REPLACEMENT OF THE ISIS WHITE-CIRCUIT CHOKE

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INTRODUCTION

The ISIS accelerator is based on an 800 MeV synchrotron arranged as a White-Circuit [1]. Key to its operation is a large storage choke with ten main, and ten auxiliary windings. The main windings resonate with the associated capacitor banks at 50 Hz and also provide a path for a DC bias current past the capacitors. The auxiliary windings provide for the AC excitation of the magnet circuit.

Known as the “NINA” choke from its previous service on the NINA synchrotron at Daresbury Laboratory, it was built in 1963. The windings are built into a single frame and are therefore closely coupled by the magnetic circuit. In the event of a failure on any winding, the choke would have to be dismantled to replace the damaged parts. As it weighs about 90 tons without its cooling oil this would be a major task even if sufficient spare parts were available.

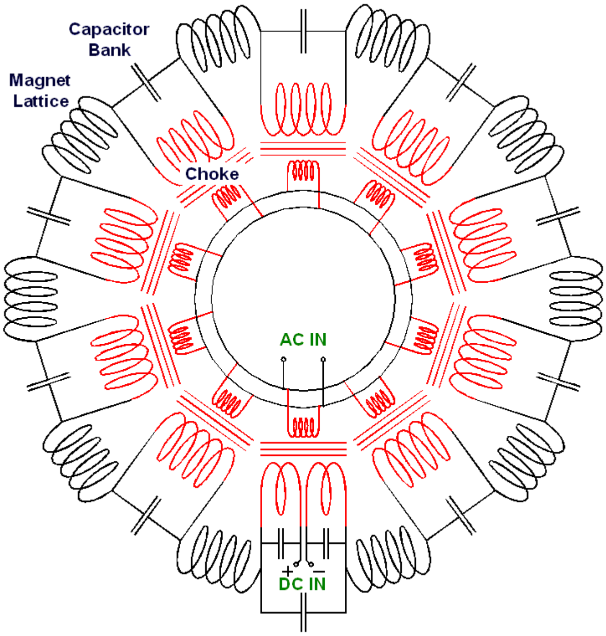

Figure 1: The “White Circuit” as it will be with 10 separate chokes. The auxiliary windings will be connected in parallel and each choke will excite the circuit AC equally.

It is estimated that a failure could result in the shutdown of ISIS for 18 to 24 months; it is therefore a high priority for the laboratory to develop a replacement system with redundancy built in. A complete spare choke of the same design was not considered practicable; the original proved very difficult to build and commission, in part because of differences in coupling between the windings; and also because of the size - few manufacturers now have the facilities to make such a device. An alternative scheme was considered whereby the magnetic circuit is split into ten smaller chokes, each with a main and auxiliary winding and with two complete spare chokes which could be switched into circuit if necessary. The loss of ISIS time in the event of a failure would be reduced to hours; a major reduction in risk to the facility. The electrical performance will remain the same. Fig. 1 shows the White Circuit as it will be with the new chokes.

PROJECT PHILOSOPHY

It was recognised that the specification for the new chokes would be tight. In particular, the very high coupling requirement is in conflict with the need to build a storage choke containing air gaps in the core. These are elements of choke and transformer design philosophy which normally do not occur together in the same reactor.

It was unlikely that any manufacturer would readily tender for a job that would be technically so risky. In order to attract sufficient interest it was decided to run a competition whereby manufacturers would be invited to supply a 1/5th scale model choke which would then be tested against any competitors. The tests would be an opportunity for their manufacturers to adjust their designs and gain experimental knowledge before tendering for the full-size chokes. In this way technical and financial risk would be contained for both ISIS and the manufacturers.

MODEL TESTS

The test circuit is shown in Fig. 2 and is essentially a White-Circuit of one superperiod. For each test one choke was used to drive the high voltage circuit while another took the place of the magnet load.

In the event, three firms provided models for evaluation and these were swapped around so that each choke was tested. Early design studies [2] had given an indication of where to expect significant challenges and were an important guide when the evaluation procedures were drawn up.

Notably it proved difficult to measure losses directly on the resonant high voltage circuit. The available power analysers proved unable to measure accurately the real power in the presence of the very high reactive component. Ultimately, the measurements were carried out indirectly using the excitation-winding input power and calculated from the differences between the three combinations of chokes.

In addition to the tests carried out by ISIS the manufacturers were allowed access to the facility to carry out their own experimental and development work on their respective models.

On completion of the tests, the manufacturers were invited to tender bids to design and build two prototypes which could be used to prove the final design and which eventually will become the two *in-situ* spares for the final ten production devices. Two of the original three firms placed bids and Imtech-Vonk with their sub-contractor Trench Austria GmbH won the contract.

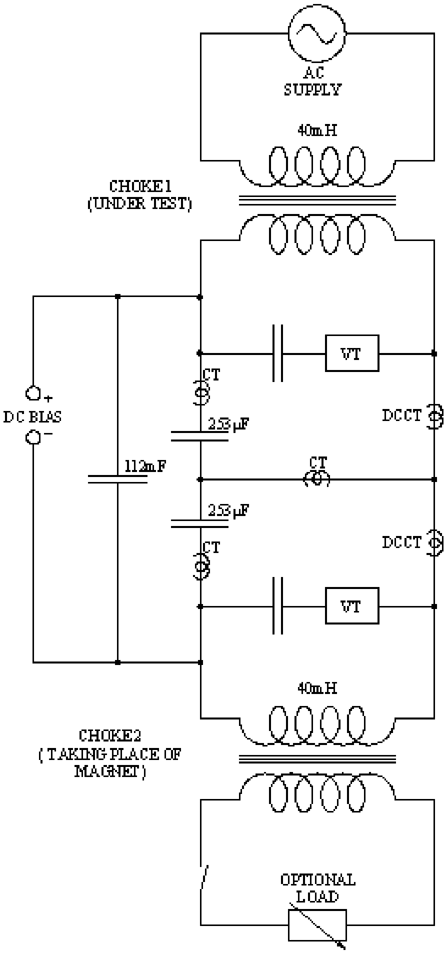

Figure 2: Circuit used for evaluation of model chokes.

PROTOTYPE

The design of the full-scale machine has proven quite challenging. In particular, the air-gaps required to make it an effective choke naturally tend to increase leakage flux and this has led to problems of eddy-current losses which have had to be overcome before the design was satisfactory.

The chokes were built around a rectangular yoked core with multiple air-gaps down each of the legs. There are two main windings, one on each leg of the frame and four auxiliary coils, one inside and one outside each main winding, connected as in Fig. 3.

The main windings are made from copper wound directly onto a stainless-steel tube which allows the demineralised cooling water direct thermal contact with the conductor: see Fig. 4.

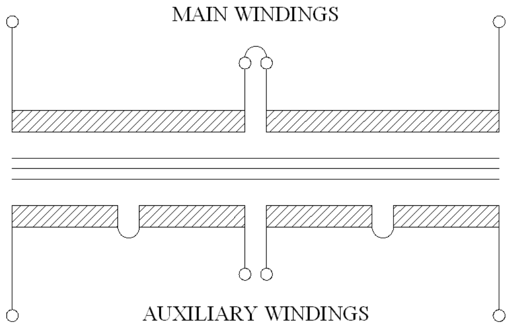

Figure 3: Choke schematic

Figure 4: Main winding cross-section.

In order to produce the required low leakage-inductance, the auxiliary windings are wound as a current sheet made from a helically coiled aluminium foil strip; shown in Fig. 5.

Figure 5: Design drawing of helical auxiliary coil

Figure 6: Prototype choke undergoing factory acceptance tests

The original 960V auxiliary winding produced unacceptably high eddy current losses which resulted in localised overheating of the coil near to the air-gaps. Therefore, it was decided to halve the width of the foil and this caused a new problem – how to maintain the current sheet. A solution was considered whereby two parallel foils would be wound next to each other in each winding but this idea was rejected in favour of increasing the turns-ratio. This has therefore changed from 16.67:1 to 9:1 and the supply voltage has almost doubled as a consequence. In the completed system the auxiliary will be supplied via a matching transformer in either case so the voltage change is relatively straightforward to accommodate.

The completed prototype can be seen in Fig. 6 undergoing factory acceptance testing in Linz during which the data below was measured.

The reader will have noted that to test the choke effectively a similar device is needed to act as a load. The second prototype was assembled and served as the "magnet" load without using the auxiliary windings.

Specified and Measured Parameters

For comparison the relevant parts of the specification are shown alongside the test results from the prototype in table 1.

Of note is the value given for coupling, the figure given in the table was derived from short-circuit tests with the auxiliary windings connected in parallel. This was checked against two other methods: open circuit with auxiliaries connected in parallel and a four winding test; one winding was energised with all others open circuit and auxiliaries unconnected. The coupling values thus calculated varied from 98.57% to 98.96%; the very close agreement increases confidence in the figures obtained.

Table 1: Specified parameter vs. actual test result

	Parameter requirement	Test result obtained
Rated inductance	160 mH ±3 %	158.6 mH
Main winding rated voltage	16 kV	16 kV
DC bias current	662 A	662 A
AC excitation current r.m.s.	318 A	318 A
Rated frequency	50 Hz	50 Hz
Turns ratio, main : aux.	16.67 : 1	9 : 1*
Corresponding aux. voltage	960 V	1780 V*
DC load loss	28.5 kW ±5 %	29.8 kW
AC load loss	21.7 kW	27.2 kW
Short-circuit reactance	1.005 Ω ±20 %	1.016 Ω
Mutual coupling factor	99 %	98.96 %
Equivalent 50 Hz rating	14.35 MVA	14.5 MVA
Applied AC voltage to earth	28 kV	28 kV

*Changes agreed during the design process.

CONCLUSION

It was expected that the design of the replacement White Circuit choke would be challenging and this has proved to be the case with a large proportion of the development effort centred on the auxiliary windings. However it is believed that the prototype that has now been built and tested is an excellent one which will prove a satisfactory replacement for the NINA choke. The critical coupling factor specified has been achieved and should allow the existing performance of the White Circuit to be maintained.

A manufacturing programme is now in place with a view to completing delivery of the ten production chokes in May 2009. It will then be possible to commission them into the ISIS main magnet circuit.

REFERENCES

[1] M.G. White et al, "A 3-BeV High Intensity Proton Synchrotron, The Princeton-Pennsylvania Accelerator", CERN Symp. 1956 Proc., p525.

[2] A.J. Kimber, J.W. Gray and A. Morris, "Redesign of the ISIS Main Magnet Power Supply Storage Choke", EPAC'04, Lucerne, July 2004. p1455.