High-speed Falling Conductor Protection for Electric Power Transmission Systems

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***Abstract*— When a power transmission line breaks, the energized conductor falls to the ground causing a ground fault and arcing. This can potentially lead to fire ignition if the protection system does not operate adequately fast. While a current-based algorithm using |I2/I1| ratio can detect a portion of broken conductor scenarios in transmission systems, its effectiveness is compromised in radial systems, series transmission lines, and lightly loaded conditions. Another shortcoming of the existing |I2/I1| method is the misoperation for far faults in the system. The current in the healthy phases can drop significantly for a remote single line-to-ground (SLG) fault due to mutual coupling, which in turn can lead to misoperation of the |I2/I1| algorithm. As a result, the |I2/I1| broken conductor detection needs to be coordinated with the primary protection functions which introduces large delays in the detection of a broken conductor.**

This paper provides a new algorithm on high-speed falling conductor protection for transmission line (HFCP-TX) using the voltage and currents of the local and remote end/ends of a transmission line. The HFCP-TX algorithm is applicable to double-ended and multi-ended line configurations. The real-time controller receives the voltage and current of the local and remote terminals from the relay(s) and processes them to monitor the change of the impedance of the line. The algorithm is immune to existing system imbalance and transient events since it is using the line Impedance Change Ratio (ICR).

The effectiveness of the proposed HFCP-TX algorithm has been validated with Hardware-in-the-Loop (HIL) testing using a Real-Time Digital Simulator (RTDS). A comprehensive set of cases including internal/external broken conductor conditions, internal/external faults, and transient events were tested for a realistic transmission network. The test results show that the proposed algorithm can detect a broken conductor condition within 500ms after the conductor breaks. Therefore, the affected circuit will be de-energized prior to the conductor hitting the ground, eliminating the risk of an arcing ground fault or energized circuit on the ground.

***Index Terms*: Falling Conductor Protection (FCP), Transmission Line, Broken Conductor Detection, and Impedance Change Ratio (ICR)**

I. INTRODUCTION

An energized overhead powerline can break and fall to the ground or on other objects for a variety of reasons such as severe weather conditions, natural disasters, conductor clamp failures, tree fall and/or pole knock-over. When the falling conductor touches the earth or other grounded objects, it may cause a high-impedance (Hi-Z) fault which cannot be reliably detected by conventional overcurrent protection schemes. Moreover, as the live conductor contacts the ground, it produces electrical arcing that can ignite flammable materials or vegetation and start a fire. An undetected Hi-Z fault is a risk to people and their properties and has the potential to evolve into a full-blown fault. Most of the existing methods cannot detect all Hi-Z faults, and operation of the relay for downed conductor faults is not guaranteed. In addition, for the broken or falling conductors, it is expected to detect the condition and trip the corresponding breaker(s) before the conductor touches the ground. Currently, the implemented methods for detection of broken/falling conductors mainly use electric currents, voltages, and conductor geometry. These methods are categorized into current-based methods, voltage-based methods, and physical/mechanical methods.

This paper addresses the challenges associated with broken conductor detection for two- and three-terminal transmission lines using the voltages and currents received from other end(s) of the line. The transmission line differential relays exchange the voltage and current of the local and remote line terminals with each other, either via the existing line differential channel or a separate communication medium. Each relay will process this data to detect falling conductors by identifying a specific pattern in the line impedances. Alternatively, a central real-time controller can be used to collect and process the data. The invented algorithm is immune to existing system imbalance and transient events since it is using the ICR over time.

II. BROKEN CONDUCTOR DETECTION METHODS

The detection of broken falling conductors in transmission and distribution systems is a challenging task as it depends on the system topology, penetration/status of transmission-connected energy resources, line loading, broken phase location, and availability of information along the power line. schemes, etc.

A. Current-based Method

Broken falling conductors can be detected using current imbalance (|I2/I1|), which is an estimated representation of Z0/(Z1+Z0), where Z0 and Z1 denote the total zero-sequence impedance of the circuit and the total positive-sequence impedance of the circuit, respectively (including local and remote sources and the line). If the calculated ratio is greater than a setpoint, a broken conductor is detected along the line. Since asymmetrical shunt faults within or beyond the zone of protection can also cause high |I2/I1| values (similar to broken-conductor events), this method poses some challenges to system protection. The following is a list of shortcomings of the |I2/I1| method:

a. During low-load conditions, |I2/I1| might drop to very low values and, thus, |I2/I1| might not reach the setpoint value during an actual broken/falling conductor condition. If the CT ratio of the line is significantly larger than the actual loading of the line (for example, to avoid CT saturation for high fault currents), the |I2/I1| method may not operate properly since the ratio does not reach the pickup setpoint (which is usually set in pu). As an example, Fig. 1 shows the non-detection zone of this method for a lightly loaded transmission line. It can be observed when the load is within ±60MW, it will not be able to protect the line for any broken conductor incident.

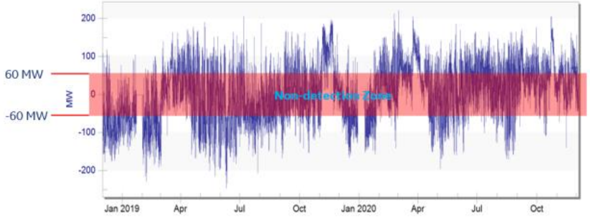

Fig. 1. Non-detection zone of |I2/I1| algorithm for a lightly loaded transmission line

b. The time coordination with protective functions of the neighboring lines and remote far lines will be quite challenging for transmission systems where power flow can be bidirectional.

c. The |I2/I1| method needs to be coordinated with the existing transmission line protection, including primary and back-up protections, which introduces long delays in the detection of a broken conductor.

d. For transmission lines in series, it is difficult to achieve selectivity as elevated |I2/I1| is seen at all locations upstream of the actual broken point.

e. The |I2/I1| method overreaches for the broken conductor incidents happening in series lines.

f. The |I2/I1| method could misoperate for remote far faults in a system with mutual coupling between transmission lines where the fault current induces currents in healthy phases and mimics the signature of a broken falling conductor. Fig.2 below is a field event for a phase C fault on one of the mutual coupling lines and Fig. 3 is the three-phase current and voltage on a healthy line that is mutual coupled with the faulty line. The |I2/I1| element on the healthy line picked up and incorrectly indicated a broken conductor event.

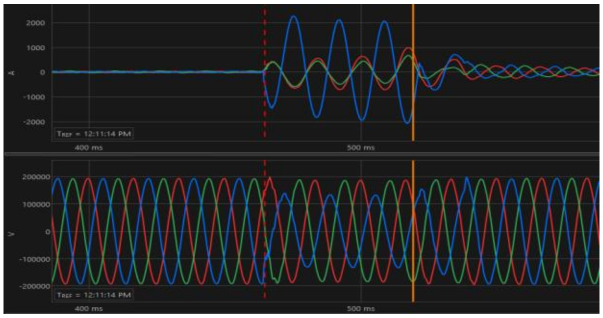

Fig. 2. A Phase C to ground fault on a mutual-coupled line

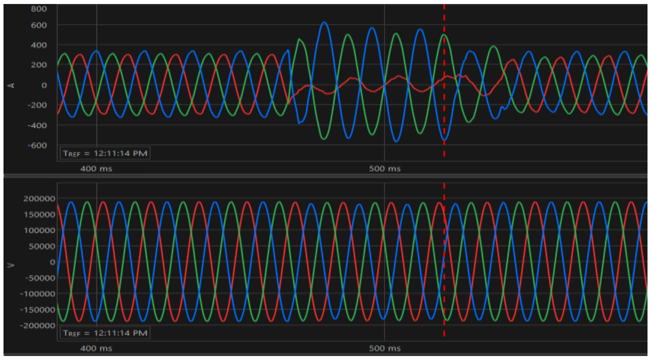

Fig. 3. |I2/I1| element on another mutual-coupled line misoperated due to phase A current drop

g. The |I2/I1| method is specific to two-terminal transmission lines and does not apply to three-terminal lines.

B. *Voltage-based Method*

The voltage-based methods are divided into four sub-categories. These are: i) loss of voltage, ii) rate of change of voltage, iii) zero- and negative- sequence voltage magnitudes, iv) zero- and negative- sequence voltage angles.

The method based on the loss of voltage uses pre-determined voltage thresholds to detect falling conductor events. Voltage measurements at multiple locations (e.g. upstream and downstream) of the distribution network are required. A falling conductor event is detected when the downstream voltage collapses below the pre-set voltage threshold.

The methods based on the rate-of-change-of-voltage calculate the rate at which the measured phase voltage magnitudes are changing with respect to time such as dV/dt. These methods are mainly implemented onto distribution systems. Moreover, these methods might be susceptible to misoperation due to the presence of distributed energy resources (DERs) in distribution system feeders.

a. The rate of change of per-phase voltage (dV/dt) in a distribution system detects the falling conductor in a distribution system. This method heavily depends on deployment of multiple PMU devices alongside a distribution system feeder. The dV/dt signatures at PMUs on opposing sides of the break have opposite polarity and after dV/dt rises above the pickup, a supervision check is also performed using dV0/dt.

b. The V0 and V2 sequence voltage magnitudes are other algorithms for detecting falling conductor events. For a falling conductor event in a given phase, occurring between two PMU locations, the PMU farther away from the source has a steep increase in the V0 and/or V2 magnitude compared with the PMU closer to the source.

c. The V0 and V2 sequence voltage angles are the third voltage-based algorithm to detect a falling conductor event. If a break occurs, phasor sequence measurements from PMUs on the two sides of the break location show specific angular relationships that point to the falling conductor location.

C. *Physical/Mechanical Method*

In this method, a physical device is installed between each pole of the system which measures the geometry it is resting at. If it detects a change in its geometry measurements outside the allowed movement sphere, a broken conductor is declared. This method is a costly solution and highly depends on mass simulation since it requires so many devices and communications between them.

III. IMPEDANCE-BASED HIGH-SPEED FALLING CONDUCTOR DETECTION

As shown in Fig. 4, the impedance-based high-speed falling conductor detection solution utilizes the local and remote voltages and currents that have already been exchanged for line differential protection through existing communication channels. As an example, besides the line currents, GE's L90 relays communicate extended Clarke voltage with other relays protecting a transmission line (L90's); the proposed invention will use this available data to detect falling conductors in transmission systems. Moreover, if the differential relays can exchange positive-sequence voltage or phase voltages, the invented algorithm could use these voltage values to detect falling conductors. The main requirement is that the exchanged data is synchronized; therefore, if the phase voltages of a two- or three-terminal line are available using IEEE C37.118 protocol (i.e., PMU data), the data also can be used by a real-time controller (RTC) or phasor data concentrator (PDC) to detect broken falling conductor conditions as shown in Fig.5.

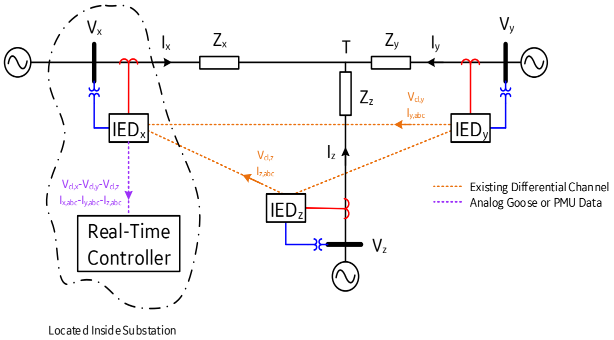

Fig. 4. Data flow for HFCP using extended Clarke voltage or positive-sequence voltage

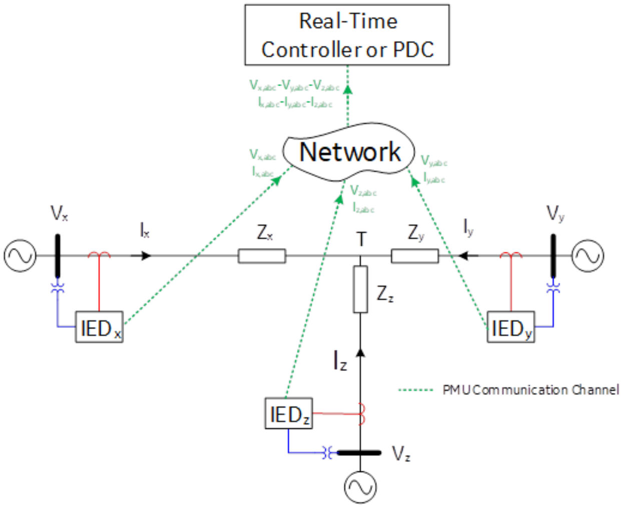

Fig. 5. Data flow for HFCP using synchrophasor data

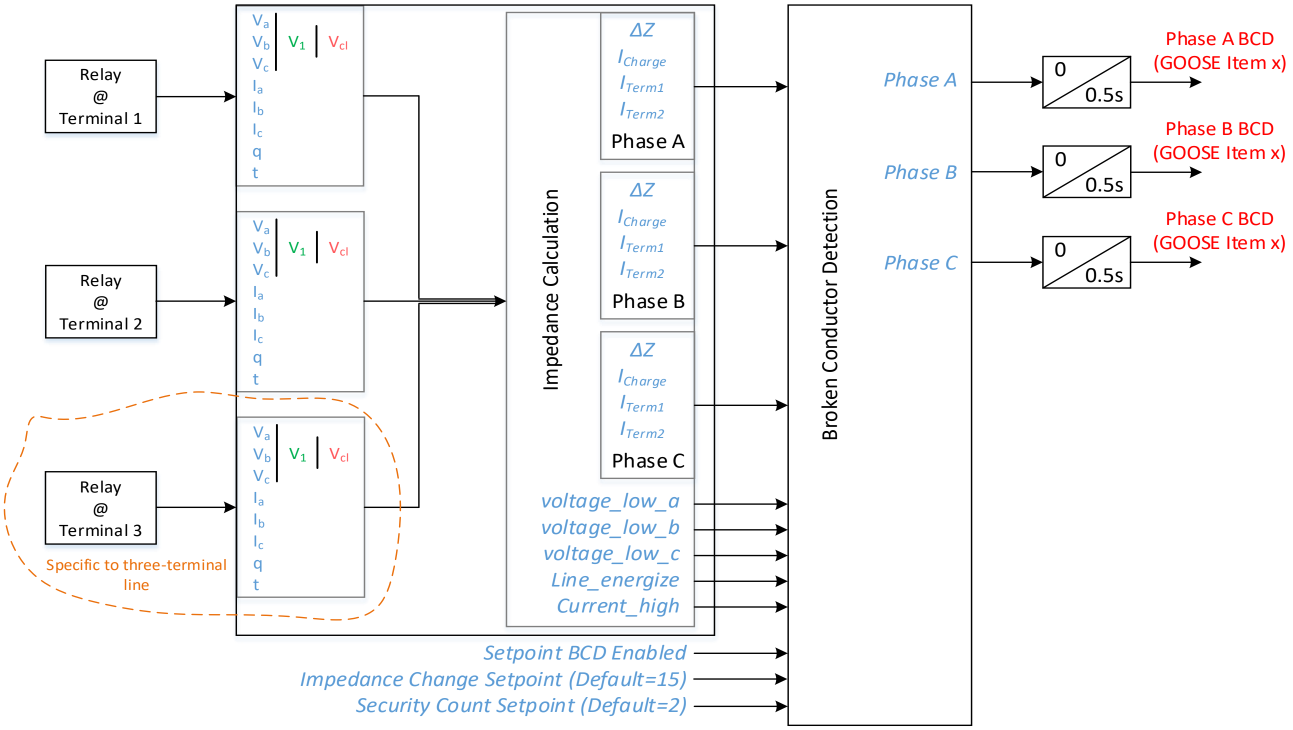

Fig. 6. Block diagram of impedance-based HFCP

The logic diagram of Fig. 6 shows the proposed detection logic using extended Clarke voltage, positive-sequence voltage, and synchrophasor data. Normally, one set of this voltage data is available in each system. The logic diagram is presented for a three-terminal line. However, the configuration for a two-terminal line is the same, except the third terminal is removed from the configuration. In other words, a two-terminal line is a reduced version of the three-terminal line.

In the block diagram of Fig. 6, Va, Vb, and Vc are voltage synchrophasors, V1 denotes positive-sequence voltage, and Vcl is extended Clarke voltage. The main building blocks of the proposed HFCP algorithm are impedance calculation, Delta-Z calculation and detection algorithm as shown in Fig. 6. They are discussed in detail below.

A. *Impedance Calculation*

This block calculates the impedance of the line using the available local and remote data. Line protection relays normally offer multi-ended fault location feature which requires the voltages of the line terminals to be exchanged over the direct differential communication channel. As a result, the local voltages are communicated to the remote line terminal through direct channel (e.g., using IEEE C37.94 standard). The proposed method uses the existing communicated data between line differential relays to detect a broken/falling conductor. For a three-terminal line, two impedances are calculated for each phase of the line at each terminal (i.e., impedances between the local terminal and two remote terminals). As a result, there will be a total of six and eighteen impedance calculations for two-terminal and three-terminal lines, respectively. Fig. 7 and 8 show the PI model of the two- and three- terminal lines.

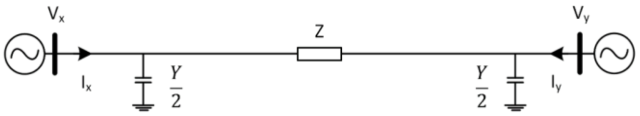

Fig. 7. PI model representation of a two-terminal transmission line

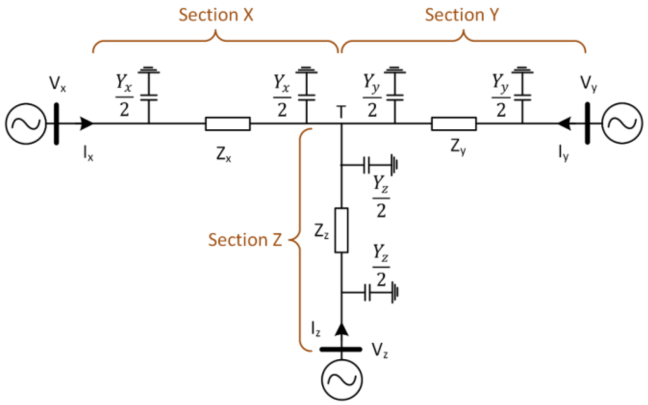

Fig. 8 . PI model representation of a three-terminal transmission line

B. *Delta Z Calculation*

Once the line impedances are calculated, the ICR of the transmission line (δ_Z) is derived by subtracting the previous impedance Z' (Z' = Zt0-n) from the current impedance Z (Zt0) and then divided by previous impedance Z', as follows:

$$\delta_{Z} = \left|\frac{Z-Z'}{Z'}\right| \quad (1)$$

Taking Phase 'a' at Terminal X of a three-terminal line as an example, the ICR ($\delta_{Z_{xy,a}}$ $\delta_{Z_{xz,a}}$) can be calculated using the following formulas (other phase ICRs are calculated similarly):

$$\delta_{Z_{xy,a}} = \left|\frac{Z_{xy,a}-Z'_{xy,a}}{Z'_{xy,a}}\right| \quad (2)$$

$$\delta_{Z_{xz,a}} = \left|\frac{Z_{xz,a}-Z'_{xz,a}}{Z'_{xz,a}}\right| \quad (3)$$

Where:

$Z_{xy,a}$ is the calculated A phase line impedance from terminal X to terminal Y.

$Z_{xz,a}$ is the calculated A phase line impedance from terminal X to terminal Z.

$Z_{xy,a}'$ is the calculated A phase line impedance from terminal X to terminal Y from a few cycles ago.

$Z_{xz,a}'$ is the calculated A phase line impedance from terminal X to terminal Z from a few cycles ago.

C. *Algorithm*

The HFCP function will identify a falling conductor condition when the rate of change of impedance for the transmission line exceeds a threshold (defaulted at 15 times the normal value). Only single-phase broken/open conductors can be detected with this algorithm. To prevent incorrect operation of the HFCP for a fault happening on the transmission line, a high current threshold is used to block the logic if the line current exceeds a predefined value (defaulted at 1.2 pu). The logic will also be blocked when the phase voltage is outside a pre-defined range at all line terminals, indicating abnormal scenarios other than a broken falling conductor.

IV. SIMULATION STUDIES AND RESULT ANALYSIS

The effectiveness of the proposed HFCP algorithm has been verified with HIL testing. A detailed model of a realistic transmission network has been created in a RTDS. The HFCP function was developed in a real-time controller that is interfaced with the RTDS. A comprehensive set of test cases including internal/external broken conductor events, internal/external faults, various line loading, and transient incidents were executed for a realistic transmission system using the HIL testbed. The test results show that the proposed algorithm can detect a broken conductor within 500ms after the broken conductor condition. Therefore, the affected circuit will be de-energized well ahead of the conductor hitting the ground, eliminating the risk of an arcing ground fault (bushfire prevention) or energized circuits on the ground.

Fig.9 shows the impedance change measured for a two-terminal transmission line in the HIL testing with GE's L90 relays and HFCP algorithm implemented in GE Power Gateway (GPG). The figure shows a broken conductor event on phase A, where the impedance of phase a changes more than 1,500 times its normal value while that of phase B and C is below the pickup threshold of 15 times. It is noted that a broken conductor on one phase causes the measured impedance for healthy phases to change as well since the voltage and current of the healthy phases also vary as a result of a broken conductor event. However, the impedance ratio change for healthy phases is way less than that for the affected phase.

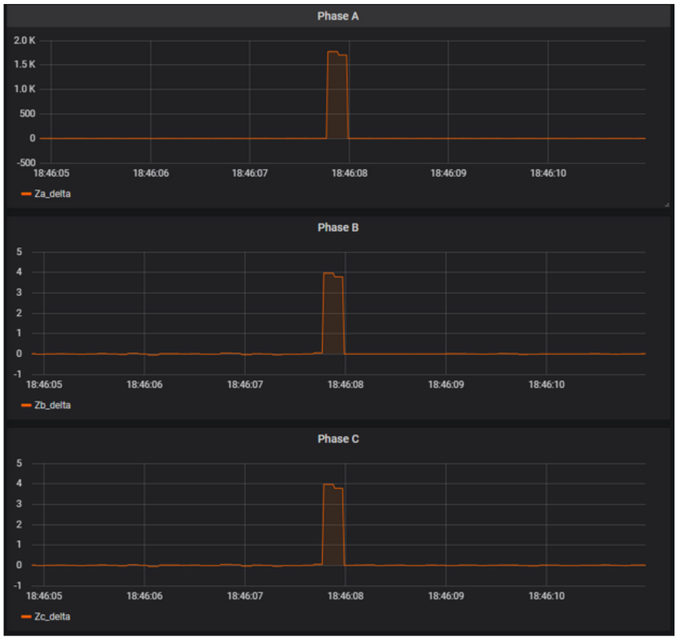

Fig. 9. ICR measurements for a phase A broken conductor simulation

Fig. 10 shows impedances measured for the phase B conductor broken of a three-terminal transmission line. Referring to Fig. 8, the broken conductor happens in phase B on section X (between Terminal X and T point). As shown in Fig. 10, the broken conductor incident causes multiple pickups of the six impedances measured for phase B. Although only one pickup is enough for a broken conductor detection, in this case multiple pickups have occurred.

Fig. 10. ICR measurements for a phase B broken conductor simulation

V. CONCLUSIONS

This paper presented an impedance-based algorithm to detect the broken/falling conductor for a power transmission line. The solution can provide sensitive and reliable protection such that the affected circuit will be de-energized prior to the conductor hitting the ground, eliminating the risk of an arcing ground fault or energized circuit on the ground.

Another salient feature of the proposed algorithm is that it can work based on available voltage of the remote end of the line. The algorithm can operate using phase voltages (synchrophasor data), positive sequence voltage, and extended Clarke voltage of the terminals of the line. The algorithm can also take advantage of the existing IEEE C37.94 communication channel between differential relays of the line. As a result, it does not require a separate communication channel and can be used with existing infrastructure.

VI. REFERENCES

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