Frequency domain Diagnosis Methods for Quality Assessment of Nb3Sn coil Insulation systems and impedance measurement

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Background

In recent years, Nb$_3$Sn superconducting cable material became the privileged mature candidate for the High Field magnets in new projects like the CERN High Luminosity LHC (HL-LHC) accelerator.

The technology needs in the years 2017-2022 to be deployed onto LHC accelerator through unprecedented magnet series production with dedicated on-line quality control. The frequency domain diagnosis on recent Dipole short model provides a good characterization of electrical circuit parameters and dielectric properties.

Objectives

- New Capacitance measurement during Nb3Sn coils Vacuum pressure impregnation to provide VPI master curves
- Characterization via dielectric frequency response of the new impregnated insulation magnet systems at the production stage and over operation under radiative environment with integrated dose level up to 30 MGy
- Measurement of the impedance and phase factor over time to derive the distributed equivalent electrical model parameters of the new Nb$_3$Sn magnets as a mean to characterize the resonance effects in future dynamic injection regime.

Experimental method

Quantitative capacitance monitoring measurement of the CTD-101K resin impregnated turn insulation subsystem (667 mH) and manufacture process.

- Thermal pollution and curing schedule includes a soak period at 60 °C, a ramp up at 85 °C and a plateau at 110 °C for 11 hours followed by post curing at 125 °C for 56 hours. [35 NPa overpressure at the end of gel]
- Initial total capacitance Cg value of 91 nF along the 5.5 m long 11T dipole CRO04 model Experimental matching within ±7%.
- Each turn layer series capacitance connected with equivalent dielectric constant limit given by [Wieners] as $\varepsilon_r = 4.5$.
- Turn capacitance estimated at 0.4 nF using $C_{unw} = C_F / (N_{sw} \cdot G^0)$.
- Measured parallel ground capacitances $C_p$ at dry condition across the inner and outer radius layers (fiber glass, polynylide and Teflon) estimated on dipole at 34 nF (ID) and 70 nF (OD), for a total value of 104 nF.
- Observed effective permittivity rate of change from 6 % to 1% per °C during temperature ramp up at about 70 deg C due to the degree of cure increase.
- Different absolute change of permittivity value as a function of temperature depending on coil type assembly attributed rheological and temperature conditions.

11T dipole Vacuum pressure impregnation

- Two layers Nb$_3$Sn Rutherford-type 40 strands cable, winding of 56 turns (2.1 L, 34 DL).
- cable insulation with 52-fiber glass braid (70 μm thick, ASY 5-2X 11 TEE 666) and a Polystyrene (80 μm thick, CORDO FRX®).
- Wind & React Nb3Sn coil manufacture, heated during 200 hours at 650 °C with an insulated cable.
- Vacuum pressure impregnation with anhydride cured diglycidyl ether bisphenol A (DGEBA-A) CTD-101K® epoxy resin system in a stainless steel mold.

Capacitance measurement results

- Each individual measure capacitance monitoring with an equivalent dielectric constant limit given by [Wieners] as $\varepsilon_r = 4.5$.
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Dielectric frequency Response

- Complex dielectric mechanism over time is based on the Davidson-Cole model [5] given relaxation time $\tau$, the variation of $\varepsilon''$ with angular frequency $\omega$ derived from classical Drude theory: $\varepsilon''(\omega) = \varepsilon_0 \varepsilon_r \frac{\omega^2}{(\omega^2 + \omega_0^2)}$, where $\omega$ is the angular frequency and $\omega_0$ the low and high frequency, $\varepsilon''$ is the stage parameter.
- Dielectric frequency response (DFR) measurement is a powerful diagnostic test used in electrical power transformers by $Z'(\omega) = Z''(\omega) = Z'$ (0).
- Installs sample of dimensions 50 x 200 mm TiN tapes plain face 11T DR on 0.125 in thick, 320 glass fiber open 0.1 in thick, Nb$_3$Sn 4% NR (Cable 566, 2022).

Magnet impedance and phase measurement

- Impedance measurement over frequency range 10Hz-20KHz in both closed and open-circuit.
- Second under four-pole electrical lumped model using both PSpice Optimizer package and Matlab Particle Swarms Optimizer PSO genetic code.

Conclusion

- The online capacitance measurement is an essential method to control the resin impregnation process on HLHC Nb$_3$Sn coil. It can potentially be further developed to check curing stage.
- The introduction of Dielectric Frequency Response analysis of Nb3Sn dipole turn insulation samples type provided some useful benchmarked dielectric permissivity and loss factor values. Increased permissivity values by factor 3 due to heat treatment. Those data serve as reference dielectric signature for ageing assessment.
- The frequency impedance measurements in closed and open circuit of the double aperture 11T dipole magnets provide essential data for fitting the electrical circuit equivalent parameters. This information is used to characterize the overall circuit transient behavior during excitation mode of new magnets inserted into the LHC dipoles chain.