NOVEL PROTECTION SYSTEMS FOR ARC FURNACE TRANSFORMERS

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INTRODUCTION

In steel facilities that use Electric Arc Furnaces (EAFs) to manufacture steel from scrap, the furnace transformer is one of the most critical pieces of electric power equipment in the plant. Failures in the furnace transformer or its buswork interrupt production and require costly and time-consuming repairs. Traditional overcurrent protection is often applied at the circuit breaker that supplies the cable serving the furnace transformer. This protection is normally set to reach into the furnace transformer primary winding for faults in the winding but may not have sufficient sensitivity to reach through the transformer into the secondary winding or into the secondary leads. Faults that occur in the secondary bus work, water cooled leads, or in the conducting arms above the furnace are not detected by the upstream overcurrent protection and are normally interrupted only after personnel manually open the circuit breaker. The damage due to the extended fault duration can result in long or costly outages.

Differential protection schemes are not typically applied on EAF transformers due to the difficulty in providing current transformers (CTs) of sufficient rating for the secondary leads carrying currents of 60 kA or more. Some modern EAF transformers are rated to deliver a steady state secondary current of 80 kA. In some cases, a CT is built into the transformer that monitors the current in only one secondary winding. This current signal might be used for metering or regulator control purposes, and the magnitude is calculated externally with a scale factor assuming the current in each winding is the same. The accuracy of this technique is not sufficient for a reliable differential protection system.

New protection concepts presented in this paper make EAF transformer differential protection schemes possible.

TRADITIONAL PROTECTION SCHEMES

Traditional power transformer differential protection is shown in Figure 1. This scheme requires careful engineering to overcome some of the inherent issues that result in less sensitivity in the protection system. CT saturation problems require sloped restraint characteristics that de-sensitize the relay scheme for true faults in the zone of protection. These schemes have not been applied on EAF transformers due to the lack of commercially available current transformers for the secondary leads and CT saturation problems due to the high current magnitudes.

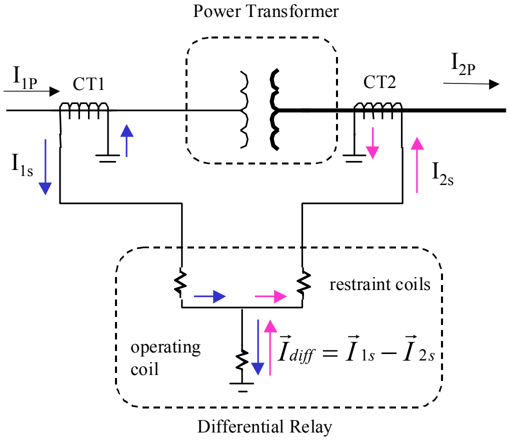


Figure 1. Traditional Power Transformer Differential Protection Scheme

PCB ROGOWSKI COILS

Rogowski coils (RCs) consist of a wire wound on a non-magnetic core. The coil is placed around the conductors whose currents are to be measured. Strict design criteria must be followed to obtain a coil immune from nearby conductors and independent of conductor location inside the coil loop. To prevent influence of nearby conductors carrying high currents, RCs must be designed with two-wire loops connected in electrically opposite directions. This cancels all electro-magnetic fields coming from outside the coil loop. One or both loops can consist of wound wire. If only one loop is made of wire wound on a non-magnetic core, then the other loop can be formed by returning the wire through the center of the winding. If both loops have wound wire, then the second winding must be wound in the opposite direction. In this way, the voltage induced in the RC from the inside conductor will be doubled.

The RC output voltage is proportional to the rate of change of measured current. To obtain measured current, coil output voltages must be integrated. The traditional method of coil construction uses flexible cores such as coaxial cables or straight rods to obtain higher measurement accuracy [1-3].

Patent [2] describes a RC consisting of two wound coils implemented on a pair of printed circuit boards (PCBs) located next to each other (Figure 2). For measurements of residual currents to embrace all three-phase conductors or to embrace parallel conductors carrying the same phase currents, PCB Rogowski coils have been designed in an oval shape [1, 2].

The considered PCB Rogowski coil design has the following characteristics: measurement accuracy reaching 0.1 %; wide measurement range (the same coil can measure currents from 1 to over 100,000 amps); linear frequency response up to 700 kHz; unlimited short-circuit withstand resulted from the window-type design; galvanic isolation from the primary conductors (like current transformers); possible encapsulation and location around bushings or cables, avoiding the need for high insulation.

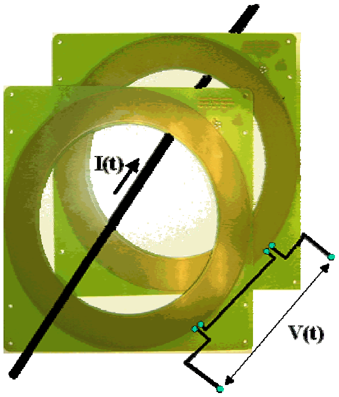


Figure 2. PCB Rogowski Coil

The RC output voltage is in the milli-volt to several-volt range and can reliably drive digital devices designed to accept low power signals. Integration of the signals can be performed in the relay itself (by using analog circuitry or digital signal processing techniques) or immediately at the coil. Connections to relays can be by wires or through fiber-optical cables.

New current and voltage sensors and intelligent electronic devices (IEDs) make possible high-level integration of protection, control, and metering systems in substations. Technical committees worldwide are actively working on standardizing low power current and voltage sensor output levels as well as interfaces between sensors, relays, and IEDs. For example, IEEE C37.92 "*Standard for Low Energy Analog Signal Inputs to Protective Relays"* standardizes analog interface links; IEC 61850-9-1 "*Specific Communication Service Mapping: Sampled analog values over serial unidirectional multidrop point to point link"* and IEC 61850-9-2 *"Sampled analog values over ISO 8802-3*" standardize communication methods of digitized sampled values over an Ethernet network specified by the IEEE 802.3 group of standards. The goal is to obtain interoperability between IEDs and sensors of different technologies and suppliers.

The PCB Rogowski coil designs considered in this paper meet the new standard and protection system requirements.

EAF TRANSFORMER PROTECTION

PCB Rogowski coils and multifunction relays can provide reliable EAF transformer protection. To protect only the EAF transformer, two sets of RCs are needed. To protect the EAF transformer and the secondary leads, three sets are needed. Figure 3 shows a single-line diagram of the differential scheme employing three sets of RCs and one multifunction relay. RCs can be designed as split-core style for installation without the need to disconnect a primary or secondary conductor.

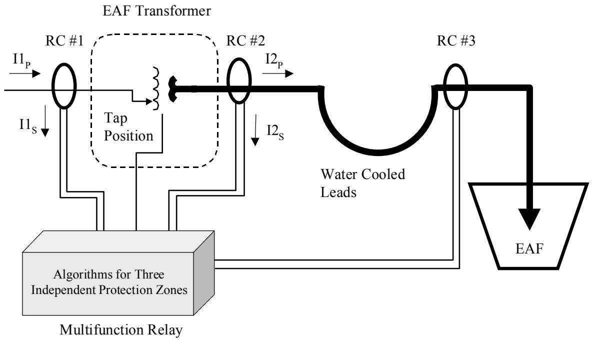


Figure 3. Protection of Arc Furnace Transformers and Secondary Leads

An external signal can be supplied to the relay to indicate the operating tap of the transformer. With suitable delays, the relay can be programmed to ride through an on-load tap change when the current mismatch will change with fixed ratio sensors. The ability of the scheme to adjust to actual transformer operating conditions reduces the main sources of error that force higher percentage differential settings in conventional schemes. The tap position can be supplied to the relay in analog or digital formats.

The concept shown in Figure 3 provides three protection zones. Zone 1 covers all electrical equipment between RC1 and RC2, Zone 2 covers all electrical equipment between RC2 and RC3, and Zone 3 covers all electrical equipment between RC1 and RC3. The multifunction relay employs three different and independent algorithms for each zone, providing independent protection of the arc furnace transformer, secondary leads, and combined transformer with secondary leads. For Zone 2 sensing faults in the secondary leads, there is no need for transformer tap position information, which simplifies the protection algorithm and allows the relay to be set more sensitively.

Figures 4 and 5 show installations of RCs and the RC designs. RC1 set can be located in the switchgear close to the primary circuit breaker, protecting also the entire cable between the circuit breakers and EAF by Zones 1 and 3.

It is very common for EAF transformers that, due to dust, faults occur outside the transformer, between secondary terminals X1 through X6 (Figure 4). These types of faults conventional overcurrent protection cannot detect since fault current levels are equal to the rated current, causing high damage to the transformer. However, the presented protection system will also protect these types of faults by Zones 1 and 3.

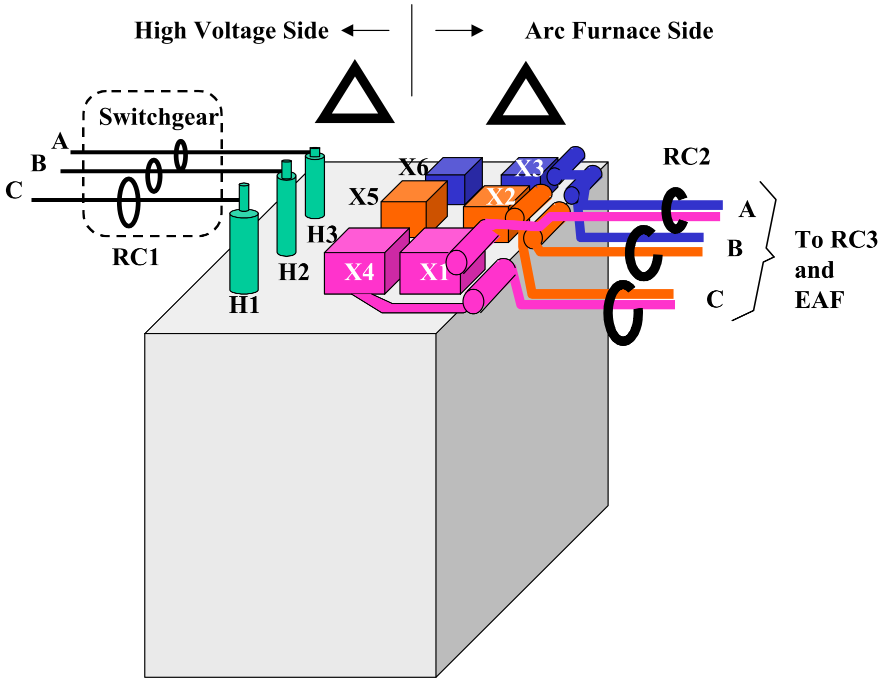


Figure 4. Rogowski Coil Installations on the EAF Transformer Primary and Secondary Sides

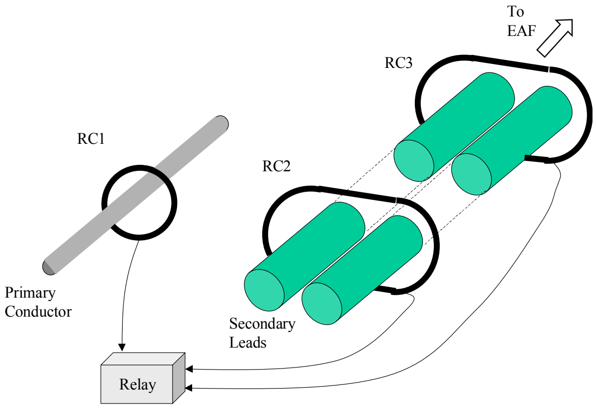


Figure 5. PCB Coil Designs for EAF Transformer Protection

Test Results

To determine accuracy and sensitivity, five RCs were tested in the Cooper Power System's (CPS) high power laboratory under actual conditions. The test setup is shown in Figure 6. To test the extreme application conditions, no shielding was applied to RCs and no integration or signal conditioning of RC output signals were performed. Secondary current, representing an arc furnace load current, was 60 kA, while the primary test current was approximately 2.5 kA. Fault current was initiated by switch SW. The results were compared to the laboratory current sensors (current transformers CT1, CT2, and a shunt that was used to measure 60 kA current). RC1 and RC2 measured primary and secondary transformer currents. RC3 measured the fault current. RC4 and RC5 were located 4 inches from the primary and secondary conductors to measure the influence of the nearby conductors. Their output signal was amplified 100 times to obtain visible waveform on the recording.

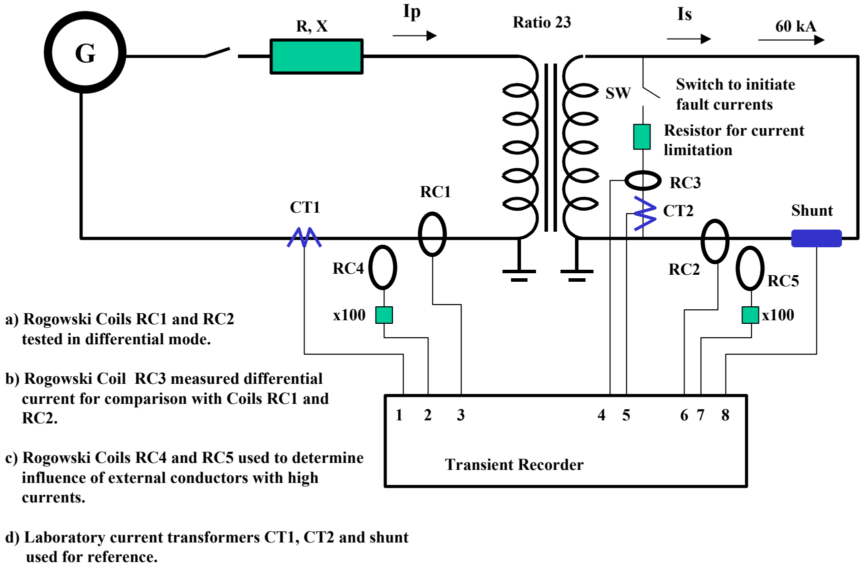
Figures 7, 8, 9 and 10 show results with a fault current of approximately 10% load current. Figure 7 shows waveforms from all tested current sensors. The results show the favorable comparison of the RC1 (integrated signal) with CT1, RC2 with the shunt, and RC3 with CT2. The results also confirmed that the influence of nearby conductors on the RC4 and RC5 was very small, bellow 0.2%.

Figure 8 shows overlapped RC1 scaled by the transformer ratio and RC2 output non-integrated waveforms. Transient recorder channel to which RC1 was connected experienced some noise, which is visible even before the test started. However, this did not impact the results. The difference between magnitudes of the primary and secondary signals is noticeable when the fault was initiated.

Figures 9 shows calculated RMS values for both non-integrated waveforms. The magnitudes between the primary and secondary signals are almost identical during normal operation. The difference in the magnitudes between the primary and secondary signals when the fault was initiated is clearly visible.

The differential current, shown in Figure 10, was obtained by digital subtraction of the primary and secondary currents. The small differential signal that exists before the test started is due to the noise in the transient recorder channel. When the test started, differential signal was almost zero during the normal operation as expected since both RC1 and RC2 output signals are equal. When the fault was initiated, differential signal increased, in this case to 0.7 V, initiating relay operation.

The presented test results correspond to fault currents of 10% rated current. However, the tests were also performed at lower fault currents, and the results confirmed that the proposed scheme reliably operates for faults of 5% rated current. Greater sensitivity is likely to achieve, but requires further investigation.



a) Rogowski Coils RC1 and RC2 tested in differential mode.

b) Rogowski Coil RC3 measured differential current for comparison with Coils RC1 and RC2.

c) Rogowski Coils RC4 and RC5 used to determine influence of external conductors with high currents.

d) Laboratory current transformers CT1, CT2 and shunt used for reference.

Figure 6. Test Setup for Rogowski Coil Testing in the Cooper's High Power Laboratory

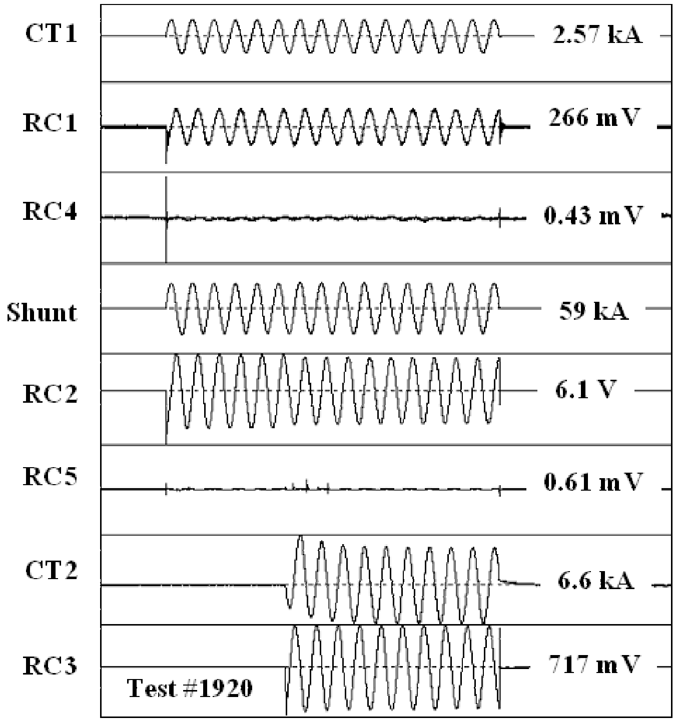


Figure 7. Rogowski Coil Test Results: Fault current 10% of Load Current

In conclusion, the PBC Rogowski coils are linear, accurate, reject well the influence of external electromagnetic field, and yield a strong differential signal providing reliable relaying.

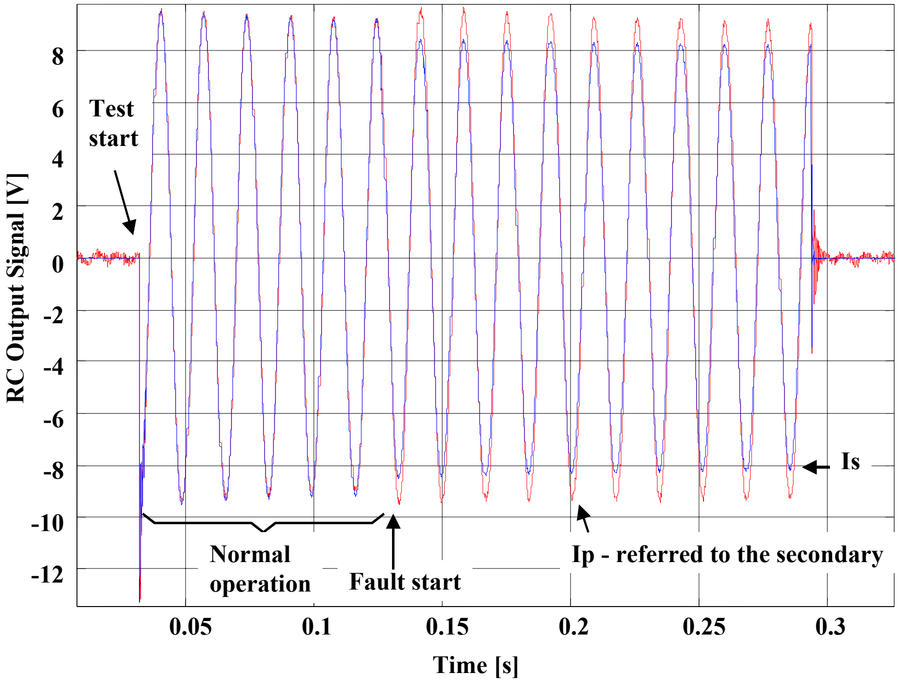


Figure 8. Rogowski Coil Test Results: Primary and Secondary Currents, Fault Current 10% of Load Current

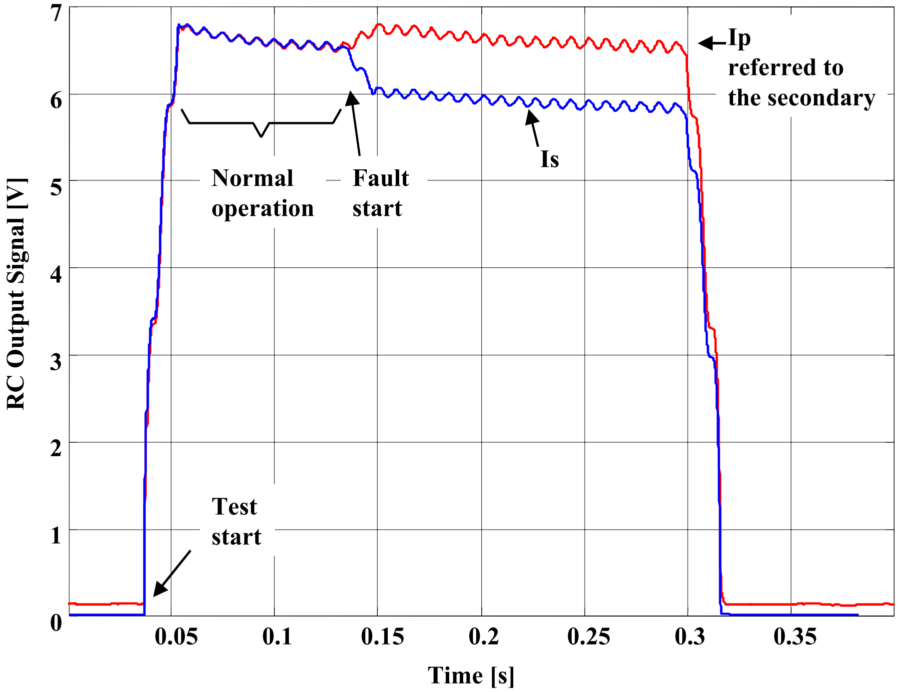


Figure 9. Rogowski Coil Test Results: RMS Values of the Primary and Secondary Currents, Fault Current 10% of Load Current

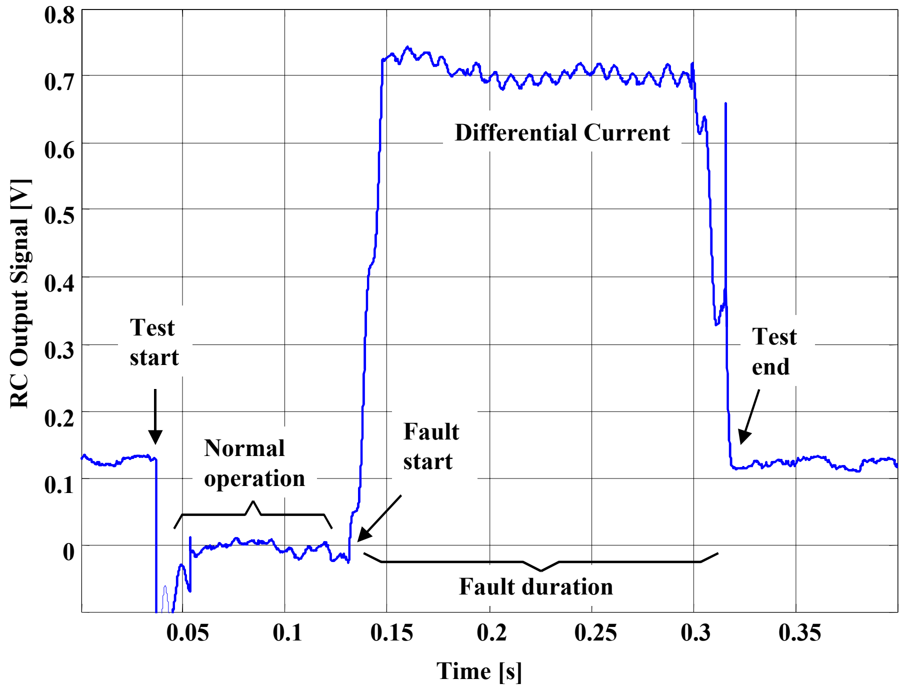


Figure 10. Rogowski Coil Test Results: Calculated Differential Current, Fault Current 10% of Load Current

CONCLUSIONS

The PCB Rogowski coils presented in this paper make EAF transformer differential protection schemes possible.

To determine accuracy and sensitivity, RCs were tested in a high power laboratory. To test the extreme application conditions, no shielding was applied to RCs and no integration or signal conditioning of RC output signals were performed.

Secondary current, representing an arc furnace load current, was 60 kA, while the primary test current was approximately 2.5 kA. This paper presented test results for fault current of 10% rated current. However, the test results also proved that the proposed scheme reliably operates for faults of 5% rated current and even smaller.

Impact of nearby conductors carrying high currents on the RCs was also tested. The results show very small influence, bellow 0.2%.

PCB Rogowski coils are linear, accurate, very well reject influence of external electro-magnetic field, and yield a strong differential signal providing reliable relaying.

REFERENCES

[1] Lj. A. Kojovic, ”PCB Rogowski Coils Benefit Relay Protection”, Computer Application in Power, IEEE Magazine, July 2002.

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[3] Lj. A. Kojovic, ”Rogowski Coils Suit Relay Protection and Measurement”, Computer Application in Power, IEEE Magazine, July 1997.