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

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Background

- In recent years, Nb_3Sn 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 over frequency** to derive the distributed equivalent electrical model parameters of the new Nb_3Sn magnets as a mean to characterize the resonance effects in future dynamic injection regime.

Conclusion

- The **online capacitance measurement is an essential method** to control the resin impregnation process on HLLHC Nb_3Sn 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 permittivity and loss factor values. **Increased permittivity values by factor 3 due to heat treatment**. Those datas 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.

Capacitance Measurement

11T dipole Vacuum pressure impregnation

- Two layers Nb_3Sn Rutherford-type 40 strands cable, winding of 56 turns (22 IL, 34 OL).
- cable insulation with S2-fiber glass braid (70 µm thick, AGY S-2® 11 TEX 636) and a Phlogopite Mica, (80 µm thick tape, COGEBI FIROX®).
- Wind & React Nb3Sn coil manufacture, heat treated during 200 hours at 650 °C with an insulated cable.
- Vacuum pressure impregnation with anhydride cured diglycidyl ether bisphenol A (DGEB-A) CTD-101K® epoxy resin system in a stainless steel mould.

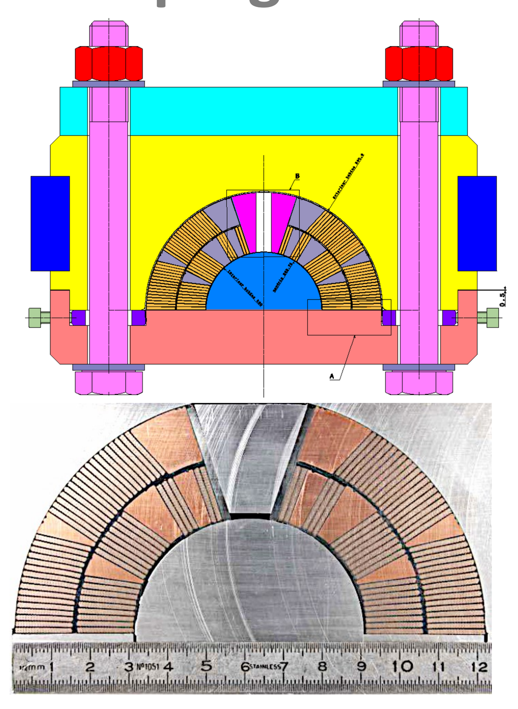


Fig.1 Cut-away views of resin impregnation mould assembly for dipole (a) and winding (b)

Experimental method

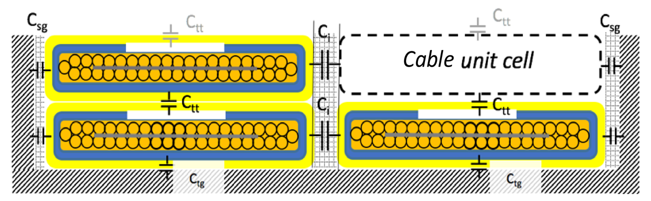


Fig.2 Cable unit cell geometry for capacitance calculation

- Thermal gellification and curing schedule includes a soak period at 60 °C, a ramp up at 85 °C and a plateau at 110 °C for 4 hours followed by post curing at 125 °C for 16 hours. (0.35 MPa overpressure at the end of gel)
- Initial total capacitance Csg value of 91 nF along the 5.5 m long 11T dipole CR004 mould. Experimental matching within +/- 7%.

Quantitative capacitance monitoring measurement of the CTD-101K resin impregnated turn insulation system (Fiber glass , Mica) manufacture process.

TABLE I
DIPOLE COIL GEOMETRY AND INSULATION SYSTEM FEATURES

Items	Value	Units
Coil ID/OD	59.8 / 121.6	mm
Coil overall length	5559	mm
Straight section length	5108	mm
Turn Inner /Outer Layer (IL) /(OL)	22 (IL) / 34 (OL)	
Resin thermoset system	Epoxy DGEBA (CTD 101-K)	
Cable strand :	RRP 0.7 mm dia., 40 strands,	
Turn insulation system	S2glass fiber - Phlogopite Mica	

Results

Capacitance measurement results

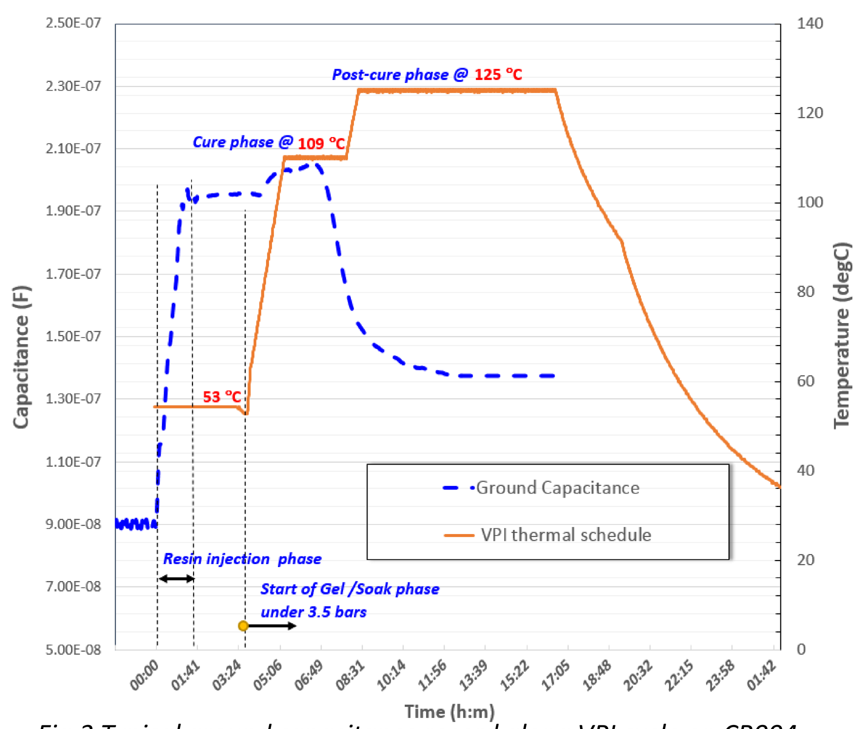


Fig.3 Typical ground capacitance record along VPI cycle on CR004 dipole model

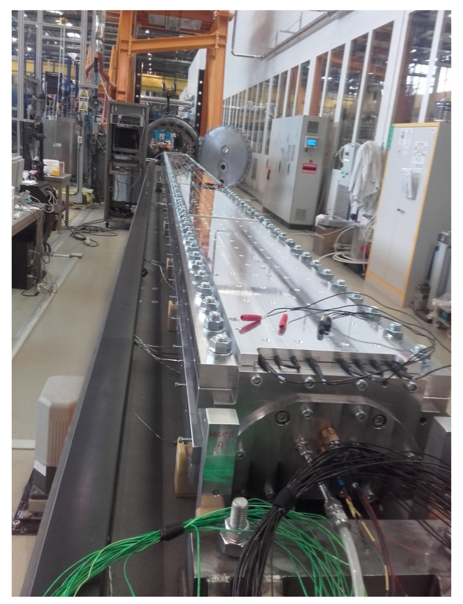


Fig.4 VPI mould assembly of MQXF coil

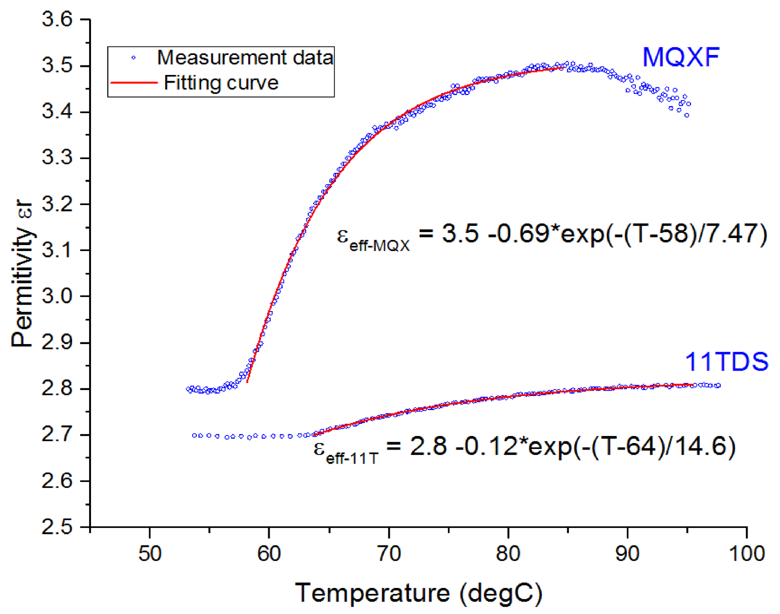


Fig. 5. Effective permittivity fitting as function of temperature during impregnation cycles

The measurement starts just after preheating phases at 100 °C under 10^{-3} mbar pressure when the CTD101K resin thermoset with specified initial maximum viscosity at 100 cPs is injected at 60 °C during few hours. The **on-line recording of the ground capacitance** allows to assess the filling rate and to generate **comparative master curves in the series coil production.**

- Each turn layer series capacitance connected with **equivalent dielectric constant limit** given by [Wiener] as $\varepsilon_{r\_eq} = \frac{1}{\frac{f1}{\varepsilon r1}+\frac{f2}{\varepsilon r2}} = 4.5$.
- **Turn capacitance estimated at 0.4 nF using $C_{tt\_eq} = C_{tt}/(n_1+n_2-1)$,**
- Monitored **parallel ground capacitances C_{sg} at dry condition** across the inner and outer radii layer gaps (fiber glass, polyimide 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 function of temperature** depending on coil type assembly attributed rheological and temperature conditions.

Dieletcric frequency Response

DSR principles

- Complex dielectric mechanism over time is based on the Davidson-Cole model [5] : given relaxation time τ, the variation of ε_r^* with angular frequency ω derived from classical Debye theory :

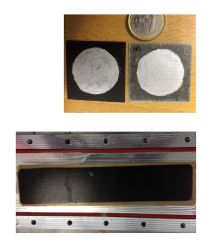
$$(\varepsilon_r^*(\omega)-\varepsilon_\infty)/(\varepsilon_0-\varepsilon_\infty) = 1/(l + j\omega\tau)^n,$$

where ε_0 and ε_∞ are the relative permittivities at low and high frequencies, 0 < n <1 shape parameter.

- ***Dielectric frequency response (DFR)*** measurement is a powerful diagnostic test used in electrical power transformers

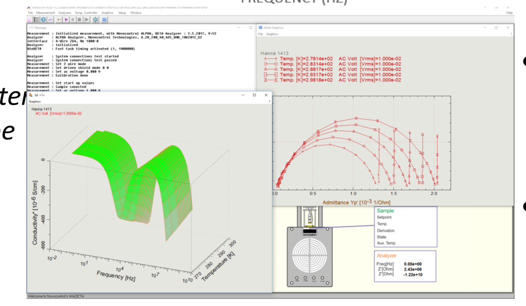
$$\overline{Z}(\omega) = Z'(\omega) + iZ''(\omega) = \frac{\overline{u}(\omega)}{\overline{I}(\omega)}$$

- Insulation samples of dimensions 50 x 220 mm (2 Mica tapes Firox ®120P34A 0.125 mm thick, 2 S2-glass fiber tapes 0.1 mm thick, TEX 33-493 aminosilane sizing) (right)



Dielectric permittivity and loss factor

- *Alpha-A Novocontrol (Germany) spectrometer mounted on a ZGS type testing round cell (above), user interface (right)*



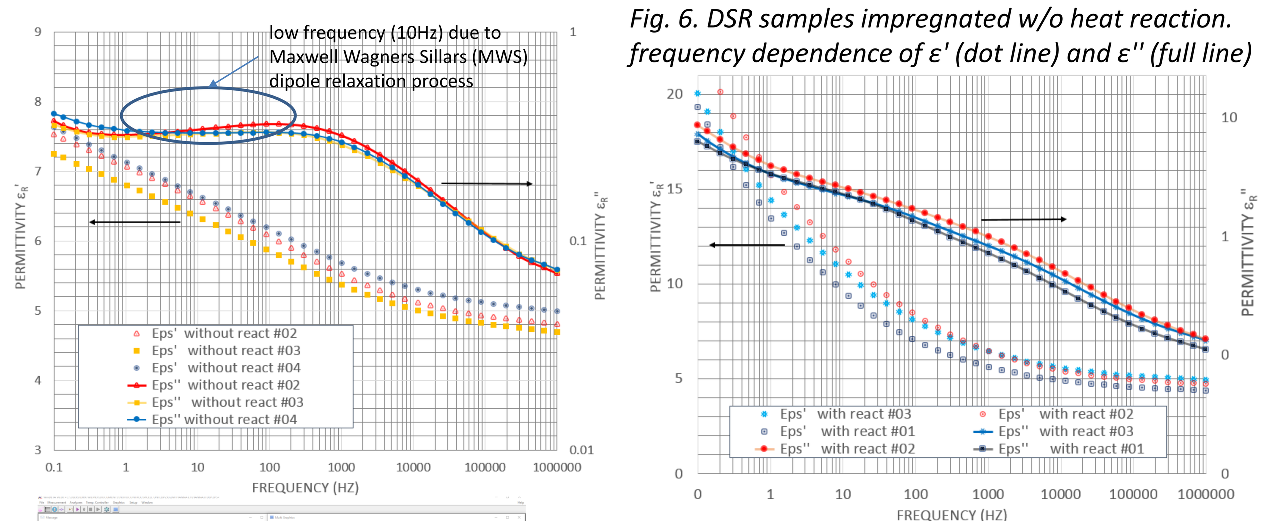


Fig. 6. DSR samples impregnated w/o heat reaction. frequency dependence of ε' (dot line) and ε'' (full line)

- Permittivity of **non-reacted specimen decreases from 7.5 to 5.3** with increasing frequency
- **Low frequency high permittivity on reacted samples in range of 20-25** due to increased conductivity effect, in presence of carbon residual from non oxidized organic compounds

Magnet Impedance and Phase

Spectral impedance measurement & fitting

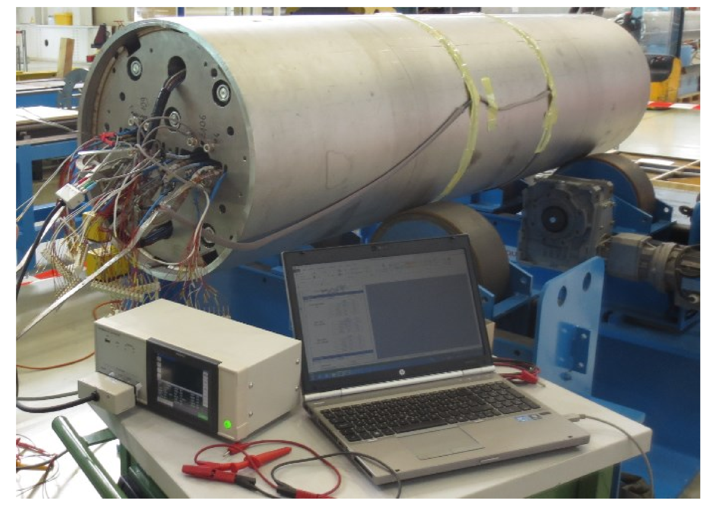


Fig. 7. Spectral analyser connected to 11T dipole 1.9m long short models (DP101, DP102)

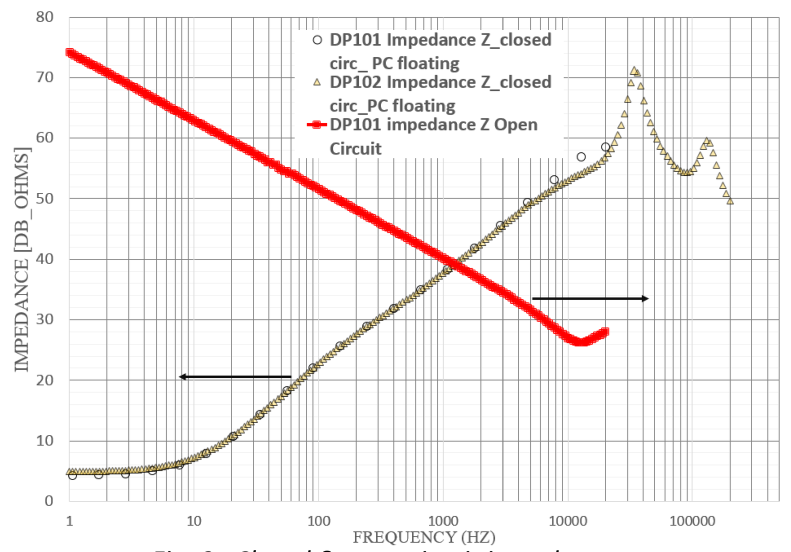


Fig. 9. Closed & open circuit impedance measurement on DP101, 102.

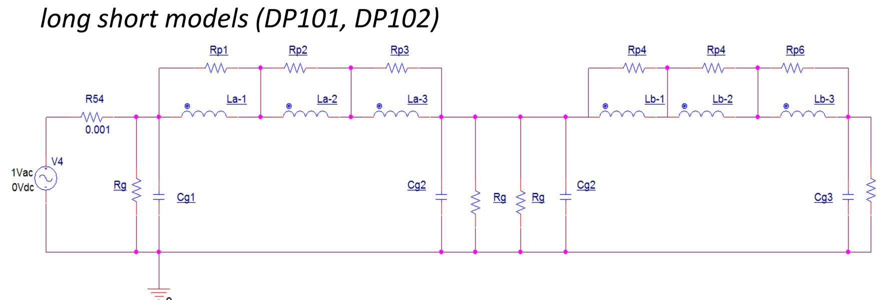


Fig. 8. Open-circuit double aperture dipole equivalent electrical PSPICE Optimiser fit model

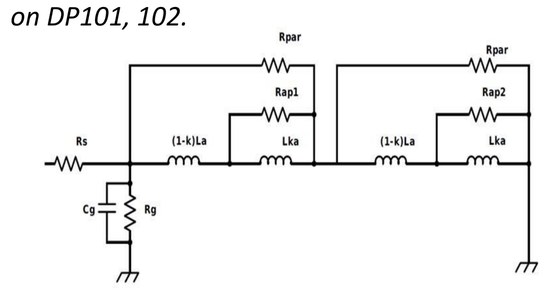


Fig. 10. Closed-circuit double aperture dipole equivalent electrical MATLAB PSO fit model

TABLE I
OPEN CIRCUIT LEAST SQUARE FITTING BY ORCAD PSPICE OPTIMIZER

DP 101 Model	*La-1 (mH)*	*La-2 (mH)*	*La-3 (mH)*	*Rp_1 (Ohms)*	*Rp_2 (Ohms)*	*Rp_3 (Ohms)*
	1.3	2.15	8	4.6	334	130
	Lb-1 (mH)	*Lb-2 (mH)*	*Lb-3 (mH)*	*Rp_4 (Ohms)*	*Rp_5 (Ohms)*	*Rp_6 (Ohms)*
	1.3	2.15	8	0.74	21	34.7
	Cg_1 (nF)	*Cg_2 (nF)*	*Cg_3 (nF)*	*Rg MOhm*	*Fit error on Z (%)*	*Fit error on P (%)*
	5.6	19	5.5	72	0.21	0.98

TABLE II
CLOSED CIRCUIT PSO FITTING PARAMETERS BY MATLAB

	La (mH)	11.2			
	k	0.76			
Models	*Rap_A (Ohms)*	*Rap_B (Ohms)*	*Cg (nF)*	*Rpar-i (Ohms)*	*Rs (Ohms)*
#DP101	1e-5	9.43	4.25	462	0.95
#DP102	295	9.55	2	1281	1.76

- **Impedance and phase measurement over frequency range 1Hz-200 kHz** in both closed and open-circuit.
- **Second order four-pole electrical lumped model** using both **Pspice Optimiser package** and **Matlab Particle Swarm Optimizer PSO** genetic code.
- **Inductance of Short dipole model of 22.4 mH** and model lumped parameters as in Table I.

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