New method for magnet protection systems based on a direct current derivative sensor

MT25

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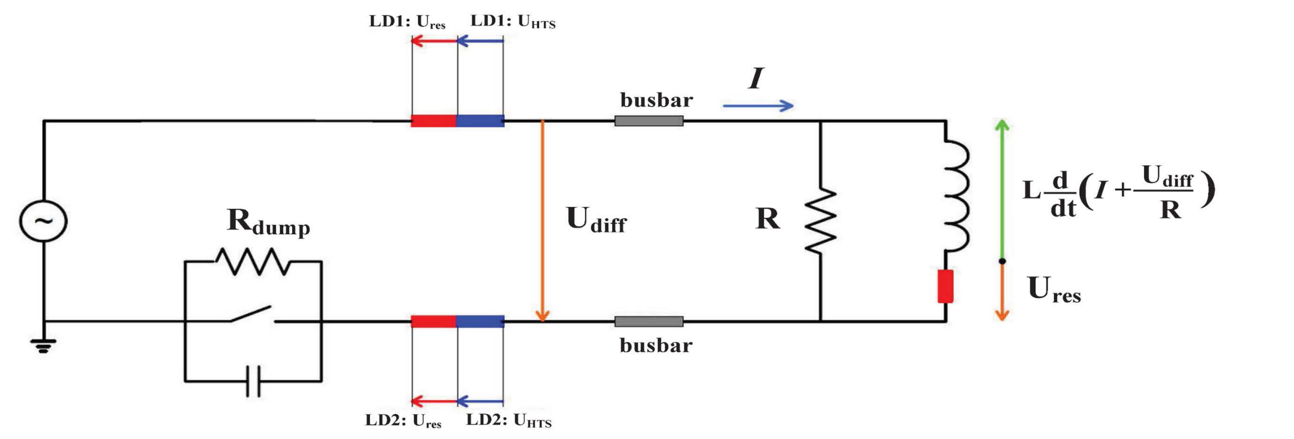
Goal

A new method of the Quench Detection Systems designed for the LHC 600A corrector magnet circuits and 6kA Individual Powered Quadrupole (IPQ) magnet circuits is presented. In order to improve the dependability of QDS a direct measurement of the current derivative is proposed:

- ❖ New sensor for measuring the derivative of the magnet current.
- ❖ 600 A magnet circuit sensor with a fine resolution of 0.05 A/s in the range of ±(0.1 - 10) A/s, and 6 kA magnet circuit sensor with a rough resolution of about 0.5 A/s for the detection of fast ramp rates, ±(50 - 200) A/s. Specifications not covered by any known commercial system.

600 A Corrector Magnet Circuit

The quench detection scheme for the 600 A corrector magnet circuits of the LHC uses the current derivative numerically evaluated from a direct current measurement.



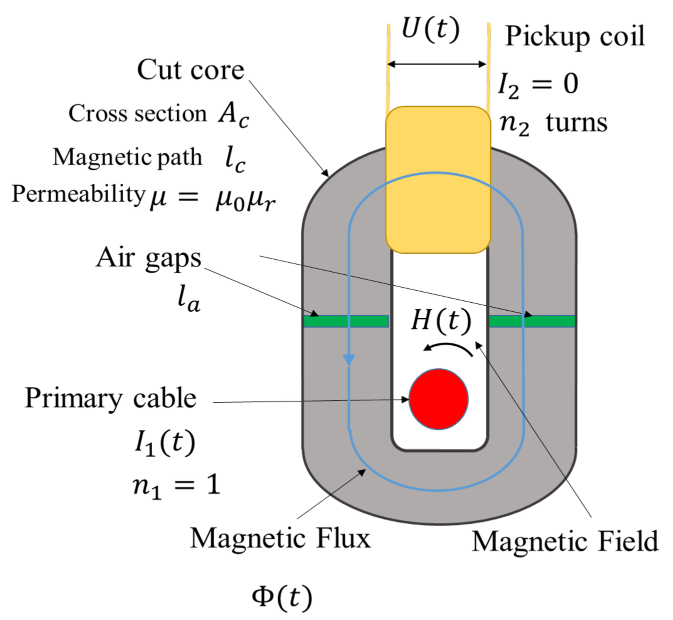
The quench detection system is based on this formula: $\mathbf{U_{res} = U_{diff} + L(I)\frac{d}{dt}\left(I + \frac{U_{diff}}{R}\right)}$

The numerical $\frac{dI}{dt}$ is heavily filtered to make the calculation stable:

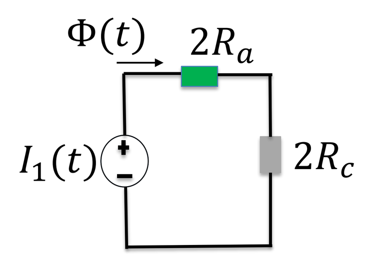
- ❖ Introduces a significant phase shift for high frequency current fluctuations (>> A/s²) restricting the operational range of circuit parameters like the acceleration (A/s²) .

Proposed Method

Direct Current Derivative Sensor



Magnetic circuit model:



Reluctances

$$R_a = \frac{l_a}{\mu_0 A_c} \quad \text{airgap}$$

$$R_c = \frac{l_c}{\mu A_c} \quad \text{core}$$

Ampere's law:

$$F = H(t)l = \frac{l\Phi}{\mu A_c} = R\Phi = I_1(t)$$

$$F_c + F_a = \Phi(t)(2R_c + 2R_a) = I_1\,(t)$$

Faraday's law:

$$U(t) = n_2\frac{d\Phi(t)}{dt}$$

Magnetic circuit solution:

$$\Phi(t) = \frac{I_1\,(t)}{(2R_c + 2R_a)}$$

Transformer-based technology:

- ❖ Easy performance optimization using a cut-core configuration.
- ❖ Non invasive installation.
- ❖ Reliability improved for the passive nature of the sensor.

Final model:

$$\boldsymbol{U(t) = \frac{\mu A_c n_2}{2(l_c + \mu_r l_a)}\frac{dI_1(t)}{dt}}$$

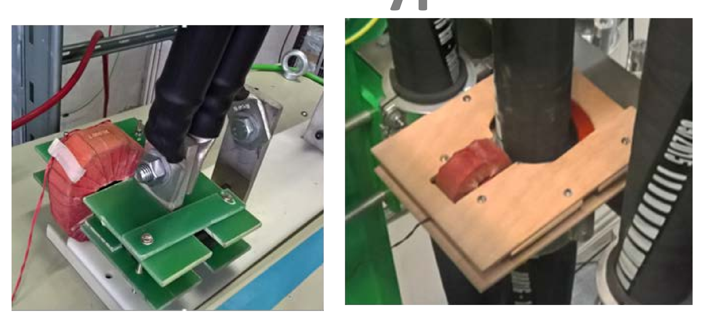
Increasing the airgap decreases the effect of the core magnetization and increase the saturation current but lowers the sensitivity.

Saturation current:

$$\boldsymbol{I_{sat} = \frac{B_{sat}A_c}{n_1}(R_c + R_a)}$$

The saturation current establishes the range of the sensor.

Prototypes



(A) (B)

- ❖ Cut-core transformers.
- ❖ Two core materials: electrical steel (μ_r=4000) and nanocristalline Vitroperm® 500 (μ_r=50000).
- ❖ Airgap and pickup coil windings are the two tuning parameters of the sensor.
- ❖ Assembly of the sensor is a sandwich-like system.
- ❖ Proof of principle prototypes: (A) 600 A and (B) 6 kA magnet sensor prototype.

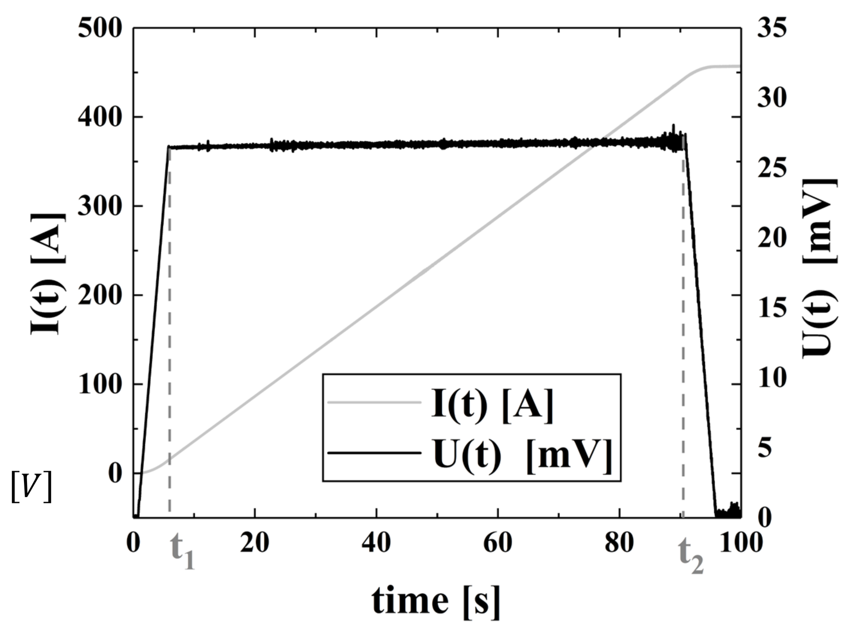
Performance Definitions

The mean sensitivity is the measurement of the sensor response to the current variation, defined as:

$$S_{mean} = \frac{U_{mean}}{\frac{dI}{dt}}\left[\frac{V}{\frac{A}{s}}\right] \quad \text{with} \quad U_{mean} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} U(t)dt \quad [V]$$

The Performance Quality Factor (PQF) is defined as:

$$PQF = \frac{\sigma}{U_{mean}} * 100[\%] \quad \text{with} \quad \sigma_{(t_1,t_2)} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(U_i - U_{mean})^2} \quad [V]$$

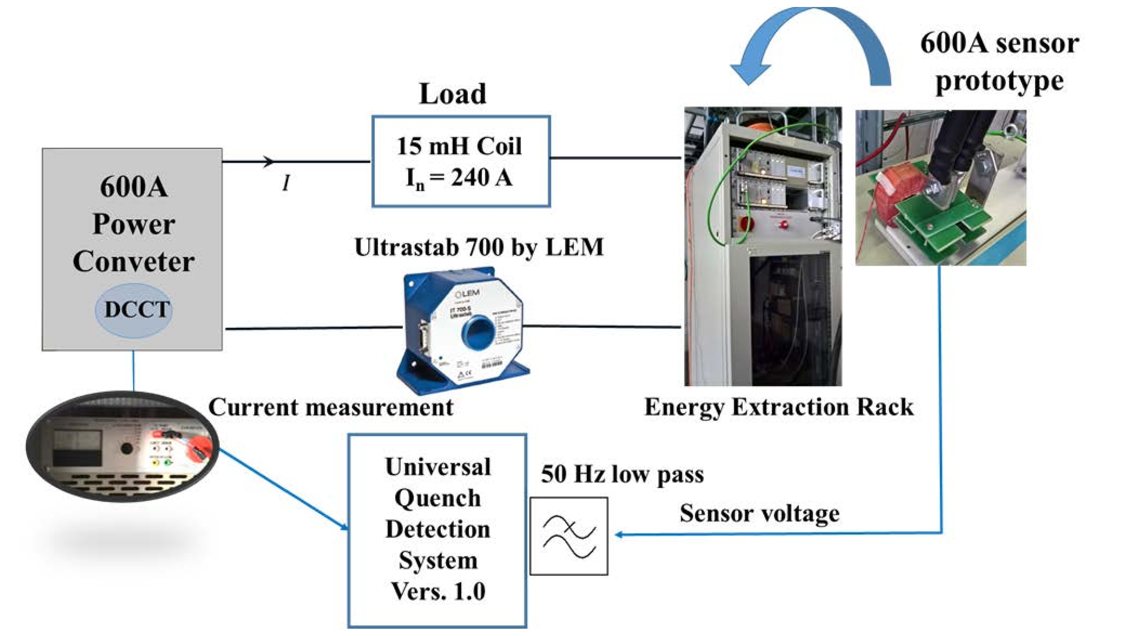


where the standard deviation σ considers the core magnetization and the noise effect.

Feasibility Tests

Identification of the core material sensor:

- ❖ Nanocristalline material (Vitroperm®, μ_r=50000) has shown the best performance (PQF < 0.5%) with respect to the laminated electrical steel (μ_r=4000, PQF of about 2.0%) on the same operational range (0.1 – 5) A/s.
- ❖ An optimization procedure was established for identifying the best configuration of the sensor (airgap and pickup coil windings, vs sensitivity and PQF).



CHARACTERIZATION TESTS FOR DIFFERENT MAGNET WORKING POINTS (A/s, A/s^2) OF THE 600 A DIDT INTEGRATED SENSOR(FIG.5) WITH AN AIR-GAP OF 1.5 mm AND A SATURATION CURRENT OF I_{sat} = 1.5 kA.

Ramp rate A/s	Acc. A/s²	Range A – A	PQF %	σ mV	S_{mean} mV/A/s
5.0	1.0	0 – 200	0.15	0.05	5.02
3.0	1.0	0 – 200	0.40	0.05	5.02
1.5	0.1	0 – 200	0.55	0.04	5.02
0.3	0.1	0 – 200	0.92	0.02	5.02

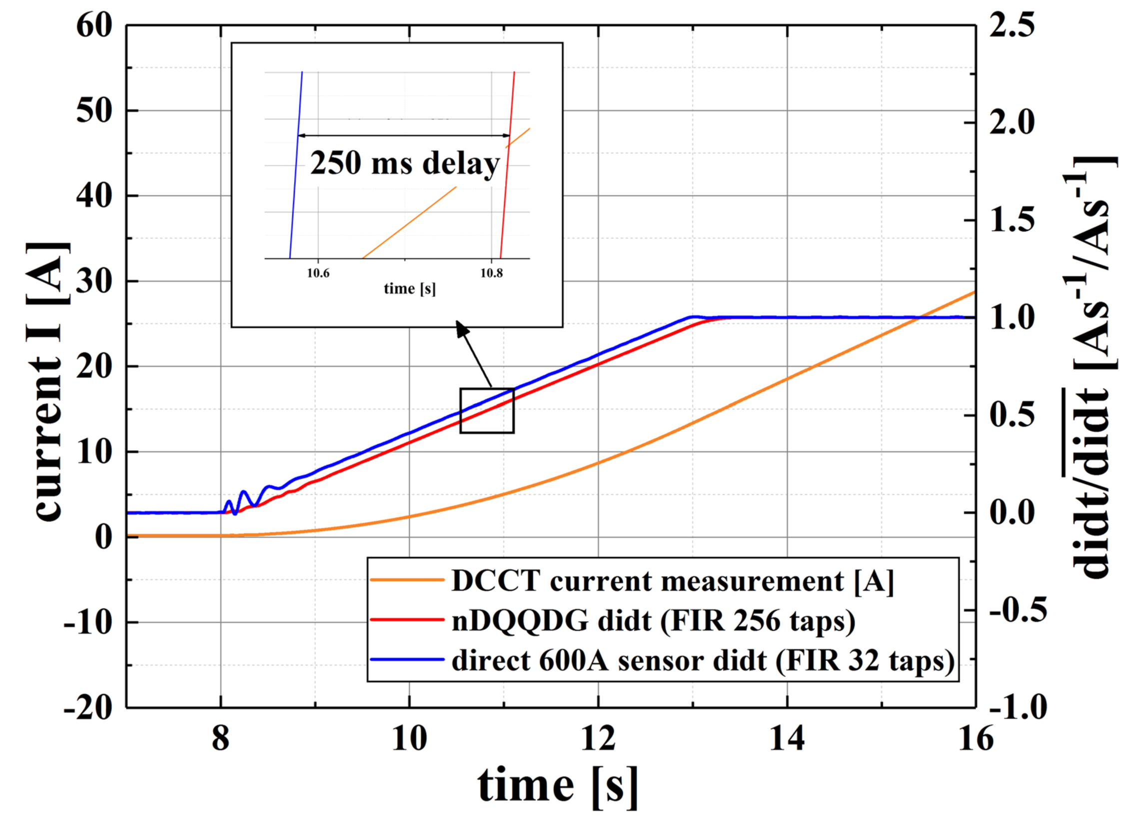
Characterization tests of the 600 A current derivative sensor (Table on the left) integrated on the top of the energy extraction rack (Figure on top):

- ❖ PQF < 0.5% for the majority of the ramp rates (1.5 - 5) A/s and accelerations (0.1 - 1) A/s² and a PQF < 1% for 0.3 A/s and 0.1 A/s².
- ❖ The fine resolution shown from the sensor is less than the specs (<0.05 A/s for a PQF < 1%).

For the 6 kA sensor prototype the characterization campaign up to 200 A verifies the performance with the model prediction (Table below).

CHARACTERIZATION TESTS FOR DIFFERENT MAGNET WORKING POINTS (A/s, A/s^2) OF THE 6 kA DIDT INTEGRATED SENSOR(FIG.3(B)) WITH AN AIR-GAP OF 3.0 mm AND A SATURATION CURRENT I_{sat} = 2.8 kA.

Ramp rate A/s	Acc. A/s²	Range A – A	U_{meas} mV	U_{mod} mV	S_{mean} mV/A/s
5.0	1.0	0 – 200	6.18	6.00	1.28
3.0	1.0	0 – 200	3.84	3.60	1.28
1.5	0.1	0 – 200	1.93	1.80	1.28



The comparison of the 600 A sensor prototype didt and the numerical didt of the nDQQDG detection system used for the LHC operational circuit shows as the proposed sensor does not present any phase shift during the current acceleration(Graph on the left).

Conclusion

- ❖ A new method for the quench detection in superconducting magnets based on a novel direct current derivative sensor.
- ❖ Possible application to the quench detection system for 600 A corrector magnets and the 6 kA IPQ magnets circuits of the LHC.
- ❖ The tests of several prototype devices confirmed the validity of the selected technology and its potential to improve the performance of the present generation of quench detection systems used in the LHC.
- ❖ Preliminary tests with the 6 kA sensor prototype (B) demonstrate the feasibility of the approach to the IPQ magnets but must be verified by tests with real magnets.
- ❖ Future activities: (1) improving the electromagnetic shielding of the sensors in order to decrease the noise effect and (2) realizing field tests with both prototypes (600 A and 6 kA magnet sensors).

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