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A multiple model filtering approach to transmission line fault diagnosis

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ABSTRACT

This paper provides justification and implementation for a multiple model filtering approach to diagnosis of transmission line three-phase short to ground faults in the presence of protection misoperations. This approach utilizes the electric network dynamics and wide area measurements to provide diagnosis outcomes. A second focus of this paper is on the reduction of computational complexity of the diagnosis algorithm. This issue is addressed by a two-step heuristic. The first step designs subsystem models through measurement selection. The second step reduces the dynamic model order. The performance of the diagnosis algorithms are evaluated on a simulated WSCC 9-bus system.

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1. Introduction

The authors of this paper recently presented the motivation, the principle, and some preliminary results of a real-time diagnosis scheme for transmission faults implemented with multiple model filters (Wu & Qin, 2015). Here, diagnosis of a transmission fault is defined as detecting a fault in a system and identifying the faulty transmission line, in the presence of relay misoperations. The scheme has three unique features: use of the transmission network dynamics and time-stamped samples of the secondary-side waveforms of instrument transformers, and tolerance to relay misoperations. This paper provides justification and implementation for the multiple model filtering approach. This diagnosis approach is intended to assist the primary protection system, i.e. to isolate a fault correctly and create the opportunity to take corrective actions when the primary protection system fails to trip or falsely trips. In addition, a reduced order approach is proposed. To emphasize the need to maintain tolerance to protection misoperations in diagnosis, this paper starts with a brief review on published works by others related to the subject.

Protection system misoperation is one of the major contributors to cascading failures in power systems (Phadke & Thorp, 1996). North American Electric Reliability Corporation (NERC) (2013) considered it as the top-rated reliability issue in the recent state of reliability report. Protective relays are designed to trip circuit breakers when a fault is believed to be present. While traditional relays are operating based on local measurements, relay misoperations are likely to occur when the system is under stress or disturbance. Such disturbance could be caused by topological changes due to faults, switching and maintenance, or power flow changes due to significant generation and load variations. The latter can also come from distributed generations. In general, there are two types of relay misoperations: failure to trip and false trip. Majority of the relay misoperations, which are caused by undetected defective settings, are false trips. Such defective settings are also referred as hidden failures (De La Ree, Liu, Mili, Phadke, & Dasilva, 2005).

Although backup relays are configured to operate when the primary relays failed to trip, the coordination of relay settings is increasingly complicated for modern power systems and it also suffers from hidden failures (Elizondo, De La Ree, Phadke, & Horowitz, 2001). Special Protection Scheme (SPS), or Remedial Action Scheme (RAS), uses wide area measurements to detect unusual system conditions and improve the stability of the system by various control actions such as tripping a line or generator (Adamiak et al., 2006; Anderson & LeReverend, 1996). While SPS has been widely used to increase the transfer capacity (McCalley & Fu, 1999), few studies has been done on correcting relay misoperations.

Various improved protection schemes have been proposed to deal with the relay misoperations. Adaptive relaying improves the reliability by integrating with the supervisory control and data acquisition (SCADA) system and central energy management system (EMS) (Horowitz, Phadke, & Thorp, 1988; Rockefeller, Wagner, Linders, Hicks, & Rizy, 1988). A few backup protection systems have been designed using wide area measurements. The backup expert decision system described by Tan, Crossley, Kirschen, Goody, and

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Downes (2000) processes the network topology and the relay operating response with an inference system. The agent-based backup protection system proposed by Wang et al. (2002) consists of rule-based controllers (agents) making decisions based on the local measurements and communications with other agents.

A self-healing protection system presented by Sheng, Li, Chan, Xiangjun, and Xianzhong (2006) combines the agent-based technique and expert system. With the idea of reducing communication burden, a hierarchical scheme was presented by He, Zhang, Chen, Malik, and Yin (2011). It first identifies the faulty area and then detects the fault by processing the voltages at both ends of each transmission line.

The deployment of Phasor measurement units (PMU) (Phadke & Thorp, 2008) enables the use of more accurate wide area measurements to detect faults and correct relay misoperations. Schweitzer, Whitehead, Zweigle, Ravikumar, and Rzepka (2010) discussed the benefit of using PMU data for real-time protection and control. Several methods are proposed for localized fault detection/location using synchronized PMU measurements (Brahma & Girgis, 2004; Dustegor, Poroseva, Hussaini, & Woodruff, 2010; Jiang, Yang, Lin, Liu, & Ma, 2000; Jiang, Lin, Yang, Too, & Liu, 2000). A relay-misoperation detection method using synchronized data from both ends of a transmission line is presented by Esmaeilian, Popovic, and Kezunovic (2015). Although these methods can obtain the exact location of a transmission line fault promptly, they are not practical as PMUs are required to be installed at both ends, or at least one end of every transmission line. However, according to the Department of Energy (2013), as of 2013, a total of 1126 PMUs were installed across the North America, which is far less than the number of transmission lines.

A few fault detection and identification schemes using sparse placement of PMU have been proposed for wide area backup protection. In Bo, Jiang, and Cao (2009), fault location is determined iteratively using genetic algorithm with the idea of superimposed impedance matrix during a fault. For large scale system the search space for this method could be very large. Eissa, Masoud, and Elanwar (2010) presented an application of PMU data in wide area back up protection. The proposed scheme divides the system into a few areas, each with PMU measurements. The voltage measurements and power flow directions are used to identify the fault area. However, to identify the fault on each transmission line, a large number of PMUs are still needed. Navalkar and Soman (2011) designed a remote fault detection scheme using the residual vector of the synchrophasor state estimator (Phadke, Thorp, & Karimi, 1986), and combined the fault detection result with backup relay to improve reliability. Based on the swing dynamics of generators, a maximum a posteriori (MAP) detector is developed by Valdez, Zhang, Torres, and Roy (2014) for fault location estimation. Since the time constants for swing dynamics are generally large, such dynamics are useful for applications with slower disturbances, such as load changes (Shames, Teixeira, Sandberg, & Johansson, 2011). They are, however, not suitable for diagnosing faults with critical clearing times of at most a few hundreds of milliseconds, such as transmission line faults.

Although the protection schemes mentioned above all addressed the relay's failure to trip, the false trip issue received little attention until recently (Wu & Qin, 2015). The authors have also performed hybrid simulations to assess the benefit of our diagnosis scheme (Qin & Wu, 2015). The efforts show that advancement of technology has made the implementation of real-time recovery from relay misoperations a possibility. In addition to detailing the improvement on multiple model filtering, and how multiple model method is applied to transmission fault diagnosis, this work also focuses on resolving the issue of computational complexity accompanying the inclusion of dynamic models of the transmission network. In this paper, faults are limited to transmission line three-phase short to ground faults, for which the simple per phase model can be retained. Unsymmetrical faults, such as single phase short to ground, or phase to phase fault can be handle similarly by modeling the system with symmetrical components (Anderson & Fouad, 2002).

Time-stamped sampled measurements from the power system are used in the multiple model filtering process. Such measurements are also available as input data for PMUs.

An improved multiple model (MM) algorithm is designed for fault diagnosis in this paper. The MM algorithm was originally developed by Magill (1965). It is also referred as multiple model adaptive estimator (MMAE) (Maybeck & Hanlon, 1993). The measurement residuals of MM filtering can be used to calculate the likelihood for each model at which the system is operating. When each model represents a system operating mode, the associate likelihood is also referred as a mode probability. A few enhancements of the algorithm are discussed by Maybeck and Hanlon (1993). A numerically robust implementation of MM algorithm is presented by Li and Zhang (2000). For system with frequent mode jumps, the interacting MM algorithm (Blom, 1984) provides better performance by reinitializing the filter states based on a pre-defined transition matrix, which captures the prior knowledge about the system mode jumps. The variable structure MM algorithm introduced by Li and Bar-Shalom (1996) uses variable models instead of a fixed set of multiple models. The models are determined based on the knowledge of current system state. For the application of power system protection, since the system mode is generally not jumping frequently, the MM algorithm is used in this paper. Also, the state of each breaker is assumed to be known and used to construct the variable structure multiple model sets.

The remainder of this paper is organized as follows: Section 2 presented the multiple model algorithm for fault diagnosis. Section 3 discussed the communication and computational complexity. Section 4 proposed a reduced order multiple model algorithm. Section 5 presented a case study on the WSCC 9-bus system. Section 6 concludes this paper.

2. Multiple model fault diagnosis

The fault diagnosis is achieved by using a variable structure multiple model algorithm. The algorithm processes the measurement data with a set of Kalman filters (Welch & Bishop, 1995). Fault diagnosis decision is made based on the measurement residuals of the Kalman filters. Here, variable structure represents the fact that the filter set is variable. At different time instances, different filters are included in the filter set according to the partial knowledge on the system configuration, such as the circuit breaker states, at that time.

2.1. System modes and models

Definitions of mode and model similar to that by Li, Zhao, and Li (2005) are used to describe the multiple model approach. A *mode* refers to a physical status of a system. For the diagnosis purpose, a system with N transmission lines has $N+1$ modes, i.e. a fault-free mode, including both pre-fault and post-fault configurations, and N faulty modes. Each faulty mode corresponds to a particular transmission line shorted to ground, regardless of the exact fault location. In general, multiple configurations exist for each mode.

During the operation of power system, the system switches among different modes occasionally, depending on the relay operations or fault occurrence. The fault diagnosis aims to correctly identify the system mode.

A *model* refers to a mathematical representation of a system mode under a certain configuration. System configuration is fixed

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