#\,boards}{segment} * \frac{\#\,segments}{machine} * 3\ phases \qquad (2)$$

The output power of the generator is given by

$$P_{elec} = \sqrt{3}V_{LL}I_L\cos\theta\,. \qquad (3)$$

A percentage reduction in open circuit voltage is assumed to represent the same percentage reduction in loaded voltage and therefore require the same percentage increase in line current to hold the output power steady. The nominal full load current of the FST is assumed to be 240 A-rms (known from previous calculations and tests) for the case with no skewing. Using this information, the increase in DC copper loss (ΔP_{Cu}) due to the reduction in voltage due to skewing can be approximated by

$$\Delta P_{Cu} = \#\ segments\left[3(I_L^2 - 240^2)R_{phase}\right] \tag{4}$$

where R_{phase} = 40 mΩ. Fig. 3.2 shows how the machine loss is affected by the skewing angle; this considers both the reduction in eddy current loss and increase in DC conductive loss.

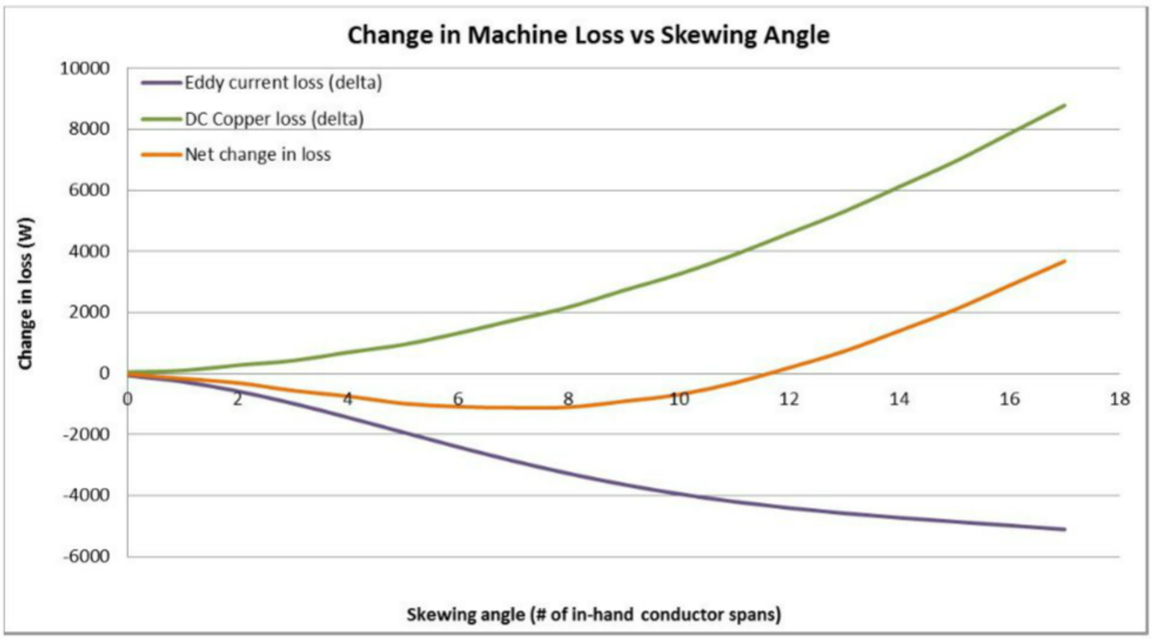


Fig. 3.2. Machine loss as a function of skewing angle.

4 Concluding Remarks

- The maximum benefit from skewing is seen at an angle of approximately 8 in-hand conductor spans. However, this only translates to an efficiency boost of approximately 0.04%.
- The method used here of holding the generator output power constant between designs is not entirely accurate. When there is less (or more) loss to overcome, the generator output power can be reduced (or increased). The effect from this is thought to be slight due to the low power losses shown here.
- The 3-slice skewing model is somewhat coarse. Improved accuracy may be achieved with more slices included in the model at the cost of an increase in calculation time. The effect of this (if any) on the results shown is not understood at this time, but may be investigated in the future.

Revision History

Rev.	Author	Date	Section	Description
00	Colton	[07-05-2103]	All	Initial Release.