MITIGATION OF BLACKOUTS DUE TO MAL-OPERATION OF DISTANCE RELAYS BY USING THE FAULT RESISTANCE INFORMATION

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ABSTRACT

Mal-operation of protective relays was a main contributor for degradation of the system state during wide area disturbances. In many previous large scale blackouts, non-real fault phenomena like power swings, voltage instability and load encroachment were reasons for the mal-operation of the protection system leading it to lose security. On the other hand, the existence of fault resistances (R_f) during normal faults and during both High Impedance Faults (HIF) like tree faults affects the dependability of the protection system.

This research work proposes a new technique to enhance the operation of protective relays by using Phasor Measurement Units (PMUs). The technique decides based on the fault resistance information either to block the relay operation (e.g. during power swing) or to issue the trip command if the protection system fails to detect the fault (i.e. due to normal R_f or HIF). Based on the proposed technique, secure and dependable operation of protective relays is achieved reducing the probability of Blackouts.

INTRODUCTION

Undesired distance relay operations were a factor for causing cascading failures as seen in previous large scale blackouts. Several phenomena like power swings, voltage instability and load encroachment that occurred during these blackouts caused distance relays to mal-operate which degraded the system conditions [1, 2]. Security of protection system during these non-real fault conditions should be maintained to prevent such system state degradation.

On the other hand, from the dependability point of view, the distance relay should be able to detect all possible faults. Some factors that could worsen dependability of the protection system is the existence of fault resistance in the fault path which could lead the relay not to operate in the allowed time delay or even not to detect the fault at all [3]. Besides, HIF generally results in very low levels of zero sequence current [3]. It is possible in some cases, although rare, that a HIF enters the protected zone and stays there for a long time before it evolves into a solid fault [4]. Such an event could be interpreted as unstable swing [4] which could lead the relay to be blocked although in this case the relay could be expected to trip. Early detection of HIF is therefore required.

The reliability of distance relays (security and dependability) is studied in many references. Several techniques have been proposed to enhance the relays operation during non-fault conditions like load encroachment and voltage instability [5], power swing [6, 7]. On the other hand there exist techniques interested in dependability of the relay in case of existence of fault resistances or tree faults like [8, 9]. In comparison to the previous techniques, the proposed technique in this paper enhances both the security and the dependability of the relay. Both non-fault phenomena and faults with/without fault resistances (including faults due to tree contact) could be detected. Detection of faults that occur during non-real fault cases (e.g. HIF during power swing) is also possible with the same function. Sensitivity and simplicity are of the main advantages of the proposed protection function which satisfies the main protection system requirements. The paper is intended to show the concept of the protection algorithm with the help of the WECC test system.

THE PROPOSED TECHNIQUE

The idea

The proposed technique is based on a notice that the fault resistance itself could be used both as a fault detection criterion and also as an indicator for occurrence of no fault or non-real fault conditions. Fig. 1 explains this remark. The fault resistance in case of a faulty transmission line, Fig. 1a, could have a value ranging between zero (bolted faults) to the maximum expected value of HIF which could reach several tens of kilo Ohms [3, 9, 10]. If the transmission line is having non-real fault conditions (or healthy), the fault resistance will not exist, Fig. 1b. It is possible in this case to assume that the fault resistance virtually exists (i.e. virtual R_f) and having an extremely high value (theoretically infinity).

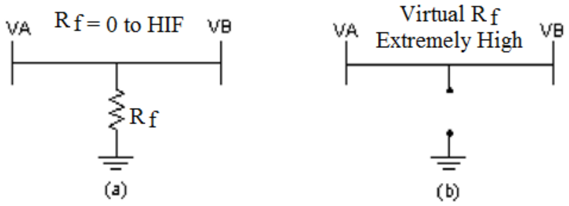

Fig.1 R_f and virtual R_f

Continuous monitoring of the fault resistance will yield two possibilities; either R_f is extremely high or R_f is relatively low. A very high value of R_f (virtual R_f) indicates no-fault conditions (or non-real fault) while relatively low R_f (0 to HIF) indicates a fault condition. This drastic change of R_f as depicted in Fig. 2 candidates

R_f to be a good and simple protection criterion in all expected system events; bolted faults, HIF including tree faults, non-real fault and healthy system conditions.

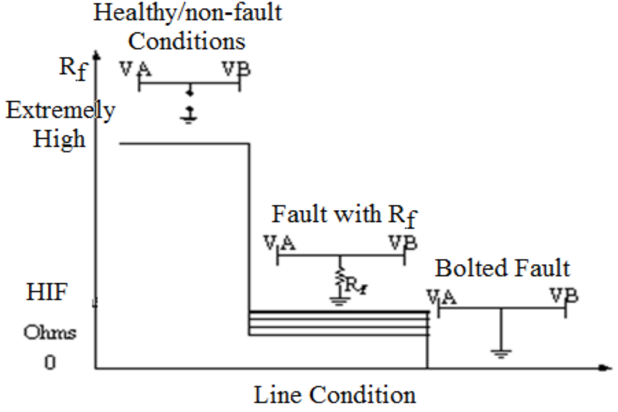

Fig.2 Regions of fault resistance

Flow Chart

Fig.3 depicts a transmission system to illustrate how the suggested protection criterion can be applied. Fig.4 shows the flow chart. In previous blackouts mal-operation of Zone 3 of distance relays caused degradation of the system state. In this illustration Zone 3 of each line will be considered.

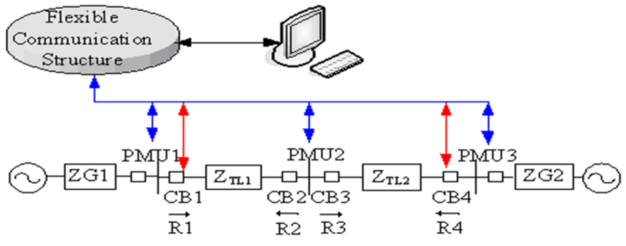

Fig.3 Protection scheme for two transmission lines

The values of voltages and currents at the terminals of transmission lines TL1 and TL2 are measured using synchronized phasor measurements device (PMU).

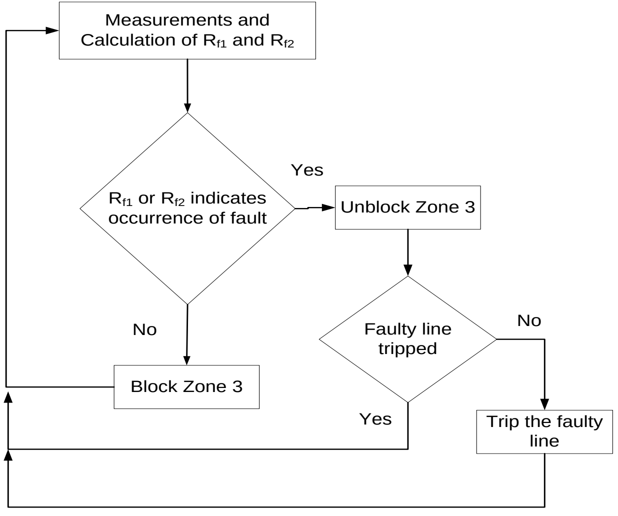

Fig.4 The new algorithm applied on zone 3

R_{f1} and R_{f2} of transmission lines TL1 and TL2 is calculated. Both R_{f1} and R_{f2} are extremely high during healthy or non-fault conditions (Fig.1) and in this case blocking of zone 3 associated for each line takes place saving the system from mal-operations of distance relays. Once a fault occurs on any of the lines, R_f of that line drastically reduces indicating a fault. Unblocking signal will be issued leaving the distance protection scheme to operate normally. Because there is a possibility for distance relays not to trip in case of existence of fault resistances, the proposed function will still monitor the operation of the relays (e.g. R3 and R4 in case of a fault on TL2). If the fault doesn't clear after time delay setting of zone 2 has passed then the algorithm will trip the breakers of TL2. This ensures faster disconnection of only the faulty line before it is tripped by zone 3 causing TL1 to be disconnected.

Calculation of R_f

From Fig.5, the voltages and currents at terminal A and B during a fault with fault resistance R_f can be described by the following equations:

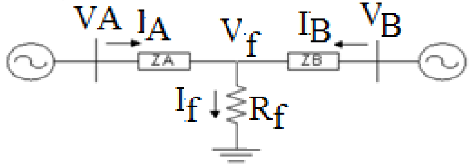

Fig. 5 System for calculation of R_f

$$\overline{V}_A = \overline{I}_A\overline{Z}_A + \overline{I}_f R_f \Rightarrow \frac{\overline{V}_A}{\overline{I}_A} = \overline{Z}_A + \frac{\overline{I}_f}{\overline{I}_A} R_f \quad (1)$$

$$\overline{V}_B = \overline{I}_B\overline{Z}_B + \overline{I}_f R_f \Rightarrow \frac{\overline{V}_B}{\overline{I}_B} = \overline{Z}_B + \frac{\overline{I}_f}{\overline{I}_B} R_f \quad (2)$$

By adding (1) and (2) we get:

$$\frac{\overline{V}_A}{\overline{I}_A} + \frac{\overline{V}_B}{\overline{I}_B} = \underbrace{\overline{Z}_A + \overline{Z}_B}_{Z_{T.L.}} + R_f\left(\frac{\overline{I}_f^{\,2}}{\overline{I}_A\overline{I}_B}\right) \quad (3)$$

Where $\overline{Z}_A + \overline{Z}_B$ is equivalent to the total impedance of the transmission line ($\overline{Z}_{T.L.}$).

From (3), R_f is equivalent to:

$$R_f = \left(\frac{\overline{V}_A}{\overline{I}_A} + \frac{\overline{V}_B}{\overline{I}_B} - \overline{Z}_{T.L.}\right) * \left(\frac{\overline{I}_A\overline{I}_B}{\overline{I}_f^{\,2}}\right) \quad (4)$$

Where $\overline{I}_f = \overline{I}_A + \overline{I}_B$

Equation (4) is valid only in case of symmetrical fault conditions. In order for the function to be used to detect single line to ground faults, the following modifications should be done to (4). First the sequence voltage at the fault point is calculated from (6), where i could be 1, 2 or 0 which represents the positive, negative and zero sequence respectively.

$$R_f = \frac{V_f}{I_f} \qquad (5)$$

$$V_{fi} = \left(\frac{\overline{V}_{Ai}}{\overline{I}_{Ai}} + \frac{\overline{V}_{Bi}}{\overline{I}_{Bi}} - \overline{Z}_{T.Li.} \right) * \left(\frac{\overline{I}_{Ai}\,\overline{I}_{Bi}}{\overline{I}_{fi}} \right) \qquad (6)$$

$$\overline{I}_{fi} = \overline{I}_{Ai} + \overline{I}_{Bi}$$

R_f for each phase will be calculated from (7) to (9)

$$R_{fa} = \frac{V_{f1} + V_{f2} + V_{f0}}{I_{Aa} + I_{Ba}} \qquad (7)$$

$$R_{fb} = \frac{a^2 * V_{f1} + a * V_{f2} + V_{f0}}{I_{Ab} + I_{Bb}} \qquad (8)$$

$$R_{fc} = \frac{a * V_{f1} + a^2 * V_{f2} + V_{f0}}{I_{Ac} + I_{Bc}} \qquad (9)$$

I_{Aa} and I_{Ba} are the phase currents of phase a from busses A and B repectively.

The effect of the transmission line stray capacitance is compensated for by subtracting the stray current from the injected current. However, the authors will discuss the effect of stray capacitance on the proposed algorithm in a future publication.

SIMULATIONS AND APPLICATIONS

WECC shown in Fig.6 has been used to test the operation of the function. The system parameters could be found in [11].

Test of the function under non-fault phenomena

Power Swing

If a three phase fault takes place at the middle of line 4-5 to initiate a power swing in the system [7]. The current and voltage waveforms at line 9-6 looking from bus 9 and the impedance seen by the distance relay at bus 9 are shown in Fig.7 and Fig.8 respectively. Depending on the settings of the relay a false tripping signal could be issued which might cause further system deterioration. During the power swing the corresponding $R_{f4\text{-}6}$ and $R_{f6\text{-}9}$ are shown in Fig.9. $R_{f6\text{-}9}$ and $R_{f4\text{-}6}$ are extremely high and indicate that a tripping of the distance relays is not required. The relay will be blocked. This blocking action will prevent further deterioration of the system.

Load Encroachment

The load at Bus 6 of the WECC in Fig.6 has been increased to simulate a load encroachment case. Fig.10 traces the locus of the measured impedance by the distance relay at Bus 9. The load encroaches into the relay characteristics as it increases. The relay in this case could mal-operate causing further disturbances to the system and a collapse might occur.

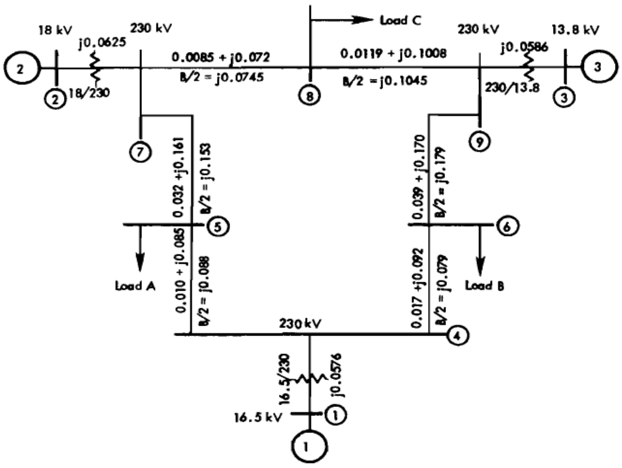

Fig. 6 WECC test system [11]

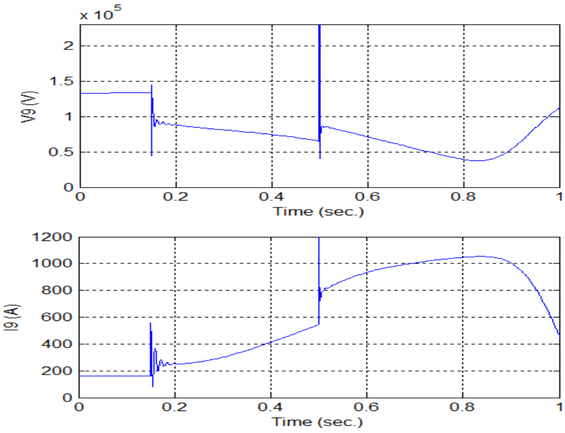

Fig.7 Voltage and current waveforms at Bus 9

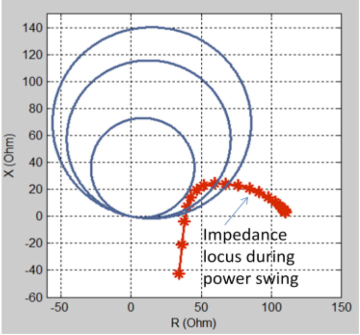

Fig.8 Impedance seen by relay at bus 9 (Line 9-6)

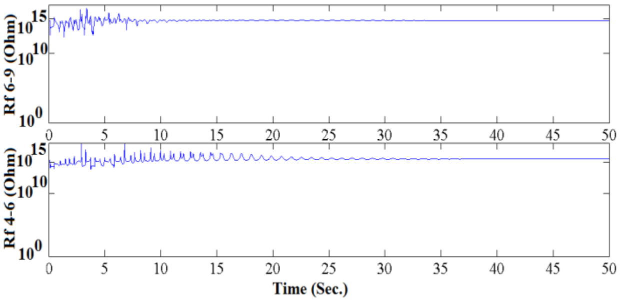

Fig.9 $R_{f4\text{-}6}$ and $R_{f6\text{-}9}$ during power swing

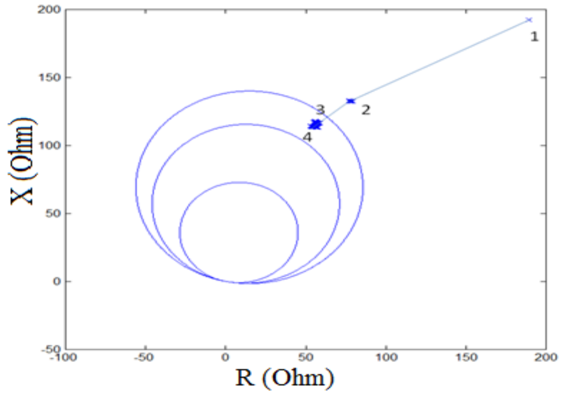

Fig.10 Load encroachment

The values of $R_{f4\text{-}6}$ and $R_{f6\text{-}9}$ during the load increase keep very high as shown in Fig.11 indicating that the distance relay at Bus9 is to be blocked.

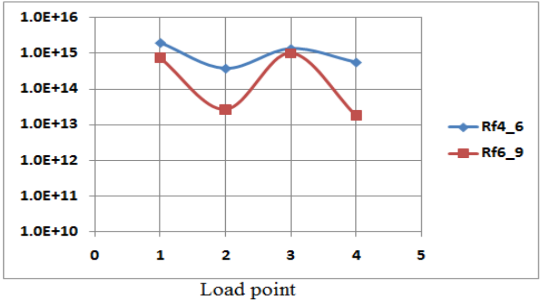

Fig.11 Change of $R_{f4\text{-}6}$ and $R_{f6\text{-}9}$ during load increase

Test of the Function in case of faults

The following tests have been carried out without initiating the power swing at the beginning of the simulation. The tests will show first the performance of the function in case of symmetrical faults then in case of single line to ground faults. Other types of faults like phase faults and double phase to ground faults could be detected by the function.

Symmetrical Faults

Assuming that a three phase fault occurred on line 4-6, $R_{f4\text{-}6}$ of phases a, b and c drastically change from being extremely high (before the fault occurs) to be very low and having the fault resistance value during the fault as depicted in Fig.12. R_{fa} is only shown due to the limited space. R_{fb} and R_{fc} are exactly like R_{fa}.

Fig.12 shows the results before, during and after a 1 Ohm fault occurs at the middle of line 4-6 after one second of the start of the simulation. The same fault has been simulated at different fault resistances and fault locations. Before the fault occurs and after the fault clearance, the value of R_f remains as in Fig.12 but during the fault, R_f calculated by (7) to (9) takes the value of the simulated R_f as shown in Fig.13.

In case of symmetrical faults it is not expected that the fault resistance could reach very high value as depicted in Fig.13, however the test has been conducted at these high values only to validate the results of (7) to (9).

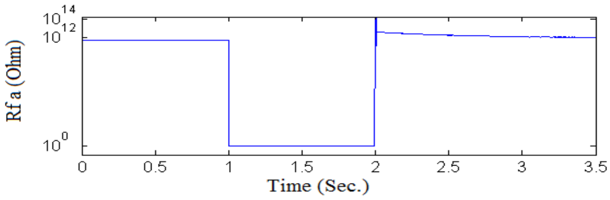

Fig.12 R_{fa}, R_{fb} and R_{fc} during a symmetrical fault

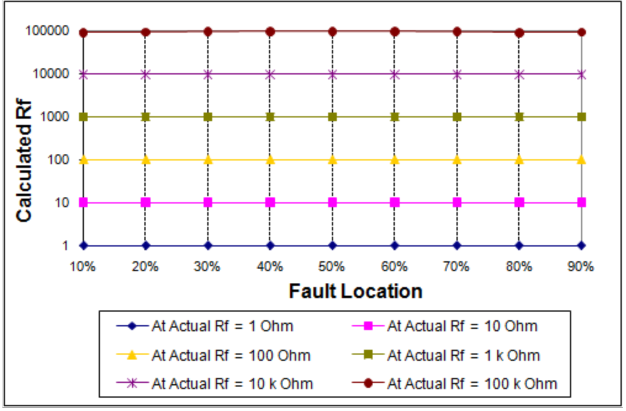

Fig. 13 Calculated R_f at different locations

Single Phase to Earth Fault

This section presents the operation of the function in case of a single line to ground fault on phase A. Estimation of R_f on line 4-6 during single line to ground fault conditions is shown in Fig.14. R_f was taken to be 1 Ohm at the middle of the line. R_{fc} is as R_{fb}.This test has been carried out for different values of R_f at different fault locations and the results are similar to Fig.13. Unlike differential relays, the fault resistance even due to tree faults can be simply detected by the algorithm. If the fault resistance is due to a tree, conventional protection might not be able to detect that fault. In this case, the proposed algorithm will detect the fault correctly. The algorithm will trip directly if used as a standalone function or after time delay if used as a backup function to permit distance relays at busses 4 and 6 to operate.

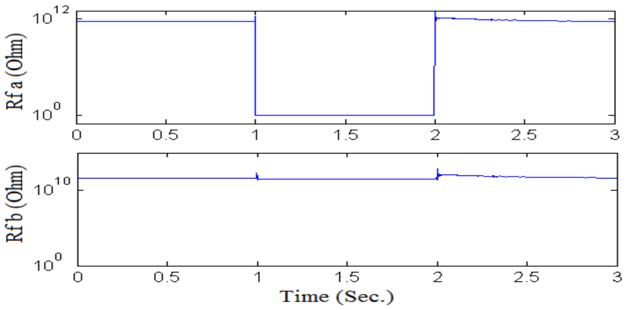

Fig.14 R_f in case of single line to ground fault

Faults during power swing

The test in this section is carried out after initiation of a power swing in order to check the function operation in case that a fault takes place during the power swing. A power swing is initiated by introducing a fault at the middle of line 4-5. After the fault is cleared by opening circuit breakers of line 4-5 the power swing is initiated in the system and the voltage and current waveforms at bus 9 looking into line 9-6 will appear as in Fig.15.

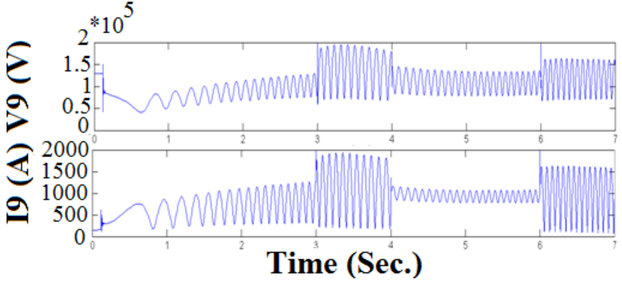

Fig.15 Voltage and current at Bus 9

If a single phase to ground fault takes place on line 4-6 during the initiated power swing, the corresponding R_{f4-6} is as shown in Fig.16. R_{fa} has drastically changed from being extremely high to the fault resistance value indicating that line 4-6 should be tripped. R_{fb} as well as R_{fc} remains high.

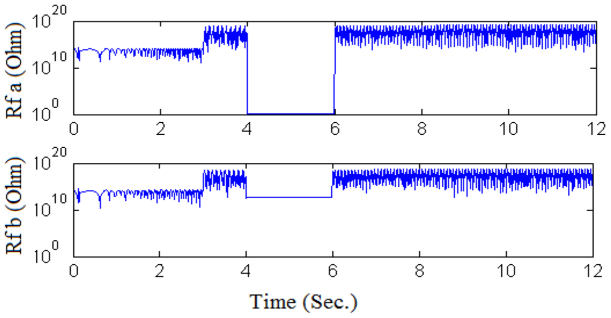

Fig.16 R_f (fault during power swing)

During the previous tests line6-9 encountered no faults. The calculated R_f of the phases of that line in all tests keeps extremely high as shown in Fig.17

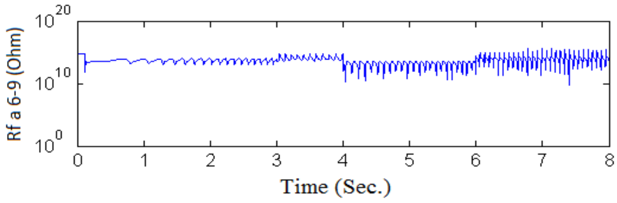

Fig.17 R_f of phases of line 6-9

CONCLUSIONS AND FUTURE WORK

In this paper a new protection fucntion has been illustrated. The function uses the fault resistance as a tripping criterion to decide whether the system is having a fault or not. Several benefits have been found by the direct use of the fault resistance as a tripping criterion, for instance, the protection system is kept secure during healthy conditions or during non-fault conditions like power swings, voltage instability and load encroachment which prevents further degradation of the system state during large area disturbances. Additionally, the function is dependable if normal faults or HIF with any value of fault resistance take place. Early detection of arcing faults could also be possible, however this should be further inspected.

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