





























































$$\begin{bmatrix} v_{a1} \\ v_{a2} \end{bmatrix} = \begin{bmatrix} \left( R_{a-Cable} i_{a1} + L_{aa-Cable} \frac{di_{a1}}{dt} + L_{ab-Cable} \frac{di_{b1}}{dt} + L_{ac-Cable} \frac{di_{c1}}{dt} \right) i_{Arc1} \\ \left( R_{a-Cable} i_{a2} + L_{aa-Cable} \frac{di_{a2}}{dt} + L_{ab-Cable} \frac{di_{b2}}{dt} + L_{ac-Cable} \frac{di_{c2}}{dt} \right) i_{Arc2} \end{bmatrix} \begin{bmatrix} x \\ R_{Arc} \end{bmatrix} \quad (4)$$

where  $[v_a, i_a, di_a/dt, di_b/dt, di_c/dt]$  are the time dependent coefficients taken from current and voltage waveforms and  $[R_{a-Cable}, L_{ab-Cable}, L_{ac-Cable}, L_{aa-Cable}]$  is the vector of constant circuit parameters. Solving the above matrix will give both unknowns. Multiplying the calculated  $x$  by 100 will give us the fault distance in meter.

### C. Load current estimation

For less than 10% of the customers, protective devices like fuses are located outside the building or factory. Therefore, the load can be easily disconnected from the network by the dispatched crew. Disconnecting the loads causes the fault current value to become equal to the measured sending end current. However, in the majority of the sites, loads cannot be disconnected due to limited access to the private customers as end users. As a consequence, the measured current at the sending end equals to the sum of fault and load current whereas the load current is unknown. This will produce an error in the estimated fault location. This error depending on the network parameters and load values can be more than %10. Hence, for developing a precise fault location algorithm, accurate estimation of load values is very important. This is achieved through an iterative method using the pre-fault data as an initial guess.

In the first iteration the difference of the post-fault measured current and pre-fault measured current is used as an initial guess for fault current. However, in time based method the subtraction post and pre-fault data should be calculated from the corresponding samples of different cycles. This has been well illustrated in Figure 3. Due to the variation of the load current during the fault the initial guess should be updated through iterative method. In all iterations, the fault current is updated according to the following method.

After calculating fault distance  $x$  by solving equation (4), the fault voltage can be calculated from the equation below:

$$v_{Fault} = v_a - x \left( R_{a-Cable} i_a + L_{aa-Cable} \frac{di_a}{dt} + L_{ab-Cable} \frac{di_b}{dt} + L_{ac-Cable} \frac{di_c}{dt} \right) \quad (5)$$

By having the fault voltage from equation (5), fault current can directly be calculated from the following equation.

$$i_{Arc} = v_{Fault} / R_{Arc} \quad (6)$$

where the fault resistance has been calculated from equation (4). The result is used for updating the fault current in equation (2). Substituting the obtained fault current with the previous value, the same procedure can be followed until the solution is converged within the allocated error. The flowchart of the algorithm has been displayed in Figure 4. More accurate calculation of the fault current will lead to the more precise fault distance estimation.

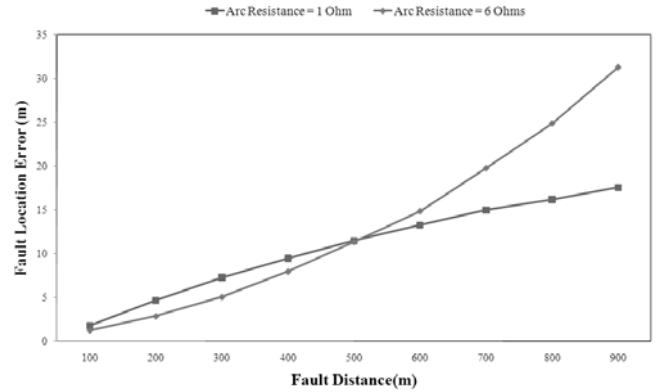


Figure 5 Fault location error for single phase fault (A→G)

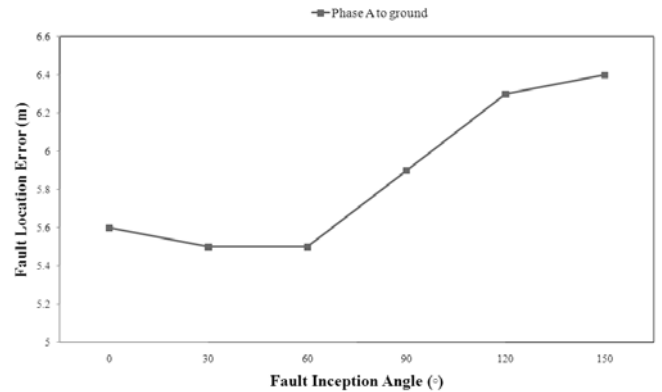


Figure 6 The effect of fault inception Angle

## IV. RESULT AND DISCUSSION

In order to test the proposed method a single section underground cable connected to the load was simulated within PSCAD-EMTDC environment. Figure 2 shows the network configuration. A series of 21.55  $\Omega$  resistive and 0.01162 H inductive element are composing the load in the circuit. The cable length is 1000 meters and its impedance matrix is:

$$Z_{Cable} = \begin{bmatrix} 0.66 + j0.503 & j0.221 & j0.221 \\ j0.221 & 0.66 + j0.503 & j0.221 \\ j0.221 & j0.221 & 0.66 + j0.503 \end{bmatrix} (\Omega/kM)$$

### A. The effect of fault resistance and fault distance variation

In LV distribution, the currents are not generally monitored. In general an earth fault or higher ohmic fault will remain unnoticed, until it draws enough current to blow a fuse. If it is assumed that the lowest practical fuse for a main cable is 125 A and it is further assumed that the load current is 60% of the fuse rating, a fault will have to draw more than 50 A to blow the fuse. Therefore, a fault resistance should always be less than 6  $\Omega$  in the LV scenario. As a result in this case, the worst case scenario for arc resistance is simulated to reflect the maximum possible error. Therefore, we will not

face with higher errors produced due to the high arc resistance.

For phase A to ground faults, the calculated fault locations for various points along the cable and two different fault resistances have been displayed in Figure 5. After investigating of the figure, it does not reveal any strict relationship between the estimation error and fault distance. However, the higher fault resistance leads to higher estimation error. For the proposed algorithm, the result for single phase to ground fault is reflecting the amount of error up to 20 meters for the worst case scenario.

#### B. Fault inception angle effect

Arcing fault can appear in a random angle of a cycle. Depending on the fault environment, the arc current will be extinguished after becoming zero or another arc will ignite. Normally for the intermittent faults, arc current will be extinguished after zero crossing. Hence, duration of arc is determined by the inception angle. In other words, the bigger the inception angle, the shorter arc duration. Figure 6 shows the effect of the inception angle to the accuracy of the fault location algorithm for 3 ohms arc resistance and 500 meter fault distance. A quick glance at the figure discloses that even very short arc provides enough data for the algorithm to locate the fault precisely. On the other hand, for faults that are longer than a quarter of cycle, arc duration does not have considerable affect on the accuracy. Because intermittent faults are normally longer than a quarter of a cycle, they can be located with a good accuracy by this algorithm. The same result is obtained for negative current values (with more than 180 degree phase angle).

### V. CONCLUSION

This paper has proposed a novel method for the location of arcing faults in low voltage distribution feeders utilizing single end measurements. The advantage of this method over current fault location methods is the ability of locating arcing faults which often occur, particularly in low voltage cables.

Utilizing the time based calculation, will enable the algorithm to find the location of the fault with a small number of samples. The proposed method is independent of the load value which is very important due to unpredictable and variable characteristics of the loads in low voltage systems.

For verification of the proposed algorithm, a low voltage feeder has been simulated within the PSCAD environment and the produced data has been analyzed via the algorithm. This algorithm provides accurate results as the short duration nature of arc is considered here whereas in the available methods, fault duration is assumed to be continued for at least one cycle. Obtaining accurate fault distance estimation proves that the algorithm is capable of calculating the location of short duration faults.

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