Time-based fault location method for LV distribution systems

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Abstract Due to the utilization of fundamental frequency, current impedance-based fault location methods are able to locate only permanent and linear faults. The duration of the arc in low and medium voltage systems can be as short as a quarter of a cycle. This period, which is normal for intermittent faults, is insufficient for fundamental frequency-based fault location algorithms. Therefore, available methods are not applicable for intermittent arcing fault location. In this paper, the time-based method previously proposed by the authors has been developed to locate short duration faults in LV distribution systems. The advantage of the proposed method over available methods is its capability for locating faults using fewer samples, which enable the user to locate both arcing faults as well as normal faults in the network. The main characteristics of an arcing fault, i.e., non-linearity and short duration, have been addressed in the proposed algorithms methodology. Various characteristics of a LV distribution system (i.e., heterogeneity, unbalanced load and line, etc.) have been taken into account in the current enhanced algorithm. The validity of the devised algorithm is studied within PSCAD-EMTDC environment and the obtained results show a good accuracy.

Keywords Arcing fault location · Single end · LV Distribution feeder

1 Introduction

A typical low voltage distribution feeder consists of numerous branches as well as laterals and different types of conductor. The presence of one-phase or three-phase loads being resistive, inductive or dynamic results in the distribution network exhibiting complicated characteristics [1]. The difficulty is further pronounced in low voltage feeders because of private customers as end users and hence the availability of one terminal for signal measurement. The acrimony of these feeders is summarized as:

- Heterogeneity of feeders given by different size and length of cables, presence of overhead and underground lines, etc.
- Unbalances due to the un-transposed lines and by the presence of single-, double- and three-phase loads.
- Presence of laterals along the main feeder.
- Presence of load taps along the main feeder and laterals.
- Dynamic characteristics of the loads [2].

Although low and medium voltage networks are similar in the above-mentioned characteristics, there are some differences among low and medium voltage with regard to fault location. Different protection scheme, lack of measurement units and different voltage levels can be counted among these differences. As the only protective devices in the LV systems are fuses, a fault will be un-noticed as long as the fuse has not blown. Hence, several short duration faults which do not heat up the fuses enough will not be detected. These faults will be detected later on when they turn to more severe faults. Moreover, as normally there is no measurement equipment installed on the low voltage feeder, the fault data cannot be recorded for further analysis. In addition, due to application of lower voltage in LV systems, network parameters' value such as loads is different which may have crucial effects on the accuracy of the estimated fault location.

Despite many similarities of low and medium voltage distribution networks, the aforementioned discrepancies hinder

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the users to apply available MV fault location methods [2–16] directly for LV systems. Lack of measurement units is the main obstacle for this.

Low voltage networks are composed of overhead lines and cables. Fault location in low voltage overhead lines is significantly easier as the permanent faults can be detected by visually inspecting the wires and temporary faults will not exist after replacing the fuse. Moreover, relatively short length of the LV networks (which prevents voltage to drop below the standard value for end customers) effectively reduces the cost and time spent for visual inspection of the line. On the other hand, due to existence of intermittent and transitory (short) faults in cables, the MV impedance-based fault location algorithms are unable to find the fault distance.

Despite numerous papers consider fault detection techniques in low voltage networks, a few of them have enhanced this study to the field of fault location in low voltage networks. The introduced methods to date for LV systems are mainly utilizing travelling wave methods. Livie et al. [17,18] have introduced an online fault location equipment for low voltage underground cables. Their algorithm is based on the time domain reflectometer (TDR) and transient recording system (TRS) method. Each of these has its own advantages and disadvantageous. TDR is more convenient, but subject to attenuation limits. The preferred point of connection for TDR mode is open end. In TRS, there is no need to connect units at open ends but at least two units are necessary. The main advantage is that they are not using reflected signals and only one transit along the different part of the cables is made by pulses.

Navaneethan et al. explain [19,20] an automatic fault location method for permanent faults in underground low voltage distribution networks. Signals measured from a TDR instrument are being pre-processed to filter out reflections due to laterals and tee-offs. The algorithm is able to locate 3-phase open or short circuit faults and also uses adaptive filtering to compare the TDR signals for fault location. Using real field data for demonstration of the relative performance of the method shows reasonably good fault distance accuracy.

Jung et al. [21] introduced a noise cancellation technique for identification of the reflective waves for fault location in a noisy environment which is based on the correlation of wavelet coefficients of stationary wavelet transform at multi-scales. Later on, the method of application of the suggested technique was described by Jung and Lee [22] for fault location on underground power cable systems. The fault location algorithm is tested by simulation on real power cable systems which proved it can detect and locate in even difficult scenarios.

Although time-based methods have not been used for low or medium voltage, the application of these methods has a long history in high voltage transmission systems. Due to the structural differences between transmission lines and low voltage networks, they cannot be directly imported and applied for use in low voltage systems.

In this paper, attempts are made to develop a ,single end impedance-based fault location algorithm for low voltage systems based on the time-domain formulations. In addition, a strategy has been introduced to record necessary data to be employed by the algorithm. Use of the proposed method alongside with a mentioned strategy will enable this method to locate intermittent and some transitory faults in a low voltage network. The algorithm covers single phase to ground, double phase and double phase to ground faults. In other words, it can cover all combination of faulty phases in network. Utilizing the time-based algorithms allows the method to locate short duration intermittent and transitory faults. Although the main focus of the proposed method is for transitory and intermittent faults in low voltage systems; however, it is capable of covering permanent faults in both MV and LV networks.

2 Fault location strategy

Despite the similarity of LV and MV systems, available MV fault location methods are not applicable to diagnose and locate faults in LV networks. Fault location in low voltage systems is slightly different from medium voltage as there is no permanent measurement unit installed in LV networks. Normally, the MV–LV transformer at the MV-LV substation is directly connected to a busbar which links LV switchgears. Each switchgear energizes a certain group of loads through a cable or overhead line feeder. Appropriate feeder type and protection are implemented depending on the load type (residential, business or industrial) and environmental restrictions. Apart from the individual protection devices for equipment and loads connected to the LV network, fuses are the main protection devices in LV systems.

Fault location in low voltage overheads is significantly easier as the permanent faults can be detected by visual inspection of the wires. Moreover, relatively short length of the LV networks (which prevents voltage to drop below the standard value for end customers) effectively reduces the cost and time spent for visual inspection of the line. As underground cables are buried in the earth, visual inspections are not necessary. In addition, pinpointing the fault location is required to avoid any unnecessary digging and reduce time and cost of the feeder maintenance.

Subsequently upon receipt of a report about the location of the fault or the blackout area, the maintenance crew are sent to the area. The measurement unit needs to be installed on the switchgear prior to the replacement of the fuse and re-energizing the system. In case of permanent or persistent faults, putting back the fuse will cause switch onto fault (SOF) which blows the new fuse as well. The measurement

unit will record the current and voltage till the fuse blows. The measured current and voltage can be used for locating the fault point. Lack of pre-fault data in case of permanent faults could deteriorate the accuracy of the results. The proposed impedance-based method can be used in parallel with other available methods for permanent fault location and gain more reliable results.

Due to complex features of intermittent faults, available methods in the market fail to locate them in LV systems. The proposed impedance-based method in this paper not only can locate permanent faults, but also it will enable the user to locate intermittent faults as well. In case of intermittent or transitory faults, the fuse does not necessarily blow straight away after inserting a fuse on the network. As duration of intermittent fault and particularly transitory faults is not long enough to heat up and blow the fuse, these faults can occur and restore automatically without the operation of protection system. The customer will suffer from power quality problems during this period. To solve this problem, the installed measurement unit needs to stay at the substation for a while preferably till the next fuse blowing fault which guarantees that at least one fault data have been recorded. Retrieving the recorded data in conjunction with proposed algorithm in this paper will identify the fault distance.

Although intermittent or transitory faults take place most likely in underground cables, however, as the described strategy is general and independent of the line, it can be used for both underground or over head line networks or even for the networks which consist both of them and it will provide the operation team with another option to hasten the location procedure. Alamuti et al. [23,24] provide a good description of transitory, intermittent and permanent faults in low voltage networks.

3 Fault location algorithm

3.1 Fault initiation time and fault type identification

To apply the measured data into the fault location algorithm, firstly the fault type (whether the fault is single phase, double phase, double phase to ground or three phase) alongside with the involved phases should be identified to select an appropriate algorithm. In addition due to application of the time-based algorithm, identifying the fault initiation time is essential to utilize the right data for fault location algorithm. Moreover, identifying the fault initiation time is necessary to distinguish between post-fault and pre-fault data. Application of the pre-fault data is needed to estimate the loading of the system. The better the estimation of load values, the higher the accuracy of the results.

The devised algorithm makes use of instantaneous current value and also the rate of rise of the current to identify

the fault initiation point. The algorithm sweeps the recorded current data to check whether its instantaneous value goes higher than the setting value or not. In parallel, the rate of rise of the current is also calculated for each step. If either instantaneous value or rate of rise of current passes the corresponding setting value, it will raise a flag to show a fault has occurred. Different flags are used for different phases. Therefore, by considering the raised flags for different phases, one can decide which phases are faulty.

The setting value depends on the rated current of the network and varies for different LV systems. However, the setting value should be higher than peak load current with a reasonable margin. For the simulated network, the initial setting value for instantaneous current was taken 300 A. consequently, the setting value for current rate of rise can be calculated as follows:

$$\text{RoR}_{\text{Set}} = 2\pi \times f \times I_{\text{Set}} \tag{1}$$

where I_{set} is instantaneous current setting and RoR_{set} is the calculated setting value for current **R**ate **o**f **R**ise.

The setting value for the current should cover a range of high resistance fault current to lower fault resistances. For relatively high fault resistance and consequently lower fault current, the proposed method is efficient. However, the induced current in healthy phases from fault current introduces an error in fault type identification. Due to mutual effect between different phases in a line/cable, the flowing current in healthy phases will increase after fault incident. For low resistance faults, the induced current will be high enough to exceed the setting value and raise the flags for healthy phases. To compensate this problem, the algorithm was further developed by use of dynamic setting value. In this method, the initial setting value will be determined according to the network specification. Hence, it will dynamically vary according to the fault current.

With the dynamic setting value, an appropriate setting parameter will be used to neutralize the effect of mutual impedance on healthy phases. It is on the basis of the idea that current amplitude generated due to the mutual impedance is significantly lower in comparison with faults. Therefore, if say a low resistance single phase fault takes place, the current amplitude could pass the setting value for all phases. However, just one phase is really faulty and instantaneous value for this phase is much higher in comparison with healthy phases. In dynamic setting value, the maximum current value among all phases (I_a, I_b, I_c) is taken and new setting (I_{SetNew}) value and the old current setting (I_{SetOld}) are shown in the following equation:

$$I_{\text{SetNew}} = \frac{\text{Max}(I_a, I_b, I_c) - I_{\text{SetOld}}}{2} \tag{2}$$

New setting value will be high enough to distinguish between current generated due to mutual impedance and fault in case of low resistance faults. At the same time, during lower fault currents there is no problem originated from mutual effect and dynamic setting value will introduce a setting value which is low enough to detect the fault.

3.2 Fault location concept

In the proposed method, a novel time-based fault location algorithm has been developed to overcome the previously mentioned problems that exist in low voltage distribution systems. The proposed algorithm utilizes the measured voltage and current data from one end of the network in conjunction with knowledge of cable/line parameters (self and mutual impedance) to find the location of the arcing fault.

The main characteristic of an arcing fault is its short duration (around a quarter of cycle) which distinguishes it from permanent or persistent faults.

Figure 1 shows the equivalent single section circuit employed in this paper for fault simulation. For the cable/line

$$v_a = x \left(R_{a\text{-Cable}} i_a + L_{aa\text{-Cable}} \frac{\Delta i_a}{\Delta t} + L_{ab\text{-Cable}} \frac{\Delta i_b}{\Delta t} + L_{ac\text{-Cable}} \frac{\Delta i_c}{\Delta t} \right) + R_{\text{Arc}} i_{\text{Arc}}$$

$$v_b = (R_{b\text{-Cable}} + R_{b\text{-Load}}) i_b + L_{ab\text{-Cable}} \frac{\Delta i_a}{\Delta t} + (L_{bb\text{-Cable}} + L_{b\text{-Load}}) \frac{\Delta i_b}{\Delta t} + L_{bc\text{-Cable}} \frac{\Delta i_c}{\Delta t}$$

$$v_c = (R_{c\text{-Cable}} + R_{c\text{-Load}}) i_c + L_{ac\text{-Cable}} \frac{\Delta i_a}{\Delta t} + L_{bc\text{-Cable}} \frac{\Delta i_b}{\Delta t} + (L_{cc\text{-Cable}} + L_{c\text{-Load}}) \frac{\Delta i_c}{\Delta t}$$

$$\begin{bmatrix} v_{a1} \\ v_{a2} \end{bmatrix} = \begin{bmatrix} \left(R_{a\text{-Cable}} i_{a1} + L_{aa\text{-Cable}} \frac{\Delta i_{a1}}{\Delta t} + L_{ab\text{-Cable}} \frac{\Delta i_{b1}}{\Delta t} + L_{ac\text{-Cable}} \frac{\Delta i_{c1}}{\Delta t} \right) & i_{\text{Arc}1} \\ \left(R_{a\text{-Cable}} i_{a2} + L_{aa\text{-Cable}} \frac{\Delta i_{a2}}{\Delta t} + L_{ab\text{-Cable}} \frac{\Delta i_{b2}}{\Delta t} + L_{ac\text{-Cable}} \frac{\Delta i_{c2}}{\Delta t} \right) & i_{\text{Arc}2} \end{bmatrix}$$
$$\times \begin{bmatrix} x \\ R_{\text{Arc}} \end{bmatrix} \quad (3)$$

illustrated in Fig. 1, the Eq. (3) gives the voltage and current relationship for each phase, on the assumption that an arc voltage occurs between phase A and the ground. Where $(v_a, v_b, v_c, i_a, i_b, i_c)$ are measured from the low voltage side of the transformer feeder and i_{Arc} is the arc (or fault) current.

In a single phase to ground fault (here it is assumed that phase A is involved), the first expression of Eq. (3) is used to locate the fault. In this expression $R_{a\text{-Cable}}$, $L_{aa\text{-Cable}}$, $L_{ab\text{-Cable}}$, $L_{ac\text{-Cable}}$, respectively, show the resistance, self- and mutual impedance of the whole cable/line. Similarly, x represents the fault position as the percentage of the cable/line length and R_{Arc} denotes the arc resistance. Both x and R_{Arc} are unknown. Generally, for solving a certain number of unknowns, it is necessary to provide the same number of equations. As here, the number of unknowns is
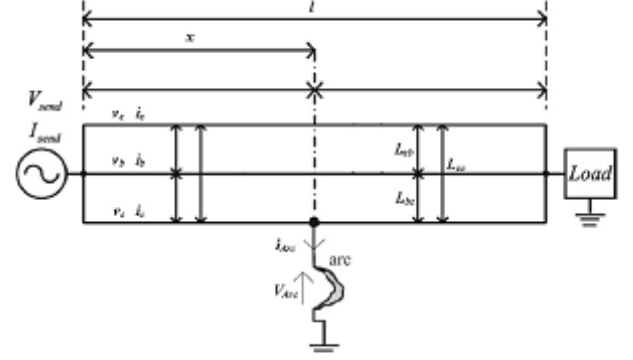

Fig. 1 Equivalent single section circuit for fault location algorithm

two (x and R_{Arc}), hence two equations are needed. As the equations contain current derivatives of phases (a, b and c), for construction of the required two equations, three readings (phase a, b and c) are necessary at each sample time. Utilization of two consecutive samples and rewriting their corresponding readings in the form of matrix yield the Eq. (3). Solution of this equation will provide values of x and R_{Arc}. Multiplying the calculated x by the line length will give the fault distance in meters.

In Eq. (3), subscripts 1 and 2 represent parameters that are assigned to samples 1 and 2, respectively. As the fault is on Phase a, hence V_{a1} and V_{a2} represent the voltage reading for the two consecutive samples.

Line voltages and currents at one terminal are uniformly sampled with the preselected sampling frequency $f_s = 1/T_s$, where T_s is the sampling period. The current derivative for each sample (1 and 2) in each phase (a, b and c) is calculated from

$$\frac{\Delta i}{\Delta t} = \frac{i(t + T_s) - i(t)}{T_s} \quad (4)$$

3.3 Load current estimation

For some 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 the sum of fault and load current, whereas the load current is unknown. This will produce an error in the estimated fault location. Depending on the network parameters and load values, this error can easily be more than 10 %. Hence, for developing a precise fault location algorithm, good estimations of load values are important. This is achieved through an iterative method using the pre-fault data as an initial guess.
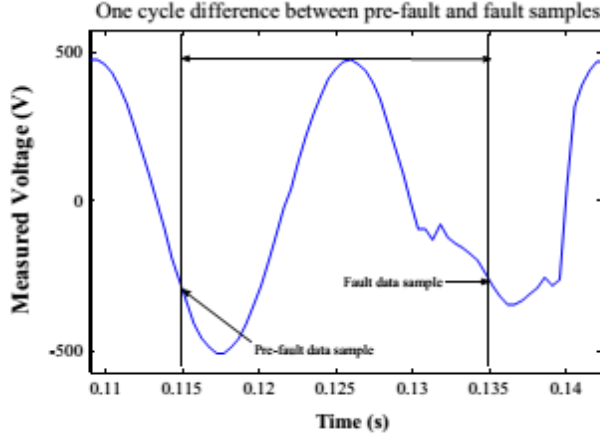
Fig. 2 Initial guess for load estimation

In the first iteration, the difference of the immediate post-fault measured current and pre-fault measured current is used as an initial guess for fault current. However, in the time-based method the subtraction of post and pre-fault data should be calculated from the corresponding samples of different cycles. This is illustrated in Fig. 2. Due to the variation of the load current during the fault, the initial guess should be updated through the iterative method. In every iteration, the fault current is updated according to the following method.

After calculating fault distance x by solving Eq. (5), the fault voltage can be calculated from the following equation:

$$v_{\text{Fault}} = v_a - x \left(R_{a\text{-Cable}} i_a + L_{aa\text{-Cable}} \frac{\Delta i_a}{dt} \right.$$
$$\left. + L_{ab\text{-Cable}} \frac{\Delta i_b}{\Delta t} + L_{ac\text{-Cable}} \frac{\Delta i_c}{\Delta t} \right) \quad (5)$$

Having determined the fault voltage from Eq. (5), fault current (i_{Arc}) can be calculated from Eq. (6).

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

where the fault resistance (R_{Arc}) has been calculated from Eq. (3).

The result is used for updating the fault current value in Eq. (3) for the next iteration. 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 Fig. 3. More accurate calculation of the fault current will lead to more precise fault distance estimation. Similar formulation can be derived for other types of vaults, i.e., phase to phase or phase to phase to ground faults.
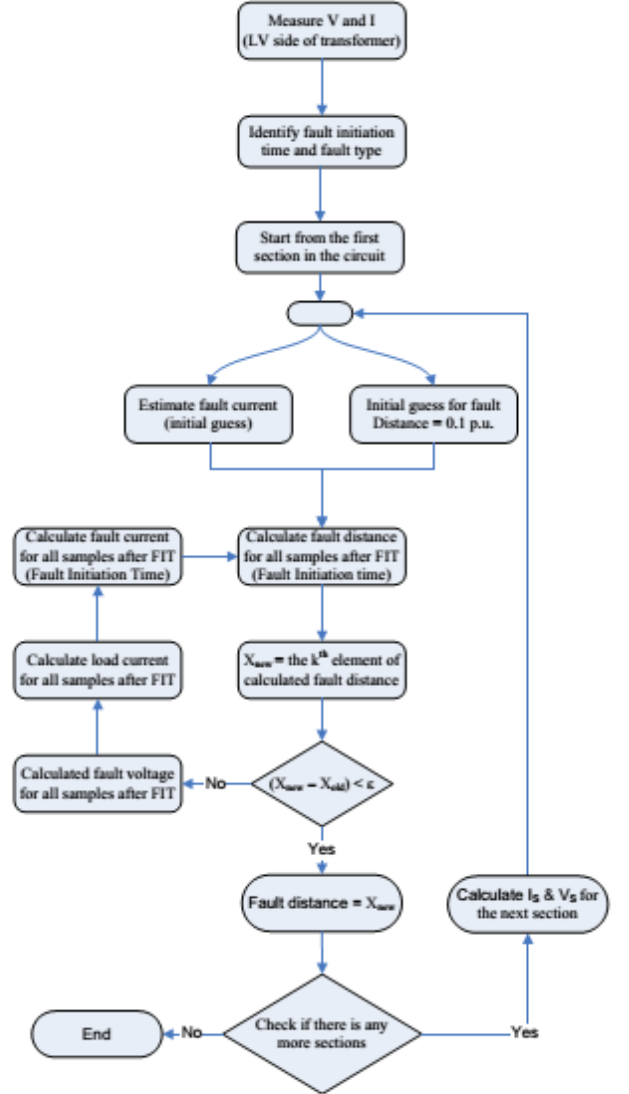

Fig. 3 Fault location flowchart

4 Generalized algorithm for multi-section distribution feeder

4.1 Time-based load flow

A distribution feeder is composed of numerous sections with unbalanced laterals and loads as well as heterogenic lines. Each section contains the overhead line or cable. Different combination of lines or underground cable with possible unbalanced (one, two or three phase) loads would be utilized in a network which is called heterogeneity. The proposed algorithm for networks of such characteristics searches each section individually for fault points and the search starts from the first section or distribution substation. If the calculated fault point is within the length of the section, the fault dis-

tance can be found. Otherwise, the sending end voltage and current values for the next section are calculated via a three-phase load flow before the algorithm proceeds to the next section.

This method of investigating network sections individually allows different line parameters, and characteristics to be set for each section. Setting different parameters for each section enables the algorithm to take into account the heterogeneity of the lines as well as unbalanced loads and laterals.

Due to considering the time-based fault location algorithm, an appropriate time-based load flow is developed to determine the voltage and sending end current of each branch. Occurrence of the fault changes the network configuration. As a result, the altered (post-fault) network is not identical to the pre-fault network and also the new configuration is not known. Alteration of the network map causes the normal load flow program to fail in evaluating the voltage and current of different nodes. Contrary to normal load flow programs which are using sending end voltage as well as network map and parameters, the developed load flow algorithm employs recorded data of substation voltage and current as well as the network data to calculate voltage and current for downstream branches. Therefore, a joint and reciprocal use of load flow and fault location algorithm is necessary to find the location of the fault in a multi-branch network. This has been explained as follows:

Starting from the first section, the fault location algorithm investigates if there is any fault or not. If the fault exists, the algorithm will terminate and shows the location of the fault. Otherwise, the voltage and current for the next node will be calculated via the following equations:

$$v_{Rabc} = R_{abc\text{-Cable}} i_{Sabc} + L_{abc\text{-Cable}} \frac{\Delta i_{Sabc}}{\Delta t} + L_{m\text{-Cable}} \frac{\Delta i_m}{\Delta t}$$
$$i_{Rabc} = i_{Sabc} \tag{7}$$

where i_m is mutual current matrix and L_m shows the mutual inductance between phases. Also subscripts S and R in Eq. (7) represent the Sending and the Receiving ends.

Because of the presence of unbalanced loads and laterals before the fault point, the sending end current of the next section will be calculated using Eq. (8) from the receiving end current of the previous section. The sending end voltage equals the receiving end voltage of the previous section. If either lateral or load does not exist for any nodes, its impedance will be replaced with infinite value which consequently leads to zero value for its current. By modeling the loads and lateral with equivalent resistance and inductance, one can calculate the current flowing into the loads and laterals in each node via the following expressions:

$$Is_{\text{NextSection}}(t) = Ir_{\text{PreviousSection}}(t) - (I_{\text{Load}}(t) + I_{\text{Lateral}}(t))$$

$$i_{\text{Load}}(t_2) = \frac{v_{abc} + i_{\text{Load}}(t_1)/\Delta t}{R_{\text{Load(estimated)}} + L_{\text{Load(estimated)}}/\Delta t}$$
$$i_{\text{Lateral}}(t_2) = \frac{v_{abc} + i_{\text{Load}}(t_1)/\Delta t}{R_{\text{Lateral(equivalent)}} + L_{\text{Lateral(equivalent)}}/\Delta t} \tag{8}$$

where R_{Load} is the load impedance which is estimated from the pre-fault data by three-phase power flow. It can be a balanced load (three phase) or unbalanced (one or two phase). R_{Lateral} is the equivalent lateral impedance which is again estimated from the pre-fault data by three-phase power flow. It can be a balanced load (three phase) or unbalanced (one or two phase). $Is_{\text{NextSection}}$ is the sending end of the next section. $Ir_{\text{PreviousSection}}$ is the receiving end of the previous section.

Since, in the time domain load flow, calculation of the current or voltage (at t_2 sample) depends on the data obtained at the previous sample (t_1); therefore the load flow calculation needs to start a few samples before the fault to let the algorithm converge to the correct values. The initial guess for all currents including load and laterals and branch current for each node has been taken as zero. Although it takes a few samples for the current value to converge to the actual value, this is not influential on the accuracy of the algorithm.

4.2 Faults on a single- or double-phase laterals

The three-phase aforementioned load flow is able to calculate sending end current and voltages of the single- and double-phase laterals. Therefore, with a minor modification into the mentioned algorithms, faults in single- or double-phase laterals can also be located. This modification can be implemented by removing the corresponding phases which are missing in the laterals from the Eq. (3). The modified expressions then can be employed for faults on single- or double-phase laterals. One has to note that in the case of phase to phase (to ground) fault in double-phase lateral, the relevant double-phase (to ground) fault expression has to be used.

4.3 Algorithm flowchart and assumptions

In the presence of laterals in complicated networks, multiple estimations will be provided by the algorithm. The number of estimates, for a fault, depends on the system configuration and the location of the fault. Various methods can be used to overcome this problem like fault indicators, customer call, or intelligent fault diagnosis schemes such as current pattern matching rules [7,25] and the artificial neural networks method [26]. Information from these techniques is combined with multiple estimates to arrive at a single estimate for the location of a fault.

Fig. 4 Equivalent LV distribution system for fault location algorithm
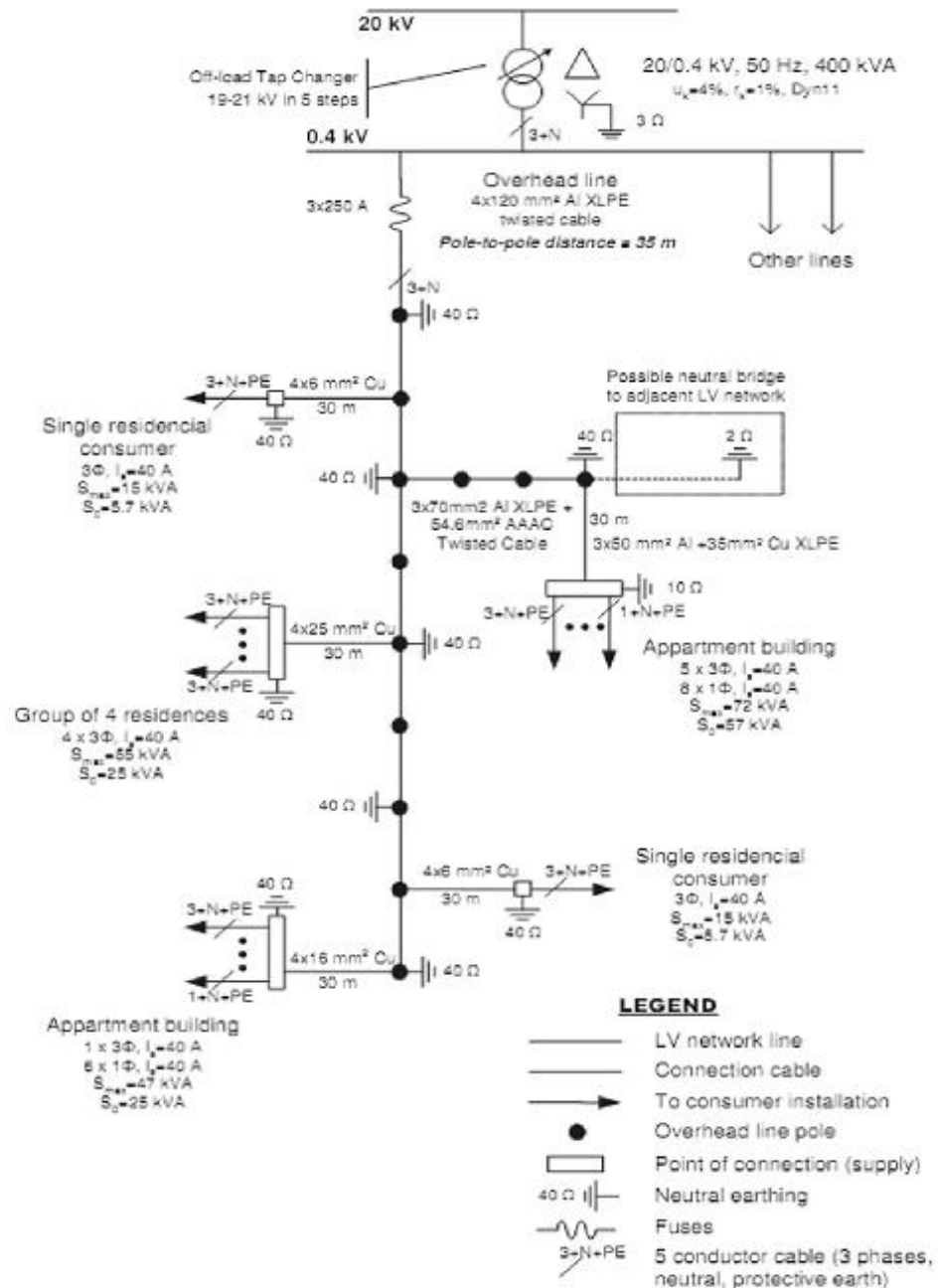
The iterative processes for finding the fault distance are explained in the following steps:

(1) Measure the voltage and current from substation node (first node of the network).
(2) Identify the fault initiation time and fault type.
(3) Start the fault investigation for the first section.
(4) Determine the post-fault current and pre-fault current.
(5) Start with an initial guess for the fault distance X_1.
(6) Use $|I - I_{load}|$ as an initial guess for the fault Current, where I is the pre-fault current at the substation node.
(7) Determine the voltage and current of the faulted point.
(8) Calculate the distance X_{i+1} from the Eq. (5).
(9) If $|X_{i+1} - X_i| < \varepsilon$ the fault is found, otherwise repeat from step (7).
(10) If the estimated distance is within the length of the section stop the algorithm, otherwise calculate the sending end current for the next section from (8), then go to step (4).

(11) Stop the algorithm when all sections have been investigated.

The above steps have also been presented as a flowchart in Fig. 3.

5 Results and discussion

5.1 Result explanation

For providing voltage and current data, a network described in Fig. 4 is simulated within the PSCAD-EMTDC environment and various faults are created at different points of the network. Network data as well as load data for each branch can be found, respectively, in Tables 1 and 2. A delta-grounded star transformer steps down the voltage level from 20 to 0.4 kV. The low voltage busbar is connected to three branches supplying residential, industrial and business loads. The measurement devices are installed on the outgoing feeders which record the fault data. For this study, different fault scenarios are created at different points with different fault types and resistances. Three different fault types namely single phase to ground, double phase and double phase to ground are simulated and the results are shown in Figs. 5, 6 and 7. The fault location error is calculated from following formula in meters (m):

$$Error(m) = |Fault\ Location - Estimated\ Location| \qquad (9)$$

Fault duration is considered as 5 mS which is a quarter of a cycle (50 Hz). The effect of the longer and shorter fault durations will be discussed in the following section. Although the algorithm is capable of calculating the fault distance for permanent or longer fault durations, but here the short duration faults are deliberately chosen to verify the ability of the proposed time-based method to locate very short duration faults which are normally not possible to locate via available frequency-based algorithms.

Inspection of Figs. 5, 6 and 7 suggests that either higher fault resistance or longer fault distance increases the fault error. Double phase to ground faults can be located with relatively low errors in comparison with other fault types. This

Table 1 Load data

Bus number	Resistance (Ω)	Reactance (Ω)
2	4845	3002.7
4	48,450	3026.7
5	21,250	13,170
6	4845	3002.7
7	21,250	13170

error would be the highest for phase to phase faults. Generally, the results show that the proposed algorithm can estimate the fault distance within a low error range.

5.2 Fault inception angle effect

An arcing fault can appear at random points within a cycle. Depending on the fault environment, the arc current normally extinguishes after crossing zero or another arc (secondary arc) may occur. In many intermittent faults, arc current will be extinguished after zero crossing. Hence, the larger the inception angle, the shorter is the arc duration.

Table 3 shows the effect of the inception angle on the accuracy of the fault location algorithm for 0.1 and 0.5 Ω fault resistance and 140 m fault distance. Tentative inspection of Table 3 reveals that a very short arc cannot provide enough data for the algorithm to locate the fault precisely. On the other hand, for faults that are longer than a quarter of a cycle, arc duration does not have considerable effects on the accuracy. As the intermittent faults are normally longer than a quarter of a cycle, they can be located with good degree of accuracy with the proposed algorithm.

In general, occurrence of the arc fault in a network will change the R/L ratio of the network. This will have effect on the current and voltage phase angle after the fault. Also faults in the form of Arc close to zero or 180° cannot be generated in the network. These cases are shown in Table 3 by the term "No Faull" (N/F). There are also cases where due to the very short length of the fault, the voltage and current are still in the transient state and the proposed algorithm is still unable to find the location. These scenarios are shown by the term "No Convergence" (N/C) sign in the Table 3. These scenarios suggest that the fault needs to be longer than a certain time for the algorithm to be able to find its distance. Outside of this interval, the algorithm can locate the fault with an acceptable accuracy.

5.3 Low voltage load's value

One of the main differences between MV and LV distribution systems is the load values. Lower voltage level and smaller customers make the load parameters to be significantly lower in LV networks. Existence of such small loads increases the error in finding the location of a relatively higher resistance faults. It is known that in the low voltage network the equivalent load value for a residential customer can be as low as 5 Ω which is about ten times less than an equivalent load value at medium voltage network. Furthermore, the existence of small loads aggravates distinguishing between load and fault impedance which in turn hinders the algorithm to converge to the correct result. In low voltage networks, the typical value for arc resistance is less than 0.5 Ω which is still detectable and locatable.

Table 2 Branch data

Bus from	Bus to	Line resistance ($\mu\Omega$/m)	Line self inductance (μH/m)	Line mutual inductance (μH/m)	Distance (m)
1	2	568.6	0.6184	0.3547	70
2	3	568.6	0.6184	0.3547	35
3	4	1125.7	0.6548	0.3820	70
3	5	568.6	0.6184	0.3547	70
5	6	568.6	0.6184	0.3547	105
6	7	568.6	0.6184	0.3547	35
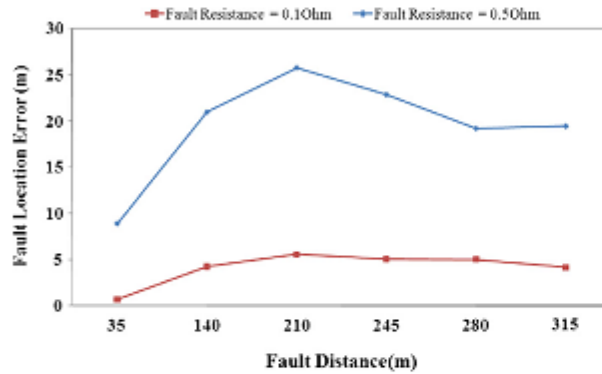
Fig. 5 Fault location error for single phase to ground fault
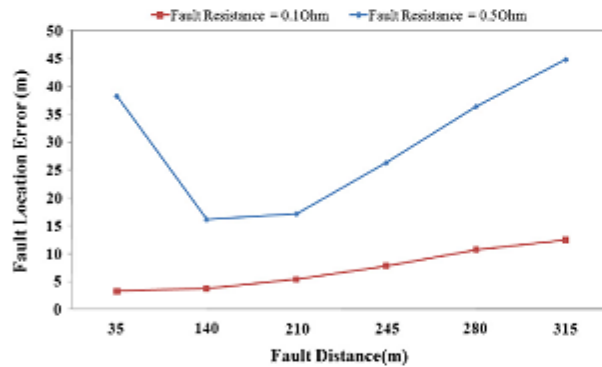
Fig. 6 Fault location error for phase to phase fault
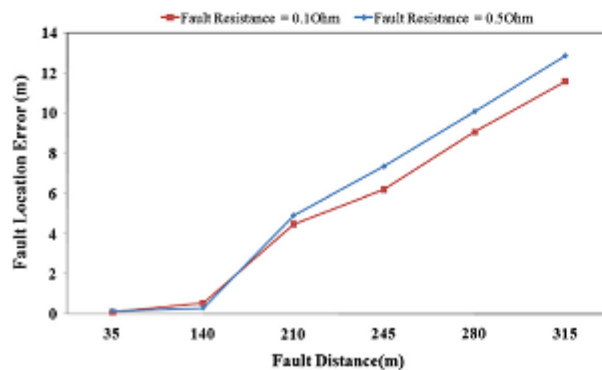
Fig. 7 Fault location error for double phase to ground fault

Since the considered load value for each section is the equivalent value of the load of the receiving end node of the mentioned section and all other downstream nodes beyond it, therefore, the equivalent load will be smaller by moving towards the source. This deteriorates the convergence process. In this case study, the equivalent load is as small as 1 Ω. Hence, if high impedance faults occur close to the substation, there is the possibility for the algorithm not to converge.

As a rule of thumb, the arc resistance is proportional to the inverse of arc current [27,28]. Assuming the arc current is close to the load current (normally is much higher), a straight forward calculation for an average network with 100 A load shows that the arc resistance can be smaller than one ohm.

Therefore the proposed algorithms are able to cover majority of faults in low voltage networks.

6 Conclusions

A typical low voltage distribution system inherits various characteristics of medium voltage systems including heterogeneity of feeders, unbalances load taps and laterals and dynamic characteristics of the loads. Despite the mentioned similarities, there are some crucial discrepancies between MV and LV systems which hinder to directly apply MV fault location methods to LV networks. The main differences are various voltage levels, smaller load values, different faults and non-existence of permanent measurement.

In this paper, a novel impedance-based algorithm is proposed to improve fault location in low voltage (LV) distribution systems which can be employed alongside with available methods to increase the speed and accuracy. The introduced strategy suggests a relatively inexpensive way to measure fault voltage and current at the main LV substation. Hence, the measured data can be used along with the proposed algorithm to find the fault distance.

Faults in LV distribution network particularly in cable networks can be categorized as permanent, intermittent and transitory faults in terms of duration. Transitory and sometimes intermittent faults are not long enough to provide

Table 3 The effect of fault duration

Fault inception angle	Phase A -> G		Phase A -> B		Phase A and B -> G	
0	RF = 0.1 Ω	RF = 0.5 Ω	RF = 0.1 Ω	RF = 0.5 Ω	RF = 0.1 Ω	RF = 0.5 Ω
30	4.25	21.43	3	11.9	0.5	0.08
60	2.97	18.21	3.58	12.2	1.48	1.36
90	2.61	16.95	3.63	11.21	2.15	2.36
120	3.42	18.52	1.57	0.6	2.9	2.66
150	N/C	N/C	N/F	N/F	N/F	N/F
180	N/F	N/F	N/F	N/F	N/F	N/F

necessary data for normal impedance-based methods. Application of time-based expressions in the proposed algorithm will enable the users to locate such a short duration faults.

Also combination of the proposed method with a time-based three phase load flow as well as a search algorithm will enable the user to locate the faults in different branches with different line characteristics. In addition, the introduced fault location strategy compensates for the lack of measurement units to capture fuse blowing and non-blowing intermittent faults.

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