A NEW TECHNIQUE FOR SHORT CIRCUIT FAULT LOCATION IN DISTRIBUTION NETWORKS

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ABSTRACT

A novel technique for short circuit fault location in distribution networks is presented. The technique computes the fault distance as reactance, based on the measurement of busbar voltages and feeding primary substation currents. The key factor is the compensation of the load currents superposed on the fault current. This leads to the accuracy, which is even better than with the previous methods, with the other difference being, that only one or two measuring device is needed, depending on the number of primary transformers at the substation.

INTRODUCTION

Traditionally the short circuit faults in power distribution lines were located by trial and error method, i.e. by dividing the line into sections and trying to close the energizing circuit breaker. This was both time consuming and also exposed additional stresses on the equipment.

When the numerical relays came available, their processing and communication capacity was soon utilized for the fault location purposes also. In Finland the most common practice was to register the fault current magnitude solely. This value was then compared to the computed current values in different feeder locations, and candidate places for fault location were hence obtained. In some European countries the alternative line of development was to use impedance relays for fault distance measurement. This leads to the better fault location accuracy, but is more costly.

The disadvantage of the both above methods is the need of modern relays in each feeder considered. In the case of existing substations, the cost of this requirement often is prohibitive. As a result, there are many substations, even in the most modern distribution companies, where the lines are not equipped with the measurement based fault location techniques.

To mitigate this problem, a novel technique has been developed, which is based on the measurement of busbar voltages and feeding primary transformer currents only. The key of the technique is the compensation of the load current superposed on the fault current. This leads to the accuracy, which is even better than with the previous methods, with the other difference being, that only one measuring device (or

relay) is needed per primary transformer.

In this paper, the different fault location algorithms are first presented. The factors affecting the accuracy of fault location are discussed. These include, in addition to the load current, the fault resistance, measurement accuracy and line impedance variations. Finally the practical implementation of the new method is discussed and its accuracy is assessed.

FAULT LOCATION BASED ON FAULT CURRENT MEASUREMENT

In this section the use of the measured fault currents to the location of short circuit is discussed. A practical implementation of this automation function is first presented.

The practical implementation of fault location

The first short circuit fault location system was based on the integration of distribution data management system (DSM), substation telecontrol system (SCADA) and the relay protection. The main idea is the comparison of the measured and computed fault currents. The computation is made on-line, assuming the same network topology as it was when the fault occurred. As a result, the estimated distance of the fault from the substation is obtained. This distance is then, in turn, compared to the network diagram, and the possible fault locations are shown on a graphical display of the distribution network in the DMS system.

When a fault happens, the operation of the fault location system is as follows [1,2]:

1. the protective relays store the fault information: currents, fault type, phases involved, feeder involved, reclosing steps.

2. this information is transmitted to the SCADA.

3. SCADA system adds the measured load current of the feeder and the active and reactive loads flows of the primary transformer

4. the DMS computes the corresponding fault currents of the feeder concerned in different locations and compares the measured data to the computation results. Before the

comparison, the load currents during the fault, are compensated for.

Performance of the fault location system

The main factors affecting the accuracy of short circuit fault location are the errors of measurement transformers and other measurement equipment, the variation of network component impedances, the load current superposed on the on the measured fault current and the fault resistance.

The errors due to the measurement transformers are usually small, only a few per cent of the actual fault distance. The most difficult is the case where the fault is close to the substation. Because of the high fault levels, the current transformers may become saturated, which deteriorates their accuracy.

When the fault location is based on the analysis of the current measurement solely, the result is also sensitive to variation of the network impedances. In addition to the variation of the resistances and reactance of the line concerned, the variation of short circuit level in the medium voltage busbar may also cause problems. The last one depends, in addition to the changes in the grid impedance, mostly on the position of the on-load tap changer of the substation transformer. For accurate fault location, the on load tap changer position should be telemetered.

The problem with the superposed load current is that its magnitude is changed dynamically with the voltage change during the fault. For the load behaviour, theoretical models have been developed, which can be used for load current compensation [3]:

$$\frac{P_1}{P_2} = \left(\frac{U_1}{U_2}\right)^{Pu} \qquad (1)$$

$$\frac{Q_1}{Q_2} = \left(\frac{U_1}{U_2}\right)^{Qu} \qquad (2)$$

Where U_1 and U_2 are voltage before and during the fault, P_1 and P_2 are the corresponding power and Q_1 and Q_2 corresponding reactive power, respectively, and *Pu* and *Qu* are the parameters, that model the voltage dependency magnitude. The parameters *Pu* and *Qu* vary with load type and time. According to the measurements made in distribution networks, the values are within the range $Pu = 1.5 … 2.0.$ and $Qu = 2.0 … 6.0.$

The largest errors are usually caused by the fault resistance, however. In the case of power arc, this can be calculated as follows [4]:

$$R = 8750/(I^{1.4 \cdot} 0.305) \quad (ohm) \qquad (3)$$

where the arc length (m) and I the fault current (A).

Resistance is increased when the fault current is decreased. Hence it is of importance especially in weak systems and for faults distant from the substation.

The fault current is known by measurement and the maximum arc length can be deduced from the line geometry. Consequently, it is possible to estimate the maximum value of the fault resistance. This gives the minimum fault distance. The other extreme case is with zero fault resistance. This gives the estimated maximum fault distance.

The best statement on fault location accuracy is based on practical experience. A fault location system, described in this section, has been in active use in several distribution companies in Finland since the beginning of 90´s. According to the practical experience in rural overhead line networks, the average error in fault distance estimation has been about 1.2 km. For comparison, the corresponding average fault distance is 13 km. Hence, the average error has been about 9 %. For close faults the absolute errors are smaller, whereas for distant faults they are larger, respectively.

FAULT DISTANCE USING DISTANCE RELAYS

A more accurate fault distance estimate is obtained, if distance relays are used. Since the fault resistance is unknown, the distance computation is made as reactance. For the three phase faults the corresponding equation becomes:

$$X = \frac{U}{I}\sin\varphi \qquad (4)$$

The errors in fault location are in this case due to measurement inaccuracy, line reactance variation, and reactive load current component. Due to its non-linearity, the power arc also appears partly as reactive, with the corresponding increase in fault location error.

Reactance relays are used for fault location in some utilities in Germany and Austria. In one application, the basis of the method is the network analysis model that is maintained for planning purposes [5]. Every feeder is split up into segments, that are physically defined by secondary substations and branching points. The segments have a length between 50 and 500 m, in few special cases longer.

With the network model an off-line short-circuit calculation is performed for every segment using power system analysis software. The short-circuit calculations are updated once a year. This results in a static reactance list for every feeder, that contains the fault reactance at the beginning and the end of every segment as well as names for the stations or branching points.

If a fault occurs, the telemetered fault reactance is transferred from the SCADA-system to a selection program on a PC or a SCADA-computer, that selects the suitable segments. There

is no on-line analysis to compute the fault location, just a segment selection. These segments are presented to the operator as probable fault locations in form of a small list (1 to 5 segments) on the screen.

The practical experiences of the fault location method have been excellent. The accuracy experienced has been better than 5 %.

THE NEW FAULT LOCATION ALGORITHM

The main error source of the reactance relays in fault location is the reactive fault current superposed on the measured fault current. This impact is stronger the heavier is the load of the feeder considered.

On the other hand, in the most of the existing substations, the relays are of relatively old construction, and do not allow the remote reading of fault currents. In these cases it is tempting to retrofit the fault location by equipping only the primary transformer compartment with the reactance measurement. However, in this case, the load current is usually very high, and conventional reactance relay applications are out of question.

To mitigate this problem, a new fault location algorithm was developed. The aim is to estimate the load currents from the measured quantities before, during and after the fault, and to make the compensation for the load current superposed on the fault current (written for the case of phases S and T):

$\underline{IL2}=\underline{I}sj-Icor,re(\underline{uL23})$ ire $\underline{I}s$ - $Icor,jl(\underline{uL23})$ ijl $\underline{I}s$

(5)

$\underline{IL3}=\underline{I}tj-Icor,re(\underline{uL23})$ ire $\underline{I}t$ - $Icor,jl(\underline{uL23})$ ijl $\underline{I}t$

Where

- $ire=\underline{I}1a/\underline{I}1$ is the p.u. share of normal state load current flowing in the parallel, sound lines,

- $ijl=(\underline{I}1-\underline{I}1a)/\underline{I}1$ is the p.u. share of normal state load current flowing in the faulty line,

- $\underline{uL23}=(\underline{U}sj-\underline{U}tj)/(\underline{U}s-\underline{U}t)$ is the p.u. voltage in substation busbar during the fault compared to the voltage before the fault occurred,

- $Icor,re(\underline{uL23})$ is the correction parameter for the compensation of load current flowing into the parallel sound lines during the fault, and

- $Icor,jl(\underline{uL23})$ is the correction parameter for the compensation of load current flowing into the faulty line during the fault.

The correction parameters are computer using Equations 1 and 2 for real and reactive parts of current, correspondingly.

In the above, Is and $\underline{I}t$ are the S- and T- phase currents before the fault, $\underline{I}1$ and $\underline{I}1a$ are the positive sequence current components before and after the fault has been disconnected, $\underline{I}sj$ and $\underline{I}tj$ are the S- and T- phase currents during the fault, $\underline{U}s$ and $\underline{U}t$ are the S- and T- phase voltages before the fault, and $\underline{U}sj$ and $\underline{U}tj$ are the S- and T- phase voltages during the fault.

After the load current compensation, the fault distance is computed as reactance as follows:

$$X = \text{Im}\left(\frac{\underline{U}_{sj} - \underline{U}_{tj}}{\underline{I}_{L2} - \underline{I}_{L3}}\right) \qquad (6)$$

The same algorithm is used for both two and three phase faults. In the latter case, Equations (5) and (6) are applied to the two phases having the biggest current. This arrangement minimises the effect of the possible power arc, since in the phases with highest current, the fault resistance must be at its smallest.

The algorithm works using the measurements obtained from the primary substation infeeding compartment. The key point is to make the compensation separately for the load current of the parallel sound lines and for the load current flowing during the fault in the faulty line. The voltage used for load current estimation (Eq. 1 and 2) is in the case of parallel lines the voltage measured in the substation busbar. In the case of estimating the load current in the faulty line, we have to use some lower voltage value. Typically this is, when the load current is assumed to be equally divided along the line, about 50% of the voltage in the busbar.

In nutshell, the algorithm is implemented as follows:

1. The relay records phase currents and phase voltages on a continuous basis, line voltage is used as a phase angle reference.

2. The fault distance computation is initiated by an opening of a feeder circuit breaker due to a fault.

3. the phase currents and phase voltages are registered in three steps: before the fault, during the fault and after the faulty feeder circuit breaker was opened.

4. The quantities during the fault are computed as three cycle mean values with the corresponding statistical deviations. These values are computed in a moving time window over several sample sets. The sample set with the smallest deviation is taken as a basis for fault distance estimation.

5. The two phases with the biggest fault current are selected.

6. The load currents during the fault the fault are compensated for using Equations (5).

7. The faulty line lenght reactance is computed using the model of Equation (6).

8. The computation result is compared to the line reactances and is shown at the network map of the distribution management (DMS) system.

Since the method is able to give only the distance from the substation to the fault (as a reactance value), usually several possible fault locations are obtained, in the different line branches. The actual fault location must be found among these candidate locations by some other means, such as by fault indicators or by trial and error [6].

Fault location accuracy of the new algorithm

The accuracy of the new fault location method was first studied by EMTP-ATP simulator programme. The simulator model used is illustrated in Figure 1. The model had three parallel 20 kV overhead lines, each of 60 km length. The load was either 1.5 MVA per line or zero. In the parallel lines, the load was located in the end of the line, whereas in the faulty line it was distributed equally in five steps along the line.

The simulated fault distances with the corresponding fault distance computation errors are shown in Table 1. The cases studied were the three-phase fault and two-phase faults between the different pairs of phases. The errors are primarily due to the ignored line capacitances and due to the inaccuracies in the load current compensation. However, the effect of these factors is small, since the errors are typically only some tens of meters, and at the maximum 133 meters, which corresponds to 0.33% of the actual fault distance 40 km. It is clear, that the simulated case gives somewhat overoptimistic results for the fault distance estimation. In real case there are errors of the measurement system and variation of the line inductances. Also the load dynamic behaviour varies compared to the model used in the simulated case.

A reliable statement for the fault location accuracy can only be given after experience with several real fault cases. So far there has been about 25 real fault cases, where the accuracy experienced was 2 % in average.
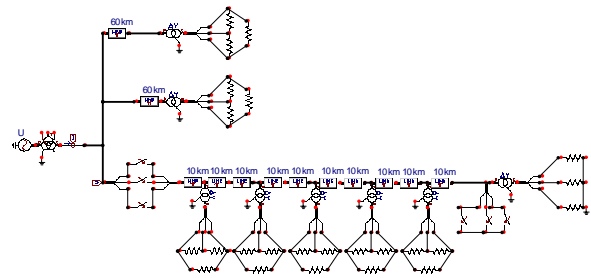

FIGURE 1: The simulator model used for the testing of the new fault location algorithm.

Table1: The errors of fault distance computation using the simulated data. R-S-T is the three phase fault. R-S is two phase fault between phases R and S.

Fault type	Load	Fault distance [km]	Error [km]
R-S-T	1,5 MVA	60	- 0,054
R-S-T	-	60	+ 0,018
R-S-T	-	30	+ 0,049
R-S-T	1,5 MVA	30	+ 0,029
R-S-T	1,5 MVA	10	+ 0,017
R-S-T	-	10	+ 0,014
R-S	-	20	+ 0,016
S-T	1,5 MVA	20	+ 0,023
S-T	1,5 MVA	40	+ 0,039
R-T	-	40	+ 0,133
R-T	-	60	+ 0,125
R-S	1,5 MVA	60	- 0,116
R-T	1,5 MVA	60	- 0,104
S-T	1,5 MVA	10	+ 0,023

CONCLUSIONS

A new method for the computation of short-circuit fault distances in radially operated distribution networks was presented. The novelty of the method is the compensation of load currents superposed on fault current. The load current is divided into two components: the one flowing in the parallel sound lines and the one flowing in the faulty line concerned. This arrangement makes it possible to obtain relatively good fault distance estimates using only one measurement device per primary transformer. Hence the algorithm is ideal for retrofitting the fault location into existing primary substations.

The soundness of the algorithm was first tested using simulated data which proved the very high inherent accuracy of the method.

According to the practical experience the accuracy of the new method with real faults is about 2 %. This is in line with the analysis of error sources, according to which the main reasons of inaccuracy are the current and voltage transformer amplitude and phase errors, as well as inaccuracy in line reactance data.

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