Development of an AC Loss Model for the ITER Central Solenoid during a Plasma Scenario

AC Loss in CS Coils

The coupling and hysteresis losses in the ITER CS coils average out to ~6 kW over the 1800 sec reference plasma pulse (which includes ~500 sec of fusion burn). This power, which does not include the eddy current heat load in the passive structures (another 1 kW), needs to be compared to the 75 kW for 8.2 K installed cryopumps and the total AC loss represents 1/3rd of the heat load on the ITER superconducting magnet system.

AC Loss Model

The AC loss power discussed in the following is per unit volume of superconducting strand (pure Copper strands are not counted). To obtain the total power density needs to be multiplied by the number of superconducting strands, the strand cross-section and the length of conductor considered. Also to be noted is that the models for the two types of AC losses are somehow related, as the hysteresis loss model is needed to obtain the parameters of the coupling loss from the conductor sample tests, as they are always coupled.

Input Parameters

The following therefore describes analytical approaches in which considerable simplifications is achieved by using AC loss parameters measured in standard tests on conductor (for coupling loss) or strand (for hysteresis loss) samples. This phenomenological approach allows to reproduce the calculation of the complex in situ current distributions present in the conductor. Further description of input parameters as well as the way they are obtained is given in a companion paper to this conference: A. Torre “Review of experimental results and models for AC losses in the ITER PF and CS conductors”.

Coupling Loss

The coupling loss power per unit volume depends on the square of the lossy (“inner”) field inside the strand and the strand Joule losses over resistance represented by the time constant (c) of the different coupling loops (first line on the left). The temperature behavior of the “inner” locally applied field after taking into account the shielding by the outer conductor is linked to the loop network behaving like a simple RLC circuit. The additional procedure applied to the inner field calculation has been described previously. A more step-by-step finite differences method (but with more or less elaborate was to assemble to calculate the field overlapped field (Al) along the conductor inside the strand is obtained through a numerical analysis with models representing the superconducting strand (Al) and the subsurface passive encasement and plasma. The parameter involved is the eddy current response of the OCE is represented by, which is typically obtained from AC loss tests on conductor samples as discussed in the companion paper noted above (or from the internal data Io). The second line on the left gives the parametric field used here.

Hysteresis Loss

The most straightforward way to calculate the hysteresis loss consists of integrating the magnetization M as a function of the applied field Be. The inductance loss power is then simply: i(0) = (B0^2) / (2πR), where R is the width of the hysteresis loop from up to down-field branch (the factor is asymptotic). The practical approach chosen is to measure the magnetization loop of a strand exposed to an applied field and use this magnetization loop to calculate the hysteresis loss of a cable where it is assumed that the applied field is the same for all the strands. This is easily done in the magnetization measurement setup where the applied field does not require larger equipment (and for this reason these measurements are less common). Also before for the coupling loss the magnetic field is represented to the internal field Be, which is not the same in the applied field Be because of the shielding effect. For the single strand case its intuitively straightforward to extend to.

AC Loss General Explanation

Coupling Loss:

The coupling losses are the result of induced currents flowing between filaments in the multi-filamentary strands, and between strands within various cable stages as well as between sub-cables. The loss causing coupling currents partially flow inside superconductor, which enhances their time constants and thus their strength as compared to a normal conductor*. Therefore, in pulsed superconducting magnets as in ITER, all means possible to suppress these coupling currents are applied. This includes twisting of the filaments, strands, and sub-cables to cut down on the inductance and increase the contact resistance with resistive coating on the strands (Cr or Ni). Finally stainless steel foil wraps over the sub-cables are also effective. But the effect cannot be suppressed entirely, as it would lead to electrically insulated strands (or filaments), preventing the transfer of currents from saturated strands and can thus lead to degraded cable performance and quench performance.

Hysteresis Loss:

Hysteresis (or “magnetization”) loss is caused by the diamagnetic effect shielding inside the superconductor in which persistent currents are induced to expel the applied magnetic field. the loss causing mechanism is the re-arrangement of screening currents and pinned magnetic field vortices due to a change of applied field. The hysteresis loss depends on the so called “effective” filament diameter and the critical current density in the superconductor. The reduced filament sizes typical for CS type strands (order 10 microns) cannot fully suppress this loss if the filaments are coupled through the Cu matrix (needed for electro-thermal stability of the strands) and thus behave like a larger filament. The critical current density should obviously be high enough to allow a large transport current to limit the superconductor cost. Since the superconductor is designed for the highest field region it can be over-designed for the low field regions in non-graded coil designs (as in ITER) additionally enhancing the hysteresis loss.

Summary

Simple analytical AC loss models are needed for fast turn-around calculations for the large superconducting coils in the ITER device.

Once validated on conductor and coil measurements such models can be used to simulate the AC loss heating inside the superconducting coils for the ITER device during the plasma pulses.

Such models have been presented here for the CS type ITER coils. In these coils the magnetic field transients are always transverse to the conductor, resulting in the simplest possible models.