Transmission system wide-area back-up protection using current phasor measurements

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A B S T R A C T
Zone-3 of distance relays might maloperate during stresses frequently encountered in power systems, such as power swing, load encroachment, and voltage instability. This paper proposes a new protection algorithm for discrimination between short-circuit faults and other stresses in the transmission networks. The proposed method compares the sum of currents at the predetermined buses before and after the disturbance occurrence using synchronized current phasor measurements. The faulted area and line are identified as well. The optimal placement of phasor measurement units (PMUs) is tackled using a mathematical model. One of the main advantages of the proposed algorithm is decreasing the number of required PMUs in comparison with those of existing wide-area back-up protection schemes. In virtue of its computational speed, the proposed method can be exploited as a practical back-up protection cooperating with conventional protection schemes. The extensive simulation studies carried out on the IEEE 57-bus test system verify applicability of the proposed algorithm as a reliable back-up protection scheme for lines.

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1. Introduction

Operation of transmission networks close to their stability margins has led to lots of protective relays maloperation and even system blackouts thus far [1–3]. One of the frequently reported causes of power system instabilities around the world is the incapability of protective relays in distinguishing faults from other stressed conditions [4–6].

Distance protection is the most common scheme used as the main and back-up protection of transmission-lines. The back-up protection of zone-3 merely takes advantage of local measurements and, therefore, does not depend upon the communication system performance. However, the apparent impedance seen by the distance relay might enter its zone-3 characteristic during stressed conditions such as power swing, load encroachment, and voltage instability. As a direct result, the relay might mistakenly operate as if a short-circuit fault has happened. Such an unwanted operation of zone-3 can result in cascading outages of lines and eventual system instability [7].

Power swing blocking (PSB) is the most common practice used to recognize the power swing condition and prevent associated unwanted tripping of lines [8]. Despite putting lots of efforts in this area, the conventional PSB scheme cannot yet correctly fulfil its task in some situations such as coincidence of fault and power swing [9,10]. In [11], an algorithm based on the rate of change of voltage is proposed to avoid undesirable operation of distance relays during voltage instability. Nonetheless, this algorithm undergoes difficulties for discriminating between faults, stresses, and switching events in the system. The high-frequency contents of signals due to fault can be used to distinguish faults from the other stressed events [12]. Such an approach, however, requires special considerations for measurement of high-frequency contents of waves. Moreover, modification of zone-3 is proposed in [13] based on the local measurements to avoid its undesirable operation under voltage stressed conditions. However, while dealing with extended power system disturbances, wide-area measurements provide more effective information than the local ones about system conditions and disturbance area.

To deal with the above mentioned problems, some wide-area protection schemes have been proposed for taking advantage of the data gathered from various locations in the network [14,15]. These algorithms rely on the synchrophasor data computed by either global positioning system (GPS)-equipped digital relays or PMUs. The use of such information would make it possible to more effectively protect and control the power networks operating with lower stability margins. In [16] transmission lines in the system are divided into various groups and for each group, some synchropha-
sor measurement buses are categorized to identify the system condition. Although, the behaviour of generator buses during fault and power swing are not considered. Also, using the algorithm for the large power systems, the proposed procedure of PMU placement might be difficult. Ref. [17] has proposed a method based on comparison of the positive-sequence voltage magnitudes for specified areas as well as the positive-sequence current phase angles difference of every tie line. However, this scheme can only be applied for interconnecting lines that are equipped with PMUs at their both sides.

Paper [18] proposes a synchrophasor data-based technique to correct zone-3 operations by discriminating the fault from different stressed situations. The number of required synchrophasor measurement devices is less than most of the similar wide-area methods. However, different behaviour of the generator buses during stressed conditions and normal operation of systems are not considered. Also, the placement of PMUs is left without proposing a mathematical method which is essential for large-scale systems. In [19], a real-time power flow calculation technique is devised to distinguish line overloads from actual faults. As a result, this method can block the operation of distance relays zone-3 during lines overloads to allow defining systems to take appropriate actions in order to prevent cascade line trips. However, for implementing this method all buses should be able to communicate with the control center. An adaptive remote back-up protection scheme based on a synchrophasor state estimator is proposed in [20]. For a non-faulty system, the residual of the estimator would be small, while the network model in the presence of a fault would have a large residual. Ref. [21] has presented an algorithm for distinguishing between fault events and stressed situations based on comparison of voltage from different paths. Although this algorithm could remarkably decrease the number of required synchronized devices in the network, it still requires that about half of the buses be equipped with PMUs. A wide-area backup protection algorithm is proposed in [22] using the protection fitness function built by the contribution of different zones of all distance relays within the system. Although the algorithm works well even when the wide-area communication channel is inactive, it requires a complicated communication infrastructure to transmit all relays information to the protection center.

In this paper, a new technique is presented for the transmission-lines back-up protection using synchrophasor measurements. Being constructed essentially based on the Kirchhoff's current law (KCL) at the predefined buses, the proposed algorithm is carried out in two stages. In the first stage, the fault and stressed conditions would be distinguished. In the case of a fault occurrence, the faulted area is identified using data from the strategic buses. In the second stage, the faulted line is detected to be separated from the power system. The operation time of the proposed algorithm is short enough, which makes it a reliable back-up protection scheme for lines. The algorithm needs less synchronized measurement devices compared to the existing wide-area protection schemes. It covers various two and three-terminal lines and is able to provide reliable output even when some of PMUs are not available. Numerous simulations carried out in the 57-bus system verify applicability of the algorithm as a reliable back-up protection scheme.

2. The proposed algorithm

The proposed algorithm uses synchronized phasor measurements from predefined locations in the network. The algorithm distinguishes the fault from other stresses in the first step. To do so, the sum of estimated currents at predefined buses not equipped with PMU is obtained. In the case of a fault event, the algorithm detects the faulted area and also the faulted line in the next step. Therefore, if the main protection scheme does not operate in a reasonable time, the faulted line is tripped out by the wide-area backup scheme.

Upon every update of the captured data in the control center, the algorithm checks receiving any signal from the distance relays that whether or not the measured impedance has entered the zone-3 area. The distance relays located at PMU-equipped buses are involved in the algorithm that means no extra communication link is required for zone-3 trigger signal. In other words, the dedicated link for PMU data communication is also used for sending the zone-3 signal. According to the optimized PMU placement strategy, each line in the network is covered at least by one distance relay’s zone-3 at the PMU-equipped buses.

Most of the wide-area backup protection schemes are focused on improving or replacing the zone-3 backup protection. This is due to the fact that zone-3 includes a large area of backup protection. This area is extremely prone to be excited during different stresses which can result in the system collapse. Therefore, the improvement of zone-3 operation under the disturbance condition is of considerable importance. Zone-2 is the main protection for the end part of transmission line and backup protection for the initial parts of the following lines. Its operation time is in a similar range with the delay of wide-area backup protection schemes. Consequently, if the operation time for wide-area backup protection would be less than zone-2 delay then, the proposed algorithm could improve the zone-2 scheme. Otherwise, the operation time of zone-2 cannot be modified and conventional schemes for blocking or tripping should be implemented.

2.1. Stressed and faulted condition discrimination

An algorithm is proposed in this part for discrimination of the faulted and stressed conditions. To start with, Fig. 1(a) is considered in which buses $i$ and $j$ are equipped with PMUs whereas the middle injection bus $k$ is not directly monitored. Using PMUs data along with (1) and (2), the lines currents at the sides of middle bus can be estimated. According to the KCL rule, the algebraic sum of currents entering to any bus is equal to zero. When there is no fault in the system, the current estimations over the lines $i-k$ and $j-k$ are correct and the sum of currents at bus $k$ would be zero as shown in (3). Albeit, due to the measurement and estimation errors, (3) would not be exactly zero in practice and it takes a slight value. When a fault happens, the current estimations over the faulted line would not be correct anymore. In such a case, (3) is violated which implies that there is a fault in the associated area.

\[
I_{ij} = \frac{1}{Z_c} \sinh(\gamma L_{ij}) V_j - \cosh(\gamma L_{ij}) I_{jk} \quad (1)
\]

\[
I_{ki} = \frac{1}{Z_c} \sinh(\gamma L_{ki}) V_i - \cosh(\gamma L_{ki}) I_{kj} \quad (2)
\]

\[
I_{ki} + I_{kj} + I_i = 0 \quad (3)
\]

In these equations, $Z_c$ is the surge impedance, $\gamma$ is the propagation constant, and $I_{jk}$ is the length of line $j-k$. Also, $V_j$ denotes the positive-sequence voltage of bus $j$, and $I_{kj}$ and $I_i$ are the positive-sequence current of line $j-k$ and load, respectively.

As an example, a fault is considered on link $j-k$ in Fig. 1(a). In this case, the current estimation of line $i-k$ at the left side of bus $k$ is correctly obtained from (2), whereas the current on line $j-k$ estimated form (1) is erroneous due to the fault in this path. Consequently, the faulted area is discriminated between buses $i$ and $j$ as a result of violation of (3).

Fig. 1(b) shows a sub-network with four buses and three lines. In this sub-network, the buses located at two ends are equipped.
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