APPENDIX B: EARTH FAULT DISTANCE COMPUTATION BASED ON TRANSIENTS

In this appendix, the transient based earth fault distance computation algorithms, outlined in chapter 4, are discussed in more detail. The methods considered are differential-equation algorithms, Fourier-transform methods and least squares fitting methods.

The algorithms

Differential-equation algorithms solve the line inductance directly in time domain. Consider the first order model, which includes the series connection of the line resistance R and inductance L. The voltage and current of the faulty phase have the following relation:

$$u(t) = Ri(t) + L\frac{di(t)}{dt} \tag{1}$$

which can be solved for inductance L, if three equally spaced pairs of samples are available. Since differentiation is sensitive to higher frequency noise, the solution is usually obtained by integrating the above. Using the trapezoidal rule we obtain:

$$L = \frac{\Delta t}{2}\left[\frac{(i_{k+1}+i_k)(u_{k+2}+u_{k+1})-(i_{k+2}+i_{k+1})(u_{k+1}+u_k)}{(i_{k+1}+i_k)(i_{k+2}-i_{k+1})-(i_{k+2}+i_{k+1})(i_{k+1}-i_k)}\right] \tag{2}$$

The above Equation yields the total inductance of the faulty line length, which in the case of a single phase to earth fault is composed of a series connection of zero, positive and negative sequence inductances.

The algorithm works in theory for all the voltage and current components which satisfy Equation (1). The best result is, however, obtained if all the other frequencies are first filtered out, except the charge transient. In the prototype system described in reference [1] the accuracy of the method has been improved by using a larger number of samples. Also in the same reference a higher order model, which allows for the capacitances of the line, has been proposed. The model is based on higher order differential quotients, which are calculated during the signal preprocessing. Using the quotients as correction factors, the final calculation can be made using the first order line model.

Fourier-transform methods solve the line impedance in the frequency domain. In the case of the first order model, the reactance of the faulty line length is obtained directly as the imaginary part of the impedance calculated from the corresponding frequency spectrum components of voltage and current. The distance estimate x is hence obtained as follows:

$$x = \frac{Im[\underline{Z}(\omega)]}{(\frac{1}{3}l_0(\omega)+\frac{2}{3}l_p)\omega} \qquad \mathbf{3}$$

In the prototype system described in reference [2], the fault distance is calculated as a weighted average of the estimates made for the n dominating frequencies in the spectrum. Also a higher order model, which allows for the phase to earth capacitances, is presented.

The least squares fitting methods solve first the parameters the voltage and current transients in time domain as follows:

$$\begin{aligned} i(t) &= I_1 e^{s_1 t} + I_2 e^{s_2 t} \\ u(t) &= U_1 e^{s_1 t} + U_2 e^{s_2 t} \end{aligned} \qquad \mathbf{4}$$

where $s_{1,2} = -\delta \pm j\omega_c$ is the complex frequency of the charge transient. In the case of oscillating transients, the amplitude coefficients U_1,U_2 and I_1,I_2 are also pairs of complex conjugates. The voltages and currents of a line have the following relation:

$$U(s) = R\,I(s) + s\,L\,I(s) \qquad \mathbf{5}$$

which is written in the complex frequency domain. Separating the subcomponents s_1 and s_2, we obtain:

$$\begin{aligned} U_1 &= RI_1 + s_1 L I_1 \\ U_2 &= RI_2 + s_2 L I_2 \end{aligned} \qquad \mathbf{6}$$

from which the inductance L can be solved with the result:

$$L = \frac{U_2 I_1 - U_1 I_2}{I_1 I_2 (s_2 - s_1)} \qquad \mathbf{7}$$

This is the basic equation for earth fault distance estimation using the first order line model. In the oscillatory case, the real parts of s_1, s_2 are canceled. Hence the solution does not depend on the attenuation constant δ.

The first order line model is a fairly good approximation for short and medium length lines if the fault resistance is small. In other cases a better result is obtained, if the capacitances at the close end of the line are taken into account. A higher ordel model which includes the capacitances also, is presented in Reference [3].

Accuracy of the fault distance estimation

The most important causes of errors in transient based fault distance estimation are parameter identification inaccuracy, measurement transformer errors, line model simplifications, line inductance variation and load impedances.

If damping of the transient is small, the total errors due to parameter identification are typically less than 2 %. Fault resistance and resistive loads increase the attenuation, with the corresponding increase in the errors. Standard current transformers have a good fidelity in the frequency range of transients. Unfortunately this is not always the case for voltage transformers, where the lowest resonant frequency can vary from 1 to 20 kHz. If the highest transient frequency is higher than about 10 % of this, the errors must be compensated for [3]. The errors of the line model simplifications include primarily, the effect of ignored capacitances at the fault location and behind it. The maximum error due to these is, in typical overhead line networks, about 2 %.

One of the two major error sources is the variation of line inductances. The zero sequence inductances of an overhead line vary with the soil type and frequency. Their values are based on simplified models, which are not necessarily in all cases accurate enough for fault location purposes. The inductances of underearth cables vary with the frequency too. For cables, the problem is the proximity effect, which makes the estimation of both zero sequence and positive sequence inductances difficult.

Perhaps the largest errors are, however, due to the low voltage loads. Theoretically the load effects could be compensated for, but in practice there are some great difficulties. Usually neither the load devices nor their impedances during the transients are known well enough. The loads can cause large errors, especially in the case of distant faults and for fault resistances higher than zero.

The highest fault resistance, that allowes for reliable distance estimation, is about 50 Ω. With zero resistance, more than 95 % of the faults can be located reliably. According to the experience in field test, the average errors are 1.6 km for the first order line model and 1.2 km for the higher order line model . The accuracy of the different methods is compared in Table I. For the comparison, data recorded in a Swedish 22 kV overhead line network was used. The network was with a 100 % compensated neutral, the rating of the suppression coil being 17 amperes. Altogether 60 fault cases were considered.

Table I Comparison of the accuracy of transient based fault location methods. Sixty faults with fault resistance 0 Ω. First order and higher order algorithms of Differential-

equation methods (a and b) [1], Fourier-transform methods (c and d) [2] and curve fitting methods (e and f) [3] respectively.

	error class in kilometers: *0.0-0.6*	*0.6-1.2*	*1.2-1.8*	*1.8-2.4*	*>2.4*
a	*15*	*11*	*3*	*5*	*26*
b	*7*	*11*	*8*	*3*	*31*
c	*14*	*11*	*14*	*2*	*19*
d	*9*	*14*	*8*	*7*	*22*
e	*24*	*19*	*7*	*1*	*9*
f	*21*	*20*	*5*	*7*	*7*

According to the results the least square methods have somewhat better accuracy compared to the others. The possible reason is, that these methods provide the most accurate estimate for the angular frequency of the transient. In the prototype system, the size of the set of the samples used for the fault location is also adapted to the length of the transient, which may also give some benefit over the other algorithms. The differential-equation algorithms and Fourier-transform methods are essentially impedance relay algorithms. Their main advantages are the numerical stability and relatively small computation burden, which makes them suitable for on-line calculations.

Conclusions

By calculational means it is possible to produce an estimate for the distance of single phase to earth faults. If the faulty feeder has several branches, there are also several possible fault locations. In this case the fault location system can be complemented by remotely read fault current indicators.

In networks with an isolated or compensated neutral, fault distance estimation is not possible using the fundamental frequency signals. That is why transient based techniques have been studied. In high impedance earthed networks, the charge transient, which is due to the voltage rise of the two sound phases, is the most useful component for fault location purposes. Its frequency varies approximately in the range 100 to 800 Hz, and the amplitude can be even 15 times that of the uncompensated steady state fault current.

The performance of earth fault location is in practice however restricted by the attenuation of the transients. In the field tests, the biggest fault resistance, that allowed for fault location, has been about 50 Ω. For those faults that could be located reliably, the average error was 1.6 km for the first order model and 1.2 km for the higher order model.

Transient based earth fault location techniques are at the present technically possible but not yet enocomically feasible. The major factor here is the price of the sampling devices. These have to be installed at each feeder included in the reach of the fault location system. The sampling frecuency needed is 10 kHz per channel, at minimum.

REFERENCES

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