



Research Article

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Detection of inter-turn faults in transformer winding using the capacitor discharge method

<https://doi.org/10.1515/phys-2017-0121>

Received Nov 01, 2017; accepted Nov 12, 2017

Abstract: The paper presents results of an analysis of inter-turn fault effects on the voltage and current waveforms of a capacitor discharge through transformer windings. The research was conducted in the frame of the Facility of Antiproton and Ion Research project which goal is to build a new international accelerator facility that utilizes superconducting magnets. For the sake of electrical quality assurance of the superconducting magnet circuits, a measurement and diagnostic system is currently under development at Gdansk University of Technology (GUT). Appropriate measurements and simulations of the special transformer system were performed to verify the proposed diagnostic method. In order to take into account the nonlinearity and hysteresis of the magnetic yoke, a novel mathematical model of the transformer was developed. A special test bench was constructed to emulate the inter-turn faults within transformer windings.

Keywords: FAIR project, diagnosis, transformer, superconducting magnet, capacitor discharge, surge test, modelling, simulation, measurement

PACS: 06.60.-c, 07.05.Kf, 07.05.Tp

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1 Introduction

The Facility of Antiproton and Ion Research (FAIR) is a new international accelerator facility which is built in Darmstadt, Germany. The Republic of Poland belongs to the group of FAIR partner countries. The physics research program at FAIR will address a broad variety of topics, from fundamental problems to their applications in physics, biology and materials science [1, 2]. The core element of the FAIR facility is the superconducting (SC) synchrotron SIS100. The key components of SIS100 are the SC dipole magnets (DPM) and quadrupole modules (QDM). A single QDM contains two SC quadrupole magnets and a various number of SC corrector magnets. All SC magnets of SIS100 are of super-ferric type. In order to investigate the quality of DPMs and QDMs in terms of electrical integrity, Faculty of Electrical and Control Engineering (GUT) is developing a measurement and diagnostic system for SC magnets of SIS100 [3].

The high demand for the stability of the electrical parameters of SC magnets requires systematic quality control to be implemented at the stages of production, factory acceptance test (FAT), site acceptance test (SAT) – at both ambient & cryogenic conditions, prior to & after the installation in the accelerator tunnel, during machine commissioning and periodically during maintenance off time [4–6].

The measurement system proposed by GUT considers a comprehensive electrical integrity investigation, *i.e.*: high voltage DC test, temperature sensor check, voltage tap check, circuit correctness check and inter-turn insulation check. This paper focuses on the surge test (capacitor discharge) subsystem which enables the investigation issues related to the inter-turn insulation quality. This subsystem is called "HV-Discharge" and it utilizes a non-destructive diagnostic method based on a synchronised voltage & current measurement during a discharge of an external capacitor on a SC magnet coil. Since there are several magnet types at SIS100 that are characterized by an inductance which varies from 0.4 to 140 mH, the system has to be built in such a way that the capacitance and ini-

tial voltage can be adjusted in accordance to the required energy level. On account of the unavailability for testing of the first SC magnets, the study of the inter-turn fault effects was conducted on a special toroidal transformer for which a very accurate mathematical model was developed [7–9]. The model takes into account the nonlinearity and hysteresis of the magnetic yoke. In order to emulate the inter-turn faults in transformer windings, a dedicated test bench was constructed. The detailed study concerning the impact of inter-turn faults on voltage and current waveforms during the capacitor discharge on the transformer winding is presented within this paper.

2 Diagnosis method

It was assumed that the analysis of measurement results of each SC magnet type will be carried out at the time of the delivery to FAIR. This will allow to check the compliance with the reference values. In addition, a characteristic signature for each SC magnet will be created during this procedure. Periodic control measurements will allow to observe changes respect to the SC magnet signature and to compare them with the reference values. Exceeding the threshold values or a significant change in reference to SC magnet signature will be an indication of an electrical fault. This allows to make a decision to either repair or replace the SC magnet.

The initially proposed diagnostic procedure concerns the frequency and the damping factor of both the discharge current and the voltage waveforms [10].

The research to select the appropriate criteria for the analysis of measured waveforms [4–6, 11] is still ongoing. In this paper, a new diagnostic procedure based on the calculation of the energy index of voltage and discharge current waveforms is proposed. In order to verify this method, a special test bench with a toroidal transformer was assembled see Figure 1. This test bench allows to emulate the inter-turn faults in transformer windings. Measurements on this test bench were conducted for system configurations that differ in the number of shorted turns.

The current $i(t)$ and voltage $u(t)$ waveforms during the discharge through the transformer winding are shown in Figure 2.

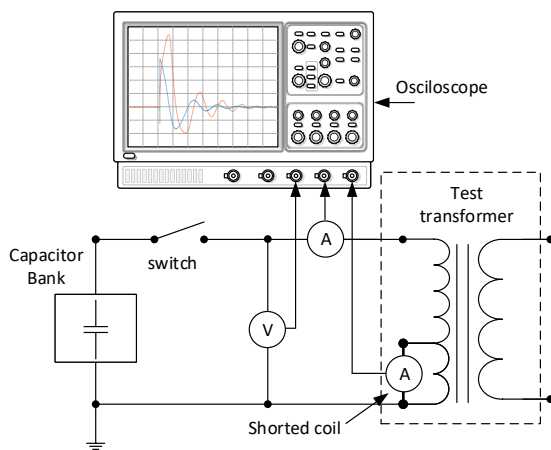


Figure 1: The capacitor discharge test bench with a special toroidal transformer

The measurement method requires a synchronised recording of the voltage and discharge current waveforms.

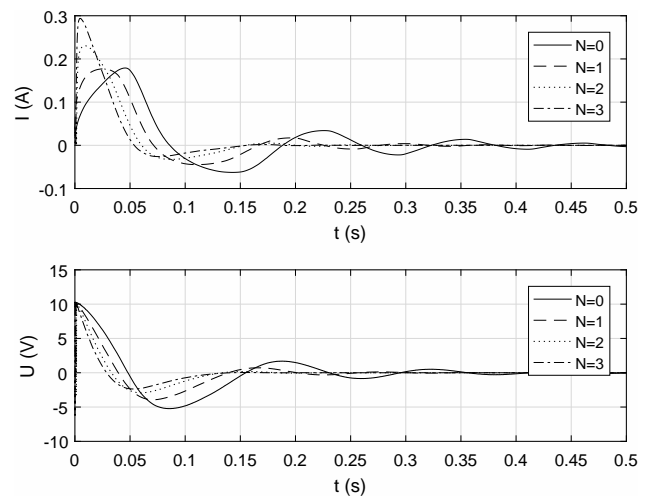


Figure 2: The current $i(t)$ and voltage $u(t)$ waveforms during surge test for various number of shorted turns ($N = 0..3$)

The basis of the diagnostic procedure is the analysis of the absolute power $|p(t)|$ waveform defined by:

$$|p(t)| = |u(t) \cdot i(t)| \tag{1}$$

Figure 3 presents waveforms of $|p(t)|$ calculated from $i(t)$ and $u(t)$ data depicted in Figure 2. It is proposed to utilize the energy index E_a defined by:

$$E_a = 1/T \int_0^T |u(t) \cdot i(t)| dt \tag{2}$$

as an acceptance criterion. The computed E_a -indexes that correspond to the various number of shorted turns ($N = 0..3$) are shown in Figure 3 as well.

The change in the E_a -index unambiguously indicates an electrical fault in a form of a shorted turn of the trans-

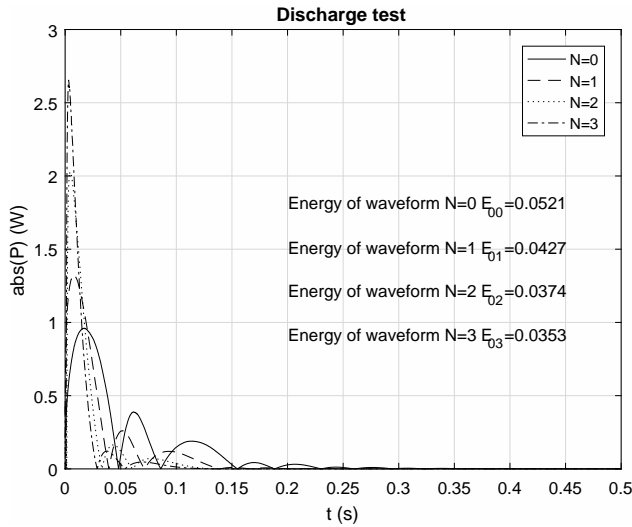


Figure 3: The waveforms of absolute power and the energy index values

former winding. In order to increase the measurement statistics, the calculation of the energy index has been repeated many times for various voltages, for which the capacitor bank was initially charged, and for a different number of shorted turns. Figure 4 shows a comparison of the energy (E) and the energy index (E_a) calculated for the performed measurements. Each bar represents the average value of 10 measurements. Using the energy as an acceptance criterion, an occurrence of a short-circuit cannot be identified. On the other hand, the E_a -index enables to identify the electrical fault.

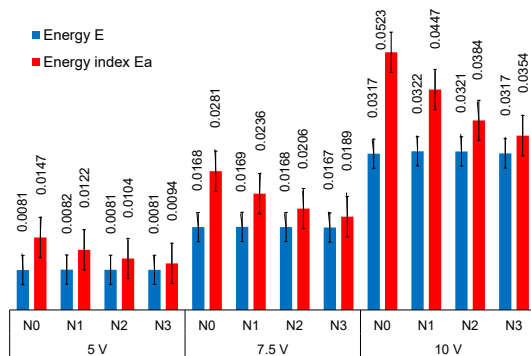


Figure 4: Energy (E) and energy index (E_a) calculated for different numbers of shorted turns ($N = 0..3$) and different values of supply voltage

3 Transformer model

The equivalent circuit model of the considered toroidal transformer connected to the "HV-Discharge" system is presented in Figure 5. The transformer is supplied from a capacitor bank C_0 via feeder resistance R_f and feeder inductance L_f . The transformer incorporates two coupled windings: primary denoted by index "P" and secondary denoted by index "S".

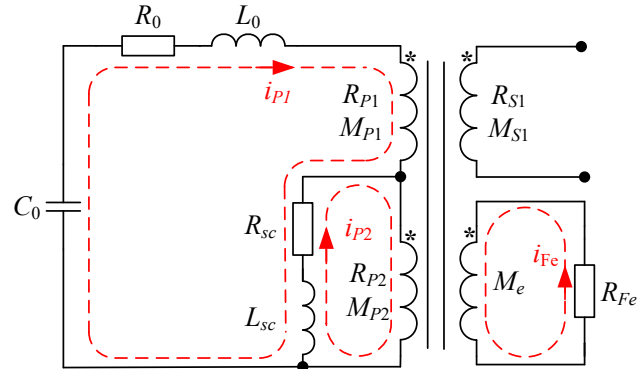


Figure 5: The equivalent circuit model of the transformer system (parameters are described in chapter 3)

The primary winding is divided in two parts: the main part modelled by resistance R_{p1} & inductance M_{p1} and the short-circuited part modelled by resistance R_{p2} & inductance M_{p2} . An electrical fault which short-circuits the turns of the primary winding is modelled as resistance R_{sc} and inductance L_{sc} . The eddy current effects and excess losses in the core are modelled with an additional circuit defined by inductance M_e and resistance R_{fe} . Resistance R_{fe} represents both the classical and anomalous eddy current losses (which may be non-linear) [8].

The Lagrange energy method is proposed to determine the mathematical model of the transformer. The generalized coordinates – loops of currents: i_{p1} , i_{p2} and i_{fe} are proposed in Figure 5. It is assumed that the electrical currents are denoted by: $i = dq/dt = \dot{q}$. The Lagrange function is defined as follows:

$$L(q\dot{p}_1, q\dot{p}_2, q\dot{f}_e, q_{p1}, q_{p2}, q_{f_e}) = \frac{1}{2} L_0 q\dot{p}_1^2 + \int_0^{q\dot{p}_1} \Psi_{P1}(q\dot{p}_1, q\dot{p}_2, q\dot{f}_e) dq\dot{p}_1 + \int_0^{q\dot{p}_2} \Psi_{P2}(q\dot{p}_1, q\dot{p}_2, q\dot{f}_e) dq\dot{p}_2 + \int_0^{q\dot{f}_e} \Psi_{Fe}(q\dot{p}_1, q\dot{p}_2, q\dot{f}_e) dq\dot{f}_e - \frac{1}{2} \frac{q_{p1}}{C_0} + \frac{1}{2} M_{sc} (q\dot{p}_1 - q\dot{p}_2)^2 \quad (3)$$

The Rayleigh dissipation function is defined as:

$$P_e(q_{P1}, q_{P2}, q_{Fe}) = \frac{1}{2}R_0q_{P1}^2 + \frac{1}{2}R_{P1}q_{P1}^2 + \frac{1}{2}R_{P2}q_{P2}^2 + \frac{1}{2}R_{sc}(q_{P1} - q_{P2})^2 + \frac{1}{2}R_{Fe}q_{Fe}^2 \quad (4)$$

The general form of the Euler-Lagrange equation system takes the form of:

$$\begin{aligned} \frac{d}{dt} \left[\frac{\partial L}{\partial \dot{q}_{P1}} \right] - \frac{\partial L}{\partial q_{P1}} + \frac{\partial P_e}{\partial \dot{q}_{P1}} &= 0 \\ \frac{d}{dt} \left[\frac{\partial L}{\partial \dot{q}_{P2}} \right] - \frac{\partial L}{\partial q_{P2}} + \frac{\partial P_e}{\partial \dot{q}_{P2}} &= 0 \\ \frac{d}{dt} \left[\frac{\partial L}{\partial \dot{q}_{Fe}} \right] - \frac{\partial L}{\partial q_{Fe}} + \frac{\partial P_e}{\partial \dot{q}_{Fe}} &= 0 \end{aligned} \quad (5)$$

Merging equations (3)-(5) results in the matrix equation:

$$\begin{aligned} &\begin{bmatrix} L_0 + M_{sc} + \frac{\partial \Psi_{P1}}{\partial q_{P1}} & M_{sc} + \frac{\partial \Psi_{P1}}{\partial q_{P2}} & \frac{\partial \Psi_{P1}}{\partial q_{Fe}} \\ -M_{sc} + \frac{\partial \Psi_{P2}}{\partial q_{P1}} & M_{sc} + \frac{\partial \Psi_{P2}}{\partial q_{P2}} & \frac{\partial \Psi_{P2}}{\partial q_{Fe}} \\ \frac{\partial \Psi_{Fe}}{\partial q_{P1}} & \frac{\partial \Psi_{Fe}}{\partial q_{P2}} & \frac{\partial \Psi_{Fe}}{\partial q_{Fe}} \end{bmatrix} \cdot \begin{bmatrix} \ddot{q}_{P1} \\ \ddot{q}_{P2} \\ \ddot{q}_{Fe} \end{bmatrix} \\ &+ \begin{bmatrix} R_0 + R_{P1} + R_{sc} & -R_{sc} & 0 \\ -R_{sc} & R_{P2} + R_{sc} & 0 \\ 0 & 0 & R_{Fe} \end{bmatrix} \cdot \begin{bmatrix} \dot{q}_{P1} \\ \dot{q}_{P2} \\ \dot{q}_{Fe} \end{bmatrix} \\ &= \begin{bmatrix} -\frac{q_{P1}}{C_0} \\ 0 \\ 0 \end{bmatrix} \end{aligned} \quad (6)$$

For the considered type of magnetic yoke, it is assumed that there is a flux Φ_c which is common to all windings. Thus, the left hand side of (6) can be expressed with (7):

$$\begin{aligned} &\begin{bmatrix} L_0 + M_{sc} + M_{IP1} & M_{sc} & 0 \\ -M_{sc} & M_{sc} + M_{IP2} & 0 \\ 0 & 0 & M_{IFe} \end{bmatrix} \cdot \begin{bmatrix} \ddot{q}_{P1} \\ \ddot{q}_{P2} \\ \ddot{q}_{Fe} \end{bmatrix} \\ &+ \frac{\partial \Phi_c}{\partial \theta} \begin{bmatrix} N_{P1}N_{P1} & N_{P1}N_{P2} & N_{P1}N_{Fe} \\ N_{P2}N_{P1} & N_{P2}N_{P2} & N_{P2}N_{Fe} \\ N_{Fe}N_{P1} & N_{Fe}N_{P2} & N_{Fe}N_{Fe} \end{bmatrix} \cdot \begin{bmatrix} \ddot{q}_{P1} \\ \ddot{q}_{P2} \\ \ddot{q}_{Fe} \end{bmatrix} \\ &+ \begin{bmatrix} R_0 + R_{P1} + R_{sc} & -R_{sc} & 0 \\ -R_{sc} & R_{P2} + R_{sc} & 0 \\ 0 & 0 & R_{Fe} \end{bmatrix} \cdot \begin{bmatrix} \dot{q}_{P1} \\ \dot{q}_{P2} \\ \dot{q}_{Fe} \end{bmatrix} \\ &= \begin{bmatrix} -\frac{q_{P1}}{C_0} \\ 0 \\ 0 \end{bmatrix} \end{aligned} \quad (7)$$

where θ defined by (8) is the total ampere-turns of all coils, N_k is the number of turns of the k -th coil and M_{lk} is the leakage inductance.

$$\theta = N_{P1}q_{P1} + N_{P2}q_{P2} + N_{Fe}q_{Fe} \quad (8)$$

The relation between Φ_c and θ involves the feedback Preisach model of hysteresis presented in [7, 8].

4 Simulation results

The measured $i(t)$ and $u(t)$ waveforms of the capacitor discharge through the transformer winding and corresponding $|p(t)|$ are in accordance with simulations performed with the presented mathematical model of the toroidal transformer, see Figure 6 (case of $U=10$ V and $N=1$).

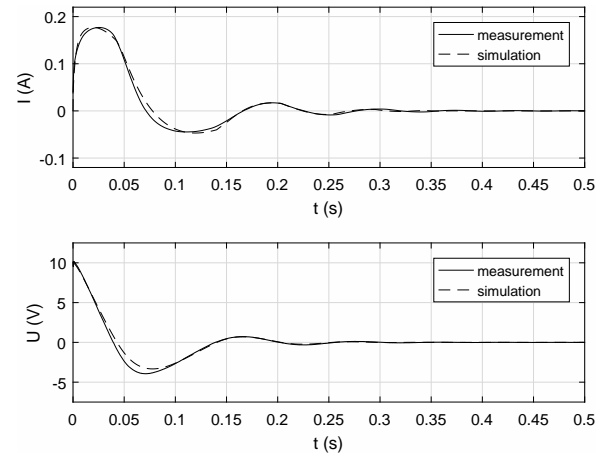


Figure 6: The comparison of current and voltage waveforms of the capacitor discharge through the transformer winding obtained from measurements and simulations for a single shorted turn and $U=10$ V

The waveforms of absolute power and the energy index obtained from simulations in respect to the various number of shorted turns ($N = 0..3$) are shown in Figure 7. The E_a -indexes were calculated with the use of equation (2).

The summary of energy indexes calculated from measurements and simulations in respect to the various number of shorted turns and for $U=10$ V is shown in Table 1.

Table 1: Comparison of energy index calculated from measurements and simulations

Number of shorted turns	Criteria (energy index)		
	Measurement	Simulation	Difference
$N = 0$	0.0521	0.0522	-0.25%
$N = 1$	0.0427	0.0425	0.26%
$N = 2$	0.0374	0.0378	-1.18%
$N = 3$	0.0353	0.0362	-2.61%

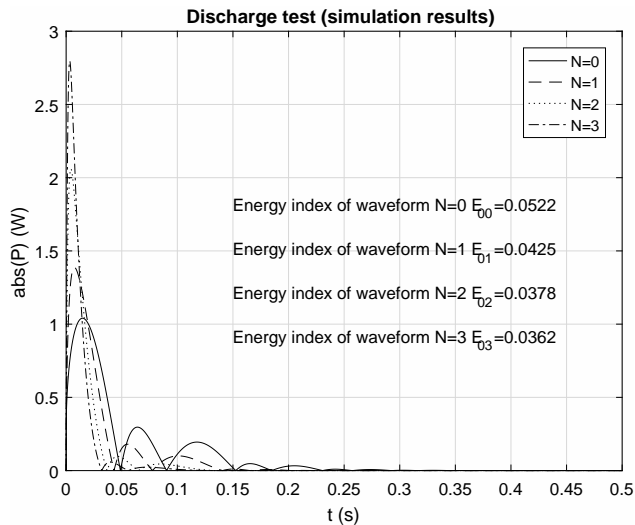


Figure 7: The waveforms of absolute power and the energy index obtained from the capacitor discharge simulation

The uncertainty of the leakage inductance of the short-circuited path (M_{p2}) in the mathematical model is higher when the number of shorted turns increases. Therefore the simulation for $N=3$ is characterized by the highest computation error.

5 Conclusion

The article presents an analysis of voltage and current waveforms measured during a capacitor discharge through a transformer winding while emulating inter-turn faults. The conducted analysis, enhanced with accurate simulations that involve the feedback Preisach model of hysteresis, allowed to select an adequate acceptance criterion for the inter-turn insulation quality of transformer/electromagnet coils. The performed study constitutes the basis for the diagnostic method to be implemented in the surge test subsystem (“HV-Discharge”) which is currently being developed by FECE/GUT in the frame of the FAIR project. At the next stage of research, the presented diagnostic method will be verified and validated by performing measurements on a SC magnet prototype.

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