Electric Power Systems Research 125 (2015) 174–183

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Transmission line relay mis-operation detection based on time-synchronized field data

Ahad Esmaeilian*, Tomo Popovic, Mladen Kezunovic

Department of Electrical and Computer Engineering Texas A&M University, College Station, TX, USA

ARTICLE INFO

Article history:
Received 20 January 2015
Received in revised form 10 April 2015
Accepted 11 April 2015
Available online 4 May 2015

Keywords:
Fault detection
Fault location
Power system faults
Power system protection
Relay mis-operation
Time-synchronized measurements

ABSTRACT

In this paper, a real-time tool to detect transmission line relay mis-operation is implemented. The tool uses time-synchronized measurements obtained from both ends of the line during disturbances. The proposed fault analysis tool comes into the picture only after the protective device has operated and tripped the line. The proposed methodology is able not only to detect, classify, and locate transmission line faults, but also to accurately confirm whether the line was tripped due to a mis-operation of protective relays. The analysis report includes either detailed description of the fault type and location or detection of relay mis-operation. As such, it can be a source of very useful information to support the system restoration. The focus of the paper is on the implementation requirements that allow practical application of the methodology, which is illustrated using the field data obtained the real power system. Testing and validation is done using the field data recorded by digital fault recorders and protective relays. The test data included several hundreds of event records corresponding to both relay mis-operations and actual faults. The discussion of results addresses various challenges encountered during the implementation and validation of the presented methodology.

1. Introduction

Transmission line faults have to be confirmed and located quickly and accurately in order to restore power delivery as quickly as possible. Historical events show that most of the large scale blackouts occurred due to a series of transmission lines experiencing disturbances leading to relay mis-operations [1–3]. When a transmission line is tripped due to the operation of protective relays, an accurate fault analysis can verify whether the operation of relay was correct. Incorrect and unwanted relay trips of healthy lines are called relay mis-operations [4]. Distance relay mis-operation can happen due to incorrect first zone setting, false trip of the second zone, false trip of the third zone after a power swing in the network, etc. Moreover, in the case of fault, it can provide the operator with an accurate estimation of the fault location to facilitate the restoration process. The confirmation and isolation of the faulted sections by the operator, as well as evaluating the relay operation by protection engineer is also possible by utilizing such fault analysis tools [5]. There are several benefits of the use of automated fault data analytics such as increased reliability, personnel productivity, redundancy, all of which enhance timely support to the operations during the restoration or other critical decision making processes during disturbances [6]. Such analytic tools can also be very useful in support of reliable implementation of new applications such as transmission line switching (topology) control [7].

Different fault analysis methods have been proposed in the literature either as a separate fault detection, classification, and location functions or as a complete fault analysis tool [8–24]. A group of methods are developed, considering line impedance calculation [8–17], while several others are based on high-frequency transients, traveling waves, and wavelet-based methods [18–21]. Regardless of different schemes presented in these works, the advantages of high-frequency based methods are the high accuracy and fast decision making. However, the majority of these methods demand very high measurement sampling rate in the order of tens of kilohertz, which is still not extensively available in utilities.

In recent decades, several researchers developed an artificial neural network (ANN) and fuzzy logic-based algorithms to detect, classify and locate faults [22–24]. Generally speaking, the huge number of training sets needed to reflect the wide range of system operating conditions (i.e., loading condition, fault resistance, fault inception instance, etc.) makes these methods difficult to

---

* Corresponding author. Tel.: +1 979 862 1097; fax: +1 979 845 9887.
E-mail address: ahadesmaeilian@tamu.edu (A. Esmaeilian).

http://dx.doi.org/10.1016/j.epsr.2015.04.008
0378-7796/© 2015 Elsevier B.V. All rights reserved.

implement in the industry environment. All of the methods described in the references above did not have a capability to detect or confirm relay mis-operations.

This paper presents an automated transmission line fault analysis that is able to detect, classify, locate faults, as well as to detect relay mis-operations. The method operates on measurements captured at both ends of the line tripped by protection relays. The purpose of the tool is to quickly confirm faults or detect relay mis-operations in order to expedite troubleshooting. Relay mis-operations detection can be very useful, especially if done within few minutes, in order to quickly mitigate the problem and prevent potential cascade. The method was validated using artificially simulated test cases and tested using actual fault and mis-operation data. The tool overcomes time response and accuracy shortcomings of the previous methods. The core algorithm is introduced in [25], and its practical implementation is demonstrated in this paper using real data captured in the field [26–30]. The paper first gives theoretical background, and then addresses requirements, challenges, and benefits related to the use of the proposed methodology.

2. Theoretical background

Researchers developed various fault analysis tools implemented with ambitions to be a complete package [31–33]. In [31,32], authors defined the algorithms based on availability of phasor measurements obtained from substation IEDs. As a result, the algorithms still needed phasor calculations which may decrease the speed and accuracy of methods. The approach presented in [33] is rather accurate but it depends on an availability of huge sets of training data and high sampling rate, which are not commonly available.

The fault analysis tool proposed in this paper, directly utilize time-synchronized sampled data recorded by event-triggered intelligent electronic devices (IEDs). The advantage of the proposed method over current differential based fault analysis methods proposed in literature is the direct use of samples without computing phasors, which reduces computational burden as well as the required available post fault data. Due to fast operations of digital relays and modern circuit breaker, the available post fault data window can be very short, which can hugely affect the accuracy of phasor based methods. It provides the operator and protection engineer with an accurate and detailed fault analysis report that includes information such as fault detection, fault type classification, internal/external fault differentiation, fault location estimate, or relay mis-operation indication. The primary goal of the presented method is to support decision making process when troubleshooting transmission line faults. The fault analysis core algorithm has been introduced in [25]. The following subsections provide an overview of fault detection, fault classification, and fault location calculation techniques implemented in the proposed solution.

2.1. *Fault detection and classification scheme*

The proposed method of fault detection and classification compares the change of direction of instantaneous powers at two ends of transmission line using synchronized sampling measurement. The method uses raw data measurements extracted from the data samples with no need for phasor calculations. The method was evaluated using both current differential and differential active power values. The use of active power displayed better accuracy as it was less affected by the presence of noise or higher frequencies in the current differential measurements.

In Fig. 1, $V_1(t), I_1(t)$ and $V_2(t), I_2(t)$ represent voltage and current measured at two ends (Bus 1 and Bus 2) of the line at instance t, respectively. Instantaneous powers can be calculated at both ends using following formulas:

$$P_1(t) = V_1(t) \times I_1(t) \tag{1}$$

$$P_2(t) = V_2(t) \times I_2(t) \tag{2}$$

The unique feature of instantaneous power measurements from both ends under fault condition makes the detection and classification of faults possible without using any thresholds. $P_1(t)$ and $P_2(t)$ phase angles are opposite to each other during the normal condition. However, during a fault, the faulty phases will be almost in phase with each other. It should be noted that, even after the fault inception, the phase opposition is maintained in phases that do not experience a faulted condition. Representing this feature mathematically can be done using a signum function defined as:

$$sgn(x) = \begin{cases} -1, & x < 0 \\ 0, & x = 0 \\ 1, & x > 0 \end{cases} \tag{3}$$

After calculation of sgn($P_1(t)$) and sgn($P_2(t)$), plotting the difference for each phase as Eq. (4) can give a clear understanding of how the algorithm differentiate between fault and normal condition.

$$Psgn(t) = sgn(P_1(t)) - sgn(P_2(t)) \quad \text{for} \quad \text{phase} \quad a, b, c \tag{4}$$

Theoretically, the sign difference introduced in Eq. (4) should be ±2 before fault and during fault it should be 0; however, due to transients, noise, and bus angle differences, some outliers may be present. A moving time window of 5 ms is applied to the samples to check whether at least 90% of Psgn(t) are 0. The 90% threshold was used to allow for a certain level of outlier tolerance. This part of the algorithm has been enhanced by using a time window with variable length and thresholds, as it will be discussed in the implementation section.

Finally, if Psgn$(t) \approx 0$ for all phases, the fault type is a three phase fault, otherwise if Psgn$(t) \approx 0$ for two phases, then the fault is a double-phase fault. If Psgn$(t) \approx 0$ for only one phase, then the fault type is a single-phase-to-ground fault and otherwise there is no fault.

2.2. *Fault location scheme*

The concept of the fault location method utilized in the fault analysis tool was introduced in [34] and further developed in [25]. After detection of a faulty line, the fault location method is triggered utilizing fault type classification output to define the correct mode of the fault location calculation. Depending on the line length, two approaches have been developed to provide a better accuracy. For short transmission lines, only serial connection of an inductance and a resistance are taken into account. Kirchhoff voltage law from each end of the line to the fault point is applied assuming the line to be homogenous. After calculation and simplification, an explicit form of the fault location equation