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Sun, H.; Nikovski, D.; Takano, T.; Kojima, Y.; Ohno, T.

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Hongbo Sun, Daniel Nikovski
Mitsubishi Electric Research Laboratories
Cambridge, MA 02139 USA

Tomihiro Takano, Yasuhiro Kojima, Tetsufumi Ohno
Mitsubishi Electric Corporation
Hyogo 661-8661 Japan

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Index Terms-- Distribution system, fault location, single-phase-to-ground fault, ungrounded, load estimation.

I. INTRODUCTION

Ungrounded distribution systems are widely used, especially at medium voltage levels. Compared with the grounded distribution systems, the ungrounded systems do not have intentional connection with the ground, but indirectly connect to ground through phase-to-ground capacitances of power lines. When a single-phase-to-ground fault occurs, the fault currents of ungrounded systems are usually less than normal load currents, thus the system can continue to operate until the fault is corrected. However, as a result of the fault, the distribution systems experience over-voltages, which can cause equipment damages when the fault is not corrected in a timely manner. Thus, fault detection and location estimation is important for the safe and stable operation of ungrounded systems.

Several fault location analysis algorithms have been proposed for distribution systems, including impedance-based methods [1], direct circuit analysis methods [2], transient based methods [3], signal injection methods [4], and knowledge-based approaches [5]. Those methods have their own limitations when applied to real time applications of ungrounded distribution systems. Impedance based methods and direct circuit analysis methods are more generic, and

much easier for implementation than other methods, but most of existing methods are designed for grounded distribution systems. Transient based approaches may get prediction results before the fault currents get into steady states, but usually require much higher sampling rate, and might not be cost effective. Signal injection methods use additional frequency signals and measures to locate the fault, and are only suitable for off-line applications. Knowledge based methods may get more accurate results if pre-training sets are closely matching with new fault events, but requires more computation efforts that other ones.

This paper proposes a new method for determining location of single-phase-to-ground faults of ungrounded distribution systems based on the during -fault measurements at the feeder breakers and intelligent switches. The reactive power factors of residual powers determined for the breakers and switches are used to determine the faulted feeder and feeder section. The power consumption for each individual load in the faulted feeder section are determined by multiplying a base power specified by load profiles with a set of uniform load scaling factor for all loads in the section. The load scaling factors are determined through a load flow based iterative procedure. The incremental changes of scaling factors for DELTA-connected loads are determined based on incremental phase-to-phase current changes which derived from mismatches of phase currents at the importing device of the section. The possible faulted line segments are determined by testing a sign change of faulted phase voltages on terminal buses of line segments, and the location of the fault is determined by finding a location along the faulted line segment having a zero voltage on the faulted phase. The test results for a sample ungrounded system are given to demonstrate the effectiveness of the proposed method.

II. PROPOSED METHOD

A. Ungrounded Distribution System and Measurements

Fig. 1 shows an example of ungrounded distribution system with a single-phase-to-ground fault. It includes a distribution substation in which a three-phase transformer with ungrounded winding connections is connected with multiple downstream feeders, and each feeder has one feeder breaker and several intelligent switches. Both the breakers and

switched are equipped with measuring units for voltages and currents. Based on the location of switches along the feeder, a feeder can be partitioned into several sections, and each feeder section has one feeder breaker or intelligent switch at its root as an importing measuring device, and may have one or multiple intelligent switches at its downstream boundaries as exporting measuring devices. The feeder section is defined as all buses and devices between the importing and exporting devices. The buses of a feeder section can be grouped into several layers according to the number of devices connected between each bus and the importing measuring device. The higher a layer number is, the farther the buses of the layer are from the importing device. In Fig. 1, the system has three feeders, each feeder has one breaker and two switches, and each feeder includes three feeder sections.
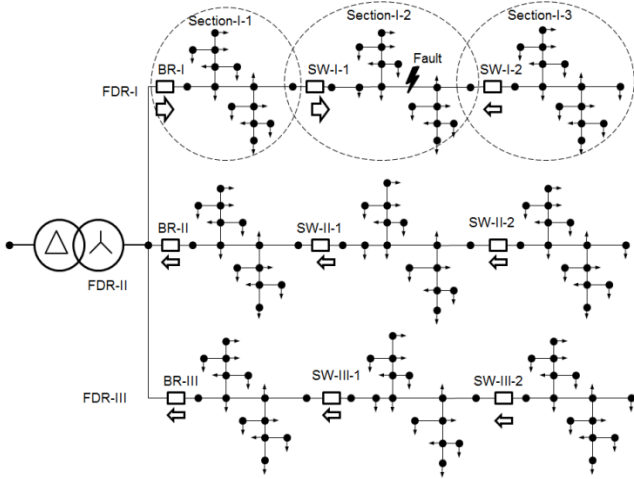

Fig.1. An example of ungrounded distribution system

The measurements collected from the feeder breakers and intelligent switches include the currents flowing through the device downstream on phase a, b and c, $I_{ps,a}, I_{ps,b}$ and $I_{ps,c}$, and the phase-to-ground voltages on phase a, b and c, $V_{p,a}, V_{p,b}$ and $V_{p,c}$, where bus p and bus s are the terminal buses of the device, and bus p is upstream to bus s. Based on the measured phase-to-ground voltages and phase currents, the residual voltage, residual current and residual power for the device can be determined as:

$$v_p^{res} = V_{p,a} + V_{p,b} + V_{p,c} \qquad (1)$$
$$i_{ps}^{res} = I_{ps,a} + I_{ps,b} + I_{ps,c} \qquad (2)$$
$$s_{ps}^{res} = v_p^{res} i_{ps}^{res^*} \qquad (3)$$

where, v_p^{res} is the residual voltage at bus p, i_{ps}^{res} is the residual current flowing from bus p to bus s and measured at bus p, and s_{ps}^{res} is the residual power for the device between bus p and bus s. The residual power can be decomposed into a real component, active residual power, and an imaginary component, reactive residual power. Accordingly, a reactive power factor of residual power, qf_{ps}^{res} can be determined as the ratio of reactive residual power over the total residual power, and also determined as the sine of the phase angle difference between the residual voltage and residual current according to:

$$qf_{ps}^{res} = \sin(\angle v_p^{res} - \angle i_{ps}^{res}) \qquad (4)$$

B. *Determination of faulted phase, feeder and section*

The faulted phase is determined according to the phase-to-ground voltages measured at the secondary side of the substation transformer, i.e. the upstream bus of the feeder breakers. When a bolted single-phase-to-ground fault occurs at a feeder, the phase-to-ground voltage of the faulted phase at the secondary side of the substation transformer drops to a small value close to zero, and the phase-to-ground voltages of two other un-faulted phase rise to values close to 1.73 times of its normal operation ones. The phase x is determined as faulted phase, if the following conditions are met:

$$|V_{sub,x}| \leq \underline{V} \quad x \in \{a, b, c\} \qquad (5)$$
$$|V_{sub,y}| \geq \overline{V} \quad y \in \{a, b, c\}, y \neq x \qquad (6)$$

where, $V_{sub,x}$ and $V_{sub,y}$ are the voltage measured at the secondary side of the substation transformer on the phase x and y respectively, and $\underline{V}$ and $\overline{V}$ are the lower and upper thresholds of voltage magnitude used for abnormal voltage determination. For examples, the lower and upper thresholds can be set as 0.30, and 1.40 per unit respectively.

The faulted feeder and feeder section can be determined by examining the reactive power factor of residual powers determined for the breakers and switches. Ignoring the asymmetry of power lines, the residual currents of an ungrounded system are mainly contributed from the phase-to-ground capacities of un-faulted phases of the faulted and un-faulted feeders, and the residual powers are dominated by reactive powers, that is the magnitude of reactive power factor for the residual power is close to 1.0. A feeder is determined as a faulted one if the reactive power factor of residual power at the feeder breaker is close to +1 as described in Eq. (7):

$$qf_{fdr}^{res} > \underline{qf} \qquad (7)$$

where, $\underline{qf}$ is a pre-determined lower threshold of reactive power factor. For example, $\underline{qf}$ is 0.9. A feeder section is determined to be a faulted one when the reactive power factors of residual powers are close to +1 at its importing measuring device, and close to -1 at one of its exporting measuring device as described as follows:

$$qf_{im}^{res} > \underline{qf} \qquad (8)$$
$$qf_{ex}^{res} < -\underline{qf} \qquad (9)$$

where, qf_{im}^{res} and qf_{ex}^{res} are the reactive power factors of residual powers at the importing device im and the exporting device ex respectively.

C. *Estimating Load Demands of the Faulted Feeder Section*

The load demands for the faulted feeder section are not measured, but determined based on the available measurements at the boundaries of the section and load profiles for each individual load in the section.

The loads include fixed loads and scalable loads. The fixed loads refer to the equivalent WYE-connected loads consumed by downstream feeder sections connected to the faulted feeder section through the exporting measuring devices. For an exporting measuring device, the equivalent power demands are determined according to:

$$S_{ex_i,x} = V_{ex_i,x} I^*_{ex_i,x} \qquad x \in \{a,b,c\} \qquad (10)$$

where, $S_{ex_i,x}$ is the equivalent power consumption at measuring device ex_i on phase x, $V_{ex_i,x}$ and $I_{ex_i,x}$ are the voltage and current of phase x measured at the measuring device ex_i. The scalable loads refer to individual DELTA-connected loads in the section. The power consumptions of an individual load at bus p, $S_{p,xy}$ are defined as:

$$S_{p,xy} = \alpha_{xy} S^{base}_{p,xy} \qquad xy \in \{ab,bc,ca\} \qquad (11)$$

where, $S^{base}_{p,xy}$ is the base power consumption given by load profile for the time interval of fault occurring, α_{xy} is an uniform scaling factor used for all load components between phase x and phase y in the feeder section.

A load flow based iterative procedure is used to determine the scaling factors for the feeder section. The upstream bus of the importing measured device of the section is treated as a constant voltage source, i.e. a swing bus. With a given set of scaling factors, the load flow of the section can be solved by using a load flow algorithm, such as backward/forward sweep method. Based on the results, a solved active power at the importing measuring device is determined, and then checked against a target active power determined by the voltage and current measurements. If the solved and target active powers on each phase are close enough, then the current set of scaling factors are the final solution. Otherwise, the scaling factors are adjusted iteratively until the difference is below threshold.

The solved active power for phase x at the importing measuring device, $P^{solved}_{im,x}$ is determined according to:

$$P^{solved}_{im,x} = |V_{im,x}| |I^{solved}_{im,x}| \cos(\angle V_{im,x} - \angle I^{solved}_{im,x})$$
$$x \in \{a,b,c\} \quad (12)$$

where, $V_{im,x}$ is the voltage on phase x measured at the importing measuring device, $I^{solved}_{im,x}$ is the solved phase current on phase x flowing into the section through the importing measuring device.

Considering the impacts of short circuit in the feeder section, the target powers are determined differently for a faulted phase and an un-faulted phase. For an un-faulted phase, the target active power on the phase at the importing measuring device is directly determined by using the corresponding voltage and current measurements on the phase. For a faulted phase, the target power is determined by using the measured voltage and an adjusted phase current which defined as the measured phase current with a subtraction of currents resulting from the fault. The target active power for faulted phase x and an un-faulted phase y, $P_{im,x}$ and $P_{im,y}$ are determined according to:

$$P_{im,x} = |V_{im,x}| |\hat{I}_{im,x}| \cos(\angle V_{im,x} - \angle \hat{I}_{im,x}) \qquad (13)$$

$$P_{im,y} = |V_{im,y}| |I_{im,y}| \cos(\angle V_{im,y} - \angle I_{im,y}) \qquad (14)$$

where, $\hat{I}_{im,x}$ is the adjusted current on faulted phase x, $V_{im,y}$ and $I_{im,y}$ are the voltage and current of un-faulted phase y measured at the importing measuring device. The adjusted current on phase x, $\hat{I}_{im,x}$ is defined as:

$$\hat{I}_{im,x} = I_{im,x} - T I_{im} + I^{shunt}_{im} \qquad (15)$$

where, I_{im} is the vector of currents measured at the importing measuring device, $T = [1 \quad 1 \quad 1]^T$, and I^{shunt}_{im} is the shunt current generated by all line segments downstream to the importing measuring device, and determined according to:

$$I^{shunt}_{im} = \sum_{ps \in DN_{im}} \frac{1}{2} T Y^{sh}_{ps} (\tilde{V}_p + \tilde{V}_s) \qquad (16)$$

where, DN_{im} is the set of line segments downstream to the importing measuring device, and p and s are two terminal buses of a line segment. Y^{sh}_{ps} is the shunt admittance matrix for a line segment between bus p and s, $\tilde{V}_p$ and $\tilde{V}_s$ are the estimated phase-to-ground voltages of bus p and bus s.

The voltages of buses of a feeder section are estimated based on the voltage measurements at the importing and exporting measuring devices of the section. The voltages at buses connected to the measuring devices are directly set as the measured values. For any bus residing in the connectivity path between each pair of the importing measuring device and one of the exporting measuring devices, its voltages are determined based its distances to two measuring devices and measured voltages at two measuring devices. If there are multiple exporting measuring devices existing, and common buses between different paths, the voltages of those common buses are set as the average of estimated voltages for all paths. The estimated phase-to-ground voltage of bus p, $\tilde{V}_p$ is determined according to:

$$\tilde{V}_p = \frac{1}{m} \sum_{i=1}^{m} \left(\frac{d_{p-ex_i}}{d_{im-p}+d_{p-ex_i}} V_{im} + \frac{d_{im-p}}{d_{im-p}+d_{p-ex_i}} V_{ex_i} \right) \quad (17)$$

where, m is the total number of paths that pass through bus p, V_{im} and V_{ex_i} are the voltages measured at the importing measuring device im and i-th exporting measuring device ex_i, d_{im-p} and d_{p-ex_i} are the sum of length of line segments residing at the path between the importing device and bus p, and between bus p and the i-th exporting measuring device respectively. For any bus not residing on any paths between the measuring devices, but fed from one of buses in the paths, its estimated voltage is set as the estimated voltage of the feeding bus on the paths.

The scaling factor adjustments are determined based on the equivalent current mismatches at the importing measuring device. After a load flow solution is obtained, a set of phase current mismatches between the solved currents and the target currents can be determined. The target currents are set as the corresponding measured or adjusted phase currents. Since the loads are DELTA-connected, those phase based current mismatches are converted into phase-to-phase based ones to be used. The current mismatches for faulted phase x, and un-faulted phase y at the importing device, $\Delta I_{im,x}$ and $\Delta I_{im,y}$ are determined according to:

$$\Delta I_{im,x} = \hat{I}_{im,x} - I^{solved}_{im,x} \qquad (18)$$

$$\Delta I_{im,y} = I_{im,y} - I^{solved}_{im,y} \qquad (19)$$

The incremental phase-to-phase current changes are derived from the phase current mismatches according to:

$$\Delta I_{im,xy} = -\Delta I_{im,y} \qquad (20)$$

$$\Delta I_{im,yz} = (\Delta I_{im,y} - \Delta I_{im,z})/2 \qquad (21)$$

$$\Delta I_{im,zx} = \Delta I_{im,z} \qquad (22)$$

where, x is the faulted phase, y and z are two un-faulted phases, $\Delta I_{im,xy}$, $\Delta I_{im,yz}$ and $\Delta I_{im,zx}$ are the incremental currents between phase x and phase y, phase y and phase z, and phase z and phase x at the importing device.

The required scale factor changes can be determined according to:

$$\Delta\alpha_{xy} = \frac{\Delta P_{im,xy}}{\sum_{p\in LD} P_{p,xy}^{base}} \qquad xy \in \{ab, bc, ca\} \quad (23)$$

where, $\Delta\alpha_{xy}$ is the required scale factor changes for loads between phase x and y, $\Delta P_{im,xy}$ is the required active power change between phase x and phase y, $P_{p,xy}^{base}$ is the base active power of load connected to bus p between phase x and y provided by the load profiles, LD is the set of load buses in the feeder section. The incremental active phase-to-phase power, $\Delta P_{im,xy}$ is determined as:

$$\Delta P_{im,xy} = |V_{im.xy}||\Delta I_{im.xy}|\cos(\angle V_{im.xy} - \angle\Delta I_{im.xy})$$
$$xy \in \{ab, bc, ca\} \qquad (24)$$

where, $V_{im,xy}$ is the phase-to-phase voltage between phase x and phase y.

D. Determining the Faulted Line Segment of Faulted Feeder Section

For a line segment having fault, the voltage on the faulted phase is substantially equals zero at the faulted location, so the voltage of faulted phase at its downstream terminal bus would have different sign than the voltage at its upstream terminal bus, if the fault currents did not flow into the ground through the fault location, but flew across the line segment and entered into its downstream bus.

A forward sweep procedure is used to determine the possible faulted line segments. The procedure sequentially assumes a single-phase-to-ground occurring downstream to a line segment, then test whether the faulted phase voltage on the downstream bus has a different sign than the voltage on the upstream bus. The procedures starts from the device connected to the first layer of the faulted section, i.e., the importing measuring device, and then moving forward to the devices downstream, and stops when all possible faulted line segments are identified. The voltages and currents of the importing measuring device are set as the measured values at the device directly.

Fig.2 shows an example of a line segment between an upstream bus p and a downstream bus s. Z_{ps}^{se} is the series impedance matrix of the line segment. I_{ps} and $I_{ps'}$ are the currents entering the line segment through the upstream bus p, and the currents leaving the segment through the downstream bus s.

The voltage of the downstream bus s, V_s is determined based on the values at its upstream bus, V_p and the phase currents on the line segment, I_{ps} according to:

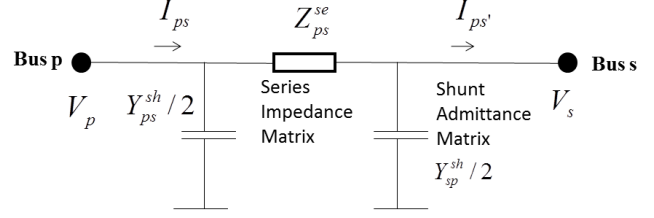$$V_s = V_p - Z_{ps}^{se}\left(I_{ps} - \frac{1}{2}Y_{ps}^{sh}V_p\right) \qquad (25)$$

Fig.2. Model of a line segment

I_{ps} is determined based on the currents of the upstream line segment, equivalent load currents at bus p, and estimated currents on all line segments adjacent to the line segment:

$$I_{ps} = I_{up'} - I_p^{load} - \sum_{t\in DD_p, t\neq s}\tilde{I}_{pt} \qquad (26)$$

where, $I_{up'}$ is the vector of currents leaving a line segment between bus u and bus p through bus p, and bus u is upstream to bus p, I_p^{load} is the vector of equivalent currents of loads at bus p, DD_p is the set of downstream buses that directly connected to bus p, $\tilde{I}_{pt}$ is the vector of estimated currents entering a device between bus p and bus t through bus p, and bus t is downstream to bus p. $I_{up'}$ is determined based on the phase current entering through the upstream bus u, and the shunt admittances of the segment between bus u and p:

$$I_{up'} = I_{up} - \frac{1}{2}Y_{ps}^{sh}(V_u + V_p) \qquad (27)$$

where, I_{up} is the vector of currents entering the line segment between bus u and bus p through bus u, and V_u is the vector of voltages at the bus u. I_p^{load} is determined based on the estimated power consumptions at the bus:

$$I_p^{load} = \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}\begin{bmatrix} S_{p,ab}^*/\tilde{V}_{p,ab}^* \\ S_{p,bc}^*/\tilde{V}_{p,bc}^* \\ S_{p,ca}^*/\tilde{V}_{p,ca}^* \end{bmatrix} \qquad (28)$$

where, $S_{p,ab}$, $S_{p,bc}$ and $S_{p,ca}$ are the power consumptions of loads at bus p between phase a and b, phase b and c, and phase c and a. $\tilde{V}_{p,ab}$, $\tilde{V}_{p,bc}$ and $\tilde{V}_{p,ca}$ are the estimated phase-to-phase voltages of bus p between phase a and b, phase b and c, and phase c and a. $\tilde{I}_{pt}$ is determined by accumulating all equivalent currents of loads and all shunt currents of line segments that fed by the line segment using the estimated phase-to-ground voltages according to:

$$\tilde{I}_{pt} = I_t^{load} + \frac{1}{2}Y_{pt}^{sh}(\tilde{V}_p + \tilde{V}_t) + \sum_{l\in DD_t}\tilde{I}_{tl} \qquad (29)$$

where, I_t^{load} and $\tilde{V}_t$ are the equivalent load currents and estimated voltage of bus t, DD_t is ,the set of downstream buses that directly connected to bus t, $\tilde{I}_{tl}$ is the estimated phase currents entering a device between bus t and bus l through bus t, and bus l is downstream to bus t. For the exporting measuring device, the estimated phase currents are set as the measured currents.

Eq. (25)-(29) can be also applied to a switch by setting the associated series impedance and shunt admittance as zeros.

A sign change of faulted phase voltages between two terminal buses of the line segment is determined according to:

$$\cos(\angle V_{p,x} - \angle V_{s,x}) \le \underline{pf} \qquad (30)$$

where, $V_{p,x}$ and $V_{s,x}$ are the voltages of faulted phase x at the upstream bus p and downstream bus s respectively. $\underline{pf}$ is a threshold for voltage sign change checking, for example -0.5.

E. Determining the Faulted Location within Faulted Line Segment

Assumed a single-phase-to-ground fault occurs at a location f along a line segment between an upstream bus p and a downstream bus s, d is the ratio of distance between the fault location f and bus p over total length of the line segment. The sub-segment between bus p and fault location f can be modeled with a series impedance dZ_{ps}^{se}, and a shunt admittance dY_{ps}^{sh} split into two terminal buses, p and f. Accordingly, the voltage at the fault location f on the faulted phase x, $V_{f,x}$ can be determined as:

$$V_{f,x} = V_{p,x} - dZ_{ps,x}^{se}(I_{ps} - \tfrac{1}{2}dY_{ps}^{sh}V_p) \qquad (31)$$

where, $Z_{ps,x}^{se}$ is the vector of series impedance matrix elements corresponding to the row of the faulted phase. The magnitude of this voltage should be zero. Thus, the location of fault can be determined by solving the root of a complex quadratic equation of distance ratio d:

$$\left(\tfrac{1}{2}Z_{ps,x}^{se}Y_{ps}^{sh}V_p\right)d^2 - \left(Z_{ps,x}^{se}I_{ps}\right)d + V_{p,x} = 0 \qquad (32)$$

After the ratio d is obtained, the exact geographic locations can be derived when the geographic coordinates of two terminal buses of the faulted line segment are known.

III. NUMERICAL EXAMPLES

The proposed method has been tested with several sample ungrounded systems, and satisfactory results are obtained.

Fig. 3 gives an example of ungrounded distribution systems. The system includes 1 three-phase transformer, and 3 feeders. Each feeder has 1 feeder breaker, 2 intelligent switches, 18 three-phase line segments, and 22 three-phase buses. Each line segment is 1.25 miles long, and the maximum length of a single feeder is 15 miles.
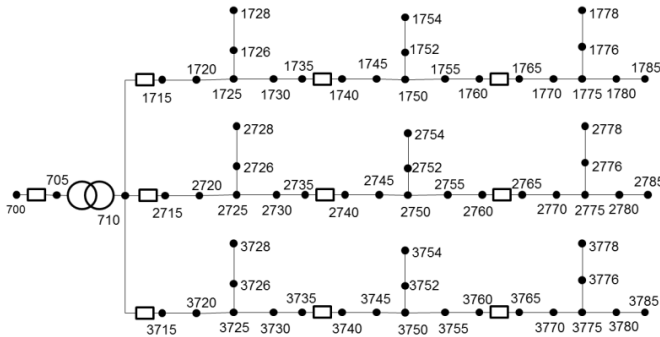

Fig.3. A sample ungrounded distribution system

Table I gives the test results on six different fault cases and two different load scenarios. For the stochastic load scenario, the power consumption of each load is set as a base value given by the base load profile plus a random load variation between -5% to +5% of its base value. For each fault case, the average and maximum estimation errors are calculated based on 100 randomly selected samples. As shown in Table I, the maximum estimation error of the proposed method is 0.0261 miles (i.e. 0.174 % of feeder length) if the base load profile scenario is used. In comparison, when the stochastic load profile scenario is applied, the maximum estimation error is 0.0358 miles (0.238 % of feeder length).

TABLE I. TEST RESULTS ON A SAMPLE SYSTEM

Fault Location	Base Load Profile		Stochastic Load Profile			
	Estimation Error		Average Estimation Error		Maximum Estimation Error	
	miles	%	miles	%	miles	%
2725	0.0049	0.033	0.0040	0.027	0.0065	0.043
2726	0.0053	0.035	0.0049	0.033	0.011	0.076
2735	0.0184	0.123	0.0180	0.120	0.0319	0.213
2750	0.0025	0.017	0.0035	0.023	0.0071	0.048
2775	0.0031	0.021	0.0034	0.023	0.0069	0.046
2780	0.0261	0.174	0.0260	0.173	0.0358	0.238

IV. CONCLUSIONS

This paper has proposed a novel method for locating single-phase-to-ground faults of ungrounded distribution systems based on the during-fault measurements at the feeder breakers and intelligent switches, and load profiles for individual loads.

The possible faulted area is first narrowed down to a specific section of a feeder by checking the reactive power factors of residual powers determined for the breakers and switches, and then the possible faulted line segment is determined using a forward sweep scheme to test a sign change of faulted phase voltages on terminal buses of line segments in the faulted section. The possible fault point is finally determined by finding a location along the faulted line segment having a zero voltage on the faulted phase.

The load demands of the faulted section are estimated based on the load profiles for each individual load and the measurements at the boundaries of the section.

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