TRANSIENT SIMULATION OF THE ISIS SYNCHROTRON SINGLET QUADRUPOLES USING OPERA 3D

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Abstract

Type QX106 singlet magnets are AC defocusing quadrupoles used in the ISIS main synchrotron ring. They have an aperture of 202 mm and a yoke length of 303 mm, so the end effects are significant. The iron poles and the yoke are asymmetric and the coils are driven by a 50Hz, 400 A AC current, biased with a DC current of 665 A. Therefore the yoke has to be laminated, and the laminations are slitted up to a depth of 90 mm on each side to further reduce the eddy current losses. Two 3D models (DC and transient) have been developed using OPERA 3D for different purposes. Both models require the use of an anisotropic BH curve for the yoke, and the transient model also requires an anisotropic conductivity and a prismatic/hexahedral mesh to overcome the limitations of the linear tetrahedral edge elements in OPERA's vector potential formulation. The quadrupole field quality was originally measured in 1982 with a DC excitation at the biased peak current (1065 A) and those measurements are now compared to both models. The iron losses due to the eddy currents are also presented and compared to the original specifications defined in 1980, as well as an estimation of the eddy currents in the coils.

MAGNET SPECIFICATIONS

The ISIS spallation neutron source injects a 200 µs, 25 mA beam of protons (H^- stripped to H^+) into the synchrotron ring at 70 MeV and extracts them at 800 MeV to two target stations, repeating this cycle 50 times per second. To produce the required guiding fields, the magnets in the ring are driven in series by a biased alternating AC current at 50 Hz, using only the 10 ms valley-to-crest region of the fields as the protons are accelerated up to the extraction energy. The QX106 magnets are singlet defocusing quadrupoles in each of the 10 synchrotron superperiods.

Recently, the requirement to build a batch of new spare coils for the QX106 magnets has shown the need to better understand/cross check the different working parameters (fields, power, cooling, etc.). Furthermore, the capability of modelling the field errors during the full AC cycle of the magnet provides important information for the beam physicists during the acceleration in the synchrotron.

Although a document with the technical specifications from 1980 was available for the singlets [1], there were some inconsistencies in several parameters, and the referenced set of drawings was found to be incorrect. In addition, the design was modified before manufacturing. The "as-built" specifications were finally found in [2] and are shown in Table 1, together with other values from [1].

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Table 1: Main QX106 Specifications

Parameter	Value	Units
Peak gradient	3.545	T/m
Aperture	212	mm
Effective length	402	mm
Inductance	3	mH
Yoke length	303	mm
Peak current	1062	A
RMS current	720	A
Power loss in coils (40 ºC)	4.7	kW
Power loss in iron	~0.5	kW

MAGNETIC SIMULATIONS

Common Modelling Requirements

The software used for the magnetic modelling of the QX106 singlet was OPERA v18R2 [3]. The QX106 yoke geometry is presented in Fig. 1, showing the maximum allowable 3D symmetry for the magnetic calculations ($1/8^{th}$). The 45º symmetry could not be used because an octupole component was included in the original design to provide some Landau damping to the circulating beam. In addition, the quadrupole has to fit under the vertical extraction septum in one of the superperiods, which imposes an asymmetry to the external profile of the yoke.

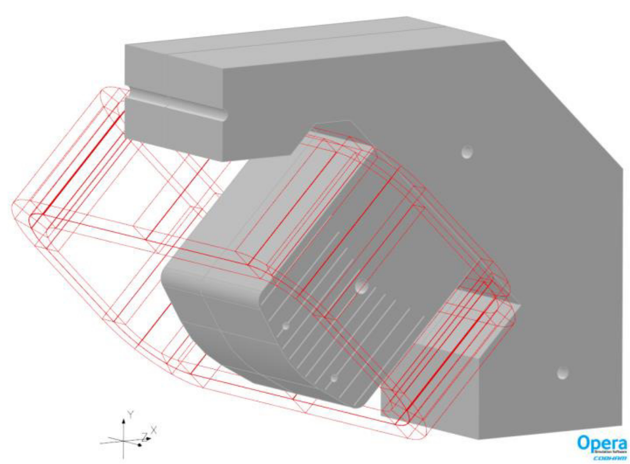

Figure 1: Geometry of $1/8^{th}$ of the yoke.

The pole ends have 0.9 mm wide slits up to a depth of about 90 mm on each end of the poles (Fig. 1). Although those slits are required to reduce the eddy currents due to the alternating axial (Z coordinate) B field, they are air gaps in the yoke that effectively reduce the permeability of the pole ends. That heavily affects the total b6 content also in the magnetostatic (DC) model. Therefore, to achieve good results, the small slits have to be modelled

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both in the magnetostatic and the transient models, making the mesh creation process much more complex and labour-intensive.

In order to reduce the eddy current losses due to the alternating B field parallel to the laminations (XY coordinates), the laminated yoke is made of 0.35 mm thickness, non-oriented grain electrical steel (British Steel Corp. TRANSIL 315-35), with a specified packing factor (PF) of 0.92. The BH curve of that steel was not available, but a very similar material was selected for the models: NIPPON STEEL GNO35H300, measured both at DC and 50 Hz. The anisotropic properties of the laminated yoke have been modelled using a homogenisation approach, to avoid the creation of extremely fine and unsolvable meshes. The anisotropic permeability has been modelled using the well-known effective permeability calculations [4] for the in-plane and the normal-to-plane directions to the laminations [Eqs. (1) and (2)], effectively diluting the isotropic BH curve in both directions. In OPERA this is done by correctly aligning the system of coordinates and then defining the packing factor for the magnetic material. The coils have been modelled as Biot-Savart conductors.

$$\mu_{r(xy)} = PF\,(\mu_r - 1) + 1 \tag{1}$$

$$\mu_{r(z)} = \frac{\mu_r}{\mu_r - PF\,(\mu_r - 1)} \tag{2}$$

Magnetostatic Model

The magnetostatic model was meshed with 3.3M elements, using 2[nd] order tetrahedrons (10 node) and the OPERA's mesh generator type II. These elements are accurate for TOSCA, the OPERA's magnetostatic solver, and make the meshing process easier.

The model has been solved for 2 excitations, at 1065 A and 265 A. The former excitation is used to compare with the DC measurements carried out in 1982, and both simulations are used to calculate the AC peak and valley field distributions in the yoke and coils. Those are useful to analytically estimate the eddy current loss (assuming no saturation in the magnetic material) due to parallel fields in both domains, by integrating Eq. (3) [4] in the volume of the magnetostatic FEM solution.

$$P_{xy}[W/m^3] = \frac{\omega^2 d^2}{24\rho}\left(\frac{B_p - B_v}{2}\right)^2 \tag{3}$$

where B_p and B_v are the XY fields at both current excitations, ρ is the resistivity of the material (52e-8 Ω.m for the laminations) and d is the thickness of 1 lamination.

The results of the magnetostatic model together with the field quality measurements made in 1982 at the peak current of 1065 A are shown in Table 2. The value of the eddy current loss in the yoke due to parallel B fields is 11.9 W, and the eddy loss estimated in the coils is 779 W at 40 ºC (both calculated using Eq. (3) in their domains).

The harmonics in Table 2 are represented per one unit of the main quadrupolar field (b2), and are referenced to a 95.4 mm radius. Several non-allowable harmonics are also shown in order to better appreciate the accuracy of the measurements and/or the manufacturing process. The harmonics not presented can be considered negligible.

Table 2: QX106 Measurements and Model Results

Parameter	1982 measurement	Magnetostatic model
Integrated field	0.13465 T.m	0.13364 T.m
b1	-7.8×10^{-4}	0
a1	23.7×10^{-4}	0
b3	2.1×10^{-4}	0
a3	-1.8×10^{-4}	0
b4	-16.6×10^{-4}	-12.9×10^{-4}
b6	-25.7×10^{-4}	-21.9×10^{-4}
b10	12.1×10^{-4}	13.5×10^{-4}
b14	-18.8×10^{-4}	-19.9×10^{-4}

The dipole component shows a possible misalignment in the positioning of the harmonic coil vs. the magnetic axis: 227 μm in one coordinate and 75 μm in the other. The sextupole error is very small, and the small difference in the octupole is probably due to the sensitivity of the pole profile coordinates that generate the pole asymmetry. The b6 multipole is always extremely sensitive to the BH curve saturation, and at lower currents the values have been proved to be almost identical to measurements, therefore a small difference at 1065 A is not surprising.

Transient Model

The transient model requires several crucial changes to the magnetostatic model as follows:

- Only the eddy losses due to the B field normal to the laminations (Z direction) have to be calculated in FEM, as the losses due to the parallel B field can be extrapolated from the steel manufacturer's data at the working frequency. Therefore, only the steel conductivity in the axes parallel to the steel laminations is required, creating an anisotropic conductivity tensor with σ_{zz}=0. However, OPERA struggles to achieve convergence in this complex model if the conductivity in Z is set to zero. Therefore, an equivalent conductivity in the Z direction has been chosen to both achieve numerical convergence and also to obtain a realistic value of the eddy current losses due to the B field parallel to the laminations in the yoke volume. The equivalent conductivity normal to the laminations is defined in [5] and presented in Eq. (4).

$$\sigma_{zz} = \frac{1}{PF}\left({}^{d}/_{a}\right)^2 \sigma \tag{4}$$

  where d is the thickness of 1 lamination, a is the yoke pole width and σ is the isotropic conductivity of the steel ($1/\rho$).
- The model is solved using ELEKTRA, the transient electromagnetic solver of OPERA. This solver uses the magnetic vector potential and only supports linear order edge elements. Therefore, the tetrahedral elements are not well suited to represent the eddy cur-

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rents, and prismatic or hexahedral elements are mandatory. This makes the meshing process more difficult, especially to model the critical slits in the yoke.
- The iron holes (filled with non-magnetic stainless steel studs) had to be removed due to a problem in the ACIS core which made very difficult to mesh the whole iron with hexas or prisms with holes present.
- The mesh was reduced (1.5M elements) at the cost of some accuracy, and the solver settings were tuned for speed: A fixed time step of 0.1666 ms (0.5 ms output), a relaxed convergence tolerance of 0.005 and a full asymmetric Jacobian were used.

The model was solved starting at zero current until a steady state waveform was achieved. The convergence of the current ramp up proved to be quicker than starting at the DC bias current (665 A). The simulation was run for 50 ms and took about 19.5 days to solve.

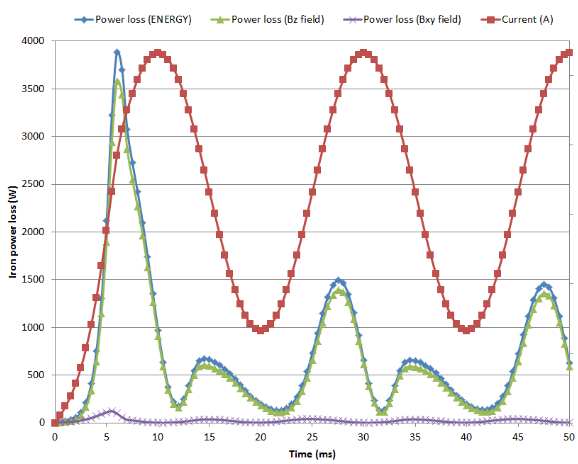

Figure 2: Eddy current losses in the yoke.

Figure 2 shows the eddy power loss in the iron due to the fields parallel (B_{xy}) and normal (B_z) to the laminations, as well as the current in the coils. The calculated eddy power loss averaged in one cycle (30 to 50 ms) is 537 W, being 518 W due to B_z field and only 19 W due to B_{xy} fields. The power due to B_{xy} is somewhat bigger than the previously estimated value using Eq. (3) and the DC model solution, but small enough in percentage of the total power to prove the validity of both approximations. The power due to the hysteresis and anomalous losses is calculated from the steel manufacturer's data at different fields and frequencies [6], and it results in 41.7 W and 24.5 W respectively (B_{xy} fields). Consequently, the total power loss in the iron is around 603 W, roughly similar to the estimation in Table 1.

The field quality and the current of the transient model solution are plotted in Fig. 3, where the DC harmonics are calculated in an additional transient model with a stationary excitation. A good agreement between DC and transient results can be observed, which confirms that the eddy currents are not playing a major role in the magnetic behaviour of the quadrupole. A small field delay of about 1 ms can be clearly noticed in the b6 response, but that field delay is almost invisible in b2, the main quadrupolar field (here not shown for the sake of clarity).

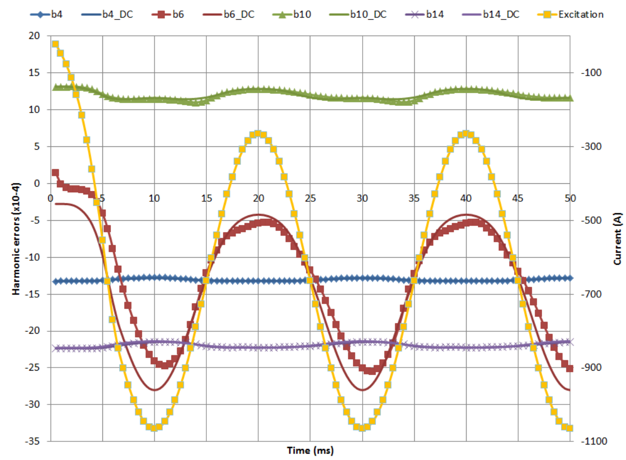

Figure 3: Dynamic field quality.

COIL LOSS CALCULATIONS

The eddy current loss in the coils has been estimated using several methods. The first method integrates Eq. (3) in the volume of the coil, and its result was already shown in the previous section. A second, more pessimistic, method [7] uses a 2D magnetostatic model to estimate the eddy loss at every conductor position in the coil cross section. Each result is then multiplied by its turn length and added to the total. The last method (probably the most precise) involves a 2D frequency domain model with the coils fully modelled to include the skin and proximity effects in the conductors while neglecting the yoke contribution to the losses. This allows the calculation of the actual AC resistance due to the eddy loss in the coils. The results of the 2 last methods were 840 W and 746 W respectively (at 40 ºC). The latter value, added to the resistive losses (DC bias and AC) for R_{DCquad} = 7.72 mΩ, results in total coil losses of ~4.8 kW, very close to the value in Table 1. The magnet AC resistance was measured with a precision LCR meter at 50 Hz, and the results were in good agreement with the previous calculations.

CONCLUSION

The results from modern advanced simulations have shown a good agreement with the original specifications, which are believed to have come from physical measurements of a prototype. A correctly designed AC magnet has been shown to behave quite similarly in both DC and transient excitations from the field quality point of view. Therefore, a DC model is a much quicker way of calculating or optimizing the magnetic behaviour of a magnet, leaving the transient model as a final check to ensure the eddy currents are well controlled. With regard to the coil loss calculations, they can be accurately estimated by using a 2D frequency domain model or a DC 3D model.

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