Electric Power Systems Research 119 (2015) 447–461

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Partial discharge diagnostic system for smart distribution networks using directionally calibrated induction sensors

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ARTICLE INFO

Article history:
Received 7 December 2013
Received in revised form 17 July 2014
Accepted 28 October 2014
Available online 17 November 2014

Keywords:
Distribution network
Substation
Partial discharge
Diagnostics
Rogowski coil
Direction of arrival

ABSTRACT

Asset management and optimization is becoming increasingly adaptable for distribution utilities with the help of developments in the digital and wireless technology. Medium voltage cables, cable accessories (joints and terminations) and distribution transformers are most prone to the insulation defects. This paper presents an online partial discharge (PD) diagnostic system to detect and locate the weak insulation spots developed in the network components spread over the distribution area. The PD pulses originating and propagating from the defect site arrive at feeder joints, terminals and T-splices and are reflected from there. This makes the interpretation of the measured signals ambiguous in order to find the location of PD faults, while using conventional location techniques. An improved technique is introduced to monitor multi-section multi-branched cable network. Identification of the faulty location is carried out by using direction of arrival (DOA) of PD signals. The DOA of PD signals is obtained by using directionally calibrated Rogowski coil induction sensors. Polarity of captured PD signals with reference to supply voltage, determines their DOA. Rogowski coil along with its directional sensing feature is simulated in ATP-EMTP. The DOA technique is integrated over a medium voltage (MV) cable network and its performance is evaluated using ATP-EMTP environment. Frequency-dependent JMarti cable model is used for simulation. An intelligent algorithm is proposed for practical implementation of DOA technique for PD monitoring and automated location. Proposed scheme can be adopted in distribution automation system to improve proactive diagnostic capabilities of the network.

1. Introduction

Distribution system consists of different types of lines carrying electric power from medium voltage (MV) substation to the consumers via distribution transformers. These lines are underground cables, overhead covered conductor (CC) and bare wire conductors. The network components (transformers and lines) are always exposed to various types of related operational and environmental stresses [1,2] leading to different type of faults. During a survey of Stockholm, out of 1392 of total failures, 263 were due to power transformers, cables caused 435 failures while overhead lines were responsible for 20 failures [3]. Similarly busbar, disconnector and circuit breakers were the source of several hundred reported faults. Insulation damage is one of the major causes of failures in these components.

Power components in a distribution network around the respective substations lie in wide geographical region. In large substations voltage is transformed down to MV level (1–36 kV) and a number of feeders (typically 10–30) are connected to the busbar leaving the substation to distribute the power to customers [4]. An outgoing feeder of substation toward low voltage (LV) transformers or bulk customers, is usually not a single cable, but divided into a number of sections (few hundred meters) and branches of cables that interconnected by ring main units (RMUs). These cables contain number of joints, terminations, cables of various lengths having different impedances. The cables are connected in both straight and branched topologies. Partial discharge (PD) faults can be located anywhere (busbar, switching components, transformers, cables, CC lines, joints and terminations) within the network. PD measurements have been widely applied to monitor the condition of the electrical insulation in power components since last 20 years [5].

Based on the physical phenomenon and the difference in electric field geometry of the discharge site, PD phenomena are divided into internal, corona, surface, and electrical tree discharges [6]. Specific discharged patterns have been studied in detail to recognize

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http://dx.doi.org/10.1016/j.epsr.2014.10.027
0378-7796/

the type of physical activity causing these discharges [5–7]. Electric field due to applied voltage across the discharge site collapses and generates a short-duration current pulse of a certain polarity, superimposed on the applied voltage. The current pulse produced at any of the above mentioned components, propagates along the power lines and can be detected using suitable sensors. The polarity of these PD pulses is determined by polarity of electric field which follows the polarity of (applied) supply voltage during each half cycle. Thus positive and negative PD current pulses are produced respectively during positive and negative half cycle of the applied alternating voltage respectively. The PD signal consists of pulses with pulse duration from nano to micro-second. Therefore, wide bandwidth sensors are needed to measure these high frequency pulses. Efficient PD diagnostics depends on the performance of PD sensor, scheme of measurements and interpretation of the sensor's data.

The research efforts directed for developing fault locating techniques such as time domain reflectometry (TDR) and time difference of arrival (TDA) [8,9], are mostly applied on a single section of the line or cable. A practical power supply network consists of multiple sections of line which are connected in single or branched route network. Here a section is referred to as a line of specific length, type or branch of an overhead CC line or cable network in a distribution system. There is a lack of literature for identifying the faulty section where the location techniques can be applied. In this work, a simple method for identifying the faulty section is presented using direction of arrival (DOA) of PD pulses. The technique is developed by employing the Rogowski coil induction sensors which determines the DOA by observing the polarity of the detected PD pulses. In [10], the authors have practically demonstrated the directional calibration of Rogowski coil to detect the DOA of PD pulse. Identification of faulty cable branch considering T-branched cable joint is practically described for 22 kV XLPE cables in [11]. In continuation to the previous work, this paper aims at integration of the proposed scheme over power distribution network. Based on the performance evaluation of the experimental work, the scheme is implemented for three phase MV cable network using ATP-EMTP simulation environment.

Considering DOA of transient fault signals along the power lines, a basic concept of polarity based DOA technique for MV transformers has been described in [12,13]. However, detailed analysis of DOA technique has revealed that only polarity comparison of the two sensors' data in the vicinity does not provide the complete picture of fault location methodology. Various factors are needed to be taken into account for true interpretation of DOA based diagnostics which have been reported in this paper. This paper presents various aspects of DOA technique such as sensor's characteristics, sensor's calibration, DOA implementation, measurement methodology (for straight and branched line network), simulation for integration of DOA into the network, and a proposed diagnostic scheme taking into account the data comparison of the multiple sensors. The paper is presented as follows: Section 2 describes the basic idea of DOA assessment for PD pulses based on directional calibration of Rogowski coil in real as well as simulated scenarios. The performance of the DOA technique for fault identification is evaluated for a CC line in Section 3. Section 4 proposes the integration of the presented technique for PD monitoring over a distribution network. In Section 5, ATP-EMTP environment is used for implementation DOA technique over a three phase medium voltage distribution network. A detailed analysis is made in Section 6 for the measured PD signals at various locations to develop an algorithm for automated identification of faulty network area. Localization of fault on an identified network area (section) is described in Section 7 while Section 8 describes the practical considerations for implementation of the technique in real networks.

2. DOA assessment based on polarity of PD pulse

2.1. Directional calibration of Rogowski coil

In this work, high frequency Rogowski coil is used as sensor for PD detection. Due to its flexible construction, Rogowski coil is suitable to perform non-intrusive measurements of PD signals by installing it around the primary current line as shown in Fig. 1(a). The voltage $V(t)$ induced by Rogowski coil in response to primary current $i_p(t)$ passing through the line is

$$V(t) = -M_c \frac{di_p(t)}{dt} \tag{1}$$

where M_c is the mutual inductance of coil between current carrying wire and Rogowski coil. Based on impulse response of its electrical equivalent 2nd order circuit [14,15] shown in Fig. 1(b), the output voltage $V_{RC}(t)$ of the coil in terms of its transfer function (in s-domain) can be expressed as

$$V_{RC}(s) = \frac{1/L_cC_c}{s^2 + (1/L_cC_c)((L_c/R_T) + RC_c)s + (1/L_cC_c)\left((R/R_T)+1\right)} V(s) \tag{2}$$

where

$$V(s) \xrightarrow{L^{-1}} V(t) = -M_c \frac{di_p(t)}{dt}$$

The undamped oscillatory response shown in Fig. 2(b) and (c) can be described as [16]

$$V_{RC}(t) = -M_c \frac{di_p(t)}{dt} - M_c \frac{di_p(t)}{dt} \cdot e^{-\xi\omega_n t} \sin\left(\omega_n \left(\sqrt{1-\xi^2}\right) t\right) \tag{3}$$

where ξ is the damping coefficient and ω_n is the natural frequency of oscillation which depends on the self-inductance (L_c) and self-capacitance (C_c) of the coil and can be calculated as

$$\omega_n = \frac{1}{\sqrt{L_cC_c}} \tag{4}$$

The geometrical view of the Rogowski coil installed at position Q on a CC line Q_1Q_2 is shown in Fig. 1(a). The coil is installed such that face A of the coil is toward the line end Q_1 and face B of the coil is toward line end Q_2. Based on installed position of the coil, the line is divided into two sections, QQ_1 and QQ_2. The possibility of presence of PD source is either within the section QQ_1 or QQ_2. A positive polarity PD pulse originated from a source located along either side of the coil will be captured by the coil. Being an induction sensor the polarity of output voltage of Rogowski coil depends upon the polarity and direction of the incoming PD pulse. Moreover, the face direction of Rogowski coil refers to direction of coil winding facing the incoming electromagnetic pulse. Therefore polarity of the output voltage measured through certain face of the coil determines the DOA of the PD signals. It has been experimentally verified that the first peak of the detected response shows the polarity and proportional amplitude of measured PD pulse [11].

During measurements using practical setup for CC line as depicted in Fig. 1(a), the PD activity was observed at a supply voltage of 5.5 kV The PD signals were measured in mV-range and are scaled for comparative view within the supply cycle as shown in Fig. 2. The PD signal polarity captured by directionally calibrated sensors and the polarity of the applied voltage determines the direction of arrival of a PD signal while making online measurements. Positive and negative PD pulses appeared due to insulation defect during positive and negative half cycles of supply voltage respectively. In this work, positive polarity pulse produced during positive cycle will always be assumed. Face A and face B of the coil are toward left and right side of point Q, respectively. Therefore,