Multi-physics Design of Electric Machines

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1. OBJECTIVES

The main objective of the research is aimed at thermal analysis methods for electrical machines, which would be suitable for coupling with electromagnetic models employed in large-scale design optimization studies.

The electromagnetic power losses are generating heat, leading to a non-uniform distribution of temperature inside the machine, which, in turn, yields further variations in the power losses. So it is necessary to deal with the thermal analysis combined with electromagnetic models.

2. APPROACH

Based on the symmetric of electromagnetic field, a technique named Computational Efficient Finite Element Analysis (CE-FEA), has been recently developed and implemented. For thermal analysis, mainly because FEA and CFD would be disproportionately slow without guaranteeing increased accuracy, an equivalent thermal network method is employed. In this proposed arrangement, the computational time for the electromagnetic and the thermal problem are comparable. Electromagnetic analysis is performed through specially developed script algorithms that employ the Maxwell software by ANSYS/Ansoft as the computational engine. An Active X interface is used to couple the electromagnetic and thermal analysis, which is performed using the specialized software, Motor-CAD. The methods, which are currently being implemented, will be demonstrated on industrial design cases.

As shown above, in order to obtain an optimum design it is essential to take into account of both the electromagnetic and thermal design aspects. ActiveX links are useful for automation of data transfer to run program functions from an externally calling routine.
3. METHODOLOGY

- Computationally Efficient Finite-Element Analysis (CE-FEA)
  
  - Computationally Efficient Finite-Element Analysis fully exploits the symmetries of electric and magnetic circuits of sine-wave current-regulated synchronous machines and yields substantial savings of computational efforts.

  - Flux linkages, $\lambda$, can be written in Fourier series form as:
    \[
    \lambda_r(\theta) = \sum_{v=1}^{V} \lambda_v \cos(v\theta + \phi_v)
    \]

  - Accordingly, resulting back emfs, $e$, can be written in Fourier series form as:

  - The symmetry property of the magnetic circuit results in the following relationships for the elemental radial and tangential components of stator core flux densities at different rotor positions:

    - Fourier series of elemental flux densities:

    - The specific hysteresis harmonic losses and eddy-current losses in the stator teeth and yokes are calculated as follows:
      \[
      w_h = \sum_{n=1}^{n_{\text{max}}} k_h(B_n)(nf_1)
      \]
      \[
      w_e = \sum_{n=1}^{n_{\text{max}}} k_e(B_n)(nf_1)^2 B_n^2
      \]

    - The total core losses in the stator can be calculated as follows:
      \[
      P_{Fe} = (w_{h\_tooth} + w_{e\_tooth})m_{tooth} + (w_{h\_yoke} + w_{e\_yoke})m_{yoke}
      \]
      where, $m_{\text{tooth}}$ and $m_{\text{yoke}}$ are the mass of the stator teeth and yoke, respectively.
Analytical Thermal-network Analysis:

- Heat-transfer analysis is the thermal counterpart to electrical-network analysis with the following equivalences: nodal temperatures to voltages, power sources to current sources, power flow through resistances to current, and thermal resistance to electrical resistance. In a thermal network, if we lump together components that have similar temperatures and separate thermal resistances by placing nodes at important locations in the electric machine, such as the stator back iron, tooth, winding hotspot, etc, we can get an equivalent thermal circuit, which is similar with electrical circuit as showing in Figure 4.

4. RESULTS

Flux linkage construction: in order to obtain the flux linkage waveform for one electrical cycle of phase A, firstly the flux linkage of phase B and phase C are phase shifted by 60° and 120°, respectively, as shown in Figure 6. The reminder of the flux density waveform, between 180° and 360° is obtained by symmetry.
To evaluate the accuracy of the CE-FEA, the torque and the induced voltage waveforms calculated with the CE-FEA method are compared to the results obtained through time-stepping FEA, as shown in the figures below.

**CONCLUSION**

The main scientific contributions of the research consist of novel thermal to electromagnetic “weak” coupling algorithms that employ “hybrid” models in which the relation between losses and temperature
for a given candidate design is derived as a simplified function based on response surface and data mining mathematical techniques.

The ultimate project objective is to reduce the number thermal to electromagnetic iterations to as little as only two, in order to make the multi-physics analysis suitable for large scale automated optimization studies.

References


