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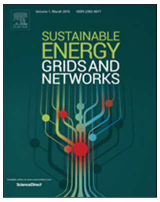

Misoperation analysis of steady-state and transient methods on earth fault locating in compensated distribution networks

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ABSTRACT

Earth fault detection and location are very important issues in distribution networks. Current methods for faulty feeder selection are based on measurements of steady-state or transient signals. The work presented here identifies and gives analyses of scenarios when ground protection based on these methods is prone to misoperation in resonance grounded systems. It is shown that the traditional watt-metric approach can malfunction depending on network and fault parameters. The admittance methods help to eliminate many issues, however they might have complex settings depending on network configurations. Special attention is paid to approaches based on transient signals as the most promising alternative solution. The current work considers methods utilizing zero sequence current, angle, power, energy and admittance transients. The paper reveals limitations for their application mainly due to presence of electrostatic asymmetry, cables in a network, fault resistance and inception angle. Nevertheless, dependability of these methods is higher than the steady-state especially for intermittent faults. It is also found that analysis of prefault information is important both for the steady-state and the transient methods. The obtained results can be used to enhance reliability of protective schemes and as drivers for further developments of new algorithms.

1. Introduction

From the current operation practice of medium voltage (MV) networks, it is well known that the vast majority of faults are single-line-to-earth type. In order to decrease fault current, a system can be operated as an isolated or a non-solidly earthed. In this work, the special type of grounding of the main distribution transformer is considered—through a Petersen coil that is quite common in Nordic countries. In resonance grounded systems, ground faults are easily detected (apart from high impedance faults) by measuring the zero sequence voltage magnitude $|\bar{U}_0|$ (exceeds thresholds at a substation), and fault current is suppressed facilitating self-extinguishing of the arc.

For permanent faults, in order to affect as few customers as possible, it is necessary to find the faulty point in the system and isolate it. Measured $|\bar{U}_0|$ does not significantly depend on fault location in a network; moreover, fault current is comparable with load currents that also jeopardizes selectivity of the protection. Typically, problem of faulty feeder selection is considered and X. Zhang et al. [1] provide comprehensive review on the developed methods for this purpose. They can be divided into three groups: injection of additional signals in a substation (voltage, current with frequencies equal to fundamental or higher), usage of steady-state signals, and utilization of transients arising during faults. The injecting methods require additional equipment and they are out of the scope of this paper.

The traditional way of faulty feeder selection based on steady-state signals is the watt-metric approach [1]: detection of a magnitude and direction of zero sequence current $\bar{I}_0$ with respect to $\bar{U}_0$—normally, healthy feeders and a faulty have different quadrants and magnitudes. In other words, $|\bar{I}_0|\cos(\phi_0)$ (where zero sequence angle ϕ_0 is between $\bar{U}_0$ and $\bar{I}_0$) will have a different sign for a faulty feeder comparing to a healthy. Thus, directionality of the ground protection is tuned according to this fact.

Paper [2] describes insufficiency of the watt-metric approach and a need for a resistor connected in parallel to a Petersen coil. Such operation leads to increase of fault current, produces transient overvoltages in a grid and it requires additional equipment; therefore, it is of interest to find new approaches. In case of sufficient line-to-ground conductance and arcing faults (small impedances), $|\bar{I}_0|\cos(\phi_0)$ can be applied without the resistor. Nevertheless, reference [3] reports the special cases when the sign of $|\bar{I}_0|\cos(\phi_0)$ in both a healthy and a faulty feeders are opposite

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compared to the prescribed polarity that can lead to misoperation of relays. It is also worth mentioning that a magnitude of zero sequence current by itself is not a reliable indicator for high impedance faults or presence of cables in a system. A new steady-state solution, in contrast to the watt-metric approach, based on zero sequence admittance is proposed in [4]. It copes with lose of sensitivity and other issues.

As an alternative, transient methods are becoming a promising solution. In addition to what was given in [1], authors of [5,6] suggest to utilize the shape of the charge–voltage curves. In [7,8] deviation of the feeder capacitance to the ground is estimated. Paper [9] suggests to measure only phase current with further detection of its relative change with respect to the previous periods. Besides the wavelet analysis, other approaches are also performed, such as the Hilbert–Huang [10] and the S-transform [11] investigations. Authors of [12] describe research on the frequency spectrum. The artificial intelligence algorithms involving the fuzzy-logic [13], application of the analytic hierarchy process [14] and the small-world network theory [15] can be found in literature as well.

The first-half-wave methods [1] based on low frequency transients deserve special attention due to suitability for compensated and isolated systems, and practical realization connected with limited sampling frequencies (few kilohertz) of used modern relays. High frequency transients might be contaminated by noise from measuring devices that makes application of associated methods difficult. The basic idea behind the first-half-wave methods is different polarity of instantaneous zero sequence current i_0 (with respect to voltage u_0) of a faulty feeder in comparison with other right after fault inception that helps to make decision in the first half of a period. Paper [16] illustrates this effect and proposes the algorithm calculating zero sequence impedance through averaged over a specified time window quantities. Authors of [17] utilize simple differential of i_0 (calculated at the first milliseconds) for faulty feeder selection. References [18,19] present extraction of transient ϕ_0 and application of it as a main indicator. In order to enhance dependability, different summation and integration techniques are proposed. For instance, papers [20–22] calculate zero sequence active power over a quarter of the period, [23]—energy (integration time is not specified). In contrast, the Cumulative Phasor Summing (CPS) technique of zero sequence admittance for different moments of a transient period is used in [24].

To summarize, effect of difference between the prescribed and a factual sign of $\cos(\phi_0)$ in a faulty feeder illustrated in [3] is a key factor leading to inadequacy of ground protection based on the watt-metric approach. As the nature of this effect has not been analyzed in literature in details, the first contribution of the current paper is a deep analysis of it. Moreover, the paper shows how the effect might jeopardize the steady-state [4] and even transient methods. From the variety of the transient methods, the paper will substantially deal with the basic approaches utilizing transients of zero sequence current [16], angle [19], energy [23], and admittance [24]. As it is slightly mentioned in [1], the transient methods are vulnerable to network and fault parameters; therefore, several adverse effects deteriorating performance of the algorithms have not been revealed in the prior studies due to simplicity of the models (e.g. ideal symmetry) and lack of simulation cases. Hence, the next contribution of the paper is revealing what network nonidealities and fault origins can affect performance of ground relays based on these transient methods. The presented results might be valuable for estimation of the limitations of the methods both in relay planning in compensated distribution systems and as background for developments of new algorithms.

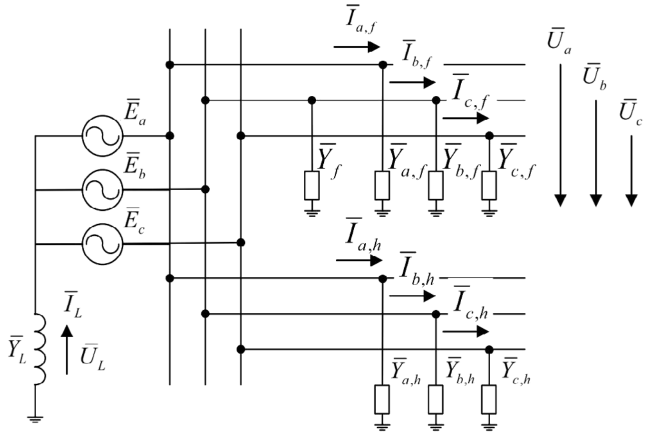

Fig. 1. Simplified network for analysis with two feeders.

2. Theoretical analysis on fault locating utilizing steady-state signals

Let us consider a simple network depicted in Fig. 1 with the ground fault in phase b of the upper feeder.

The network parameters: $\bar{Y}_{a,f} = \bar{Y}_{c,f} = k_f\bar{Y} = k_f(G + j\omega C)$, where $k_f\bar{Y}$ expresses the share of the faulty feeder in the total shunt admittance to the ground of the network per phase, $\bar{Y}$, that consist of conductance G and capacitance C of a phase. Similarly, $\bar{Y}_{a,h} = \bar{Y}_{c,h} = (1 - k_f)\bar{Y} = k_h\bar{Y}$. Indices f and h in the paper denote the faulty and the healthy feeder correspondingly. MV networks have capacitive imbalance $\Delta\bar{Y} = j\omega\Delta C$ that is normally 1%–5% from $3\bar{Y}$ [25]. Let us assume that it takes place in phase b, then $\bar{Y}_{b,f} = k_f(\bar{Y} + \Delta\bar{Y})$ and $\bar{Y}_{b,h} = k_h(\bar{Y} + \Delta\bar{Y})$. The fault impedance is assumed to be pure resistive, $\bar{Y}_f = G_F$. In this work, only permanent resistive fault is studied.

For simplified steady-state analysis of ground faults, series impedances of transmission lines and loads can be neglected in comparison with large shunt impedances of lines. Taking this into account, the following set of equations can be written to describe the system in steady-state conditions:

$$\begin{cases} 3\bar{I}_{0,h} = 3\bar{U}_0 k_h\bar{Y} + \bar{U}_b k_h\Delta\bar{Y} \\ 3\bar{I}_{0,f} = 3\bar{U}_0 k_f\bar{Y} + \bar{U}_b k_f\Delta\bar{Y} + \bar{U}_b G_F \\ \bar{I}_L = 3\bar{I}_{0,f} + 3\bar{I}_{0,h} \\ \bar{E}_{ph} = \bar{U}_{ph} + \bar{U}_L \\ \bar{I}_L = \bar{Y}_L\bar{U}_L = -\bar{Y}_L\bar{U}_0 \end{cases}, \tag{1}$$

where index ph stands for phases a, b and c; $\bar{U}_{ph}$—phase voltage; $\bar{E}_{ph}$—the balanced source of voltage; $\bar{I}_L$ and $\bar{U}_L$ are current and voltage of the Petersen coil, and $\bar{Y}_L = (j\omega L)^{-1}$ its admittance; zero sequence voltage and currents are determined as $3\bar{U}_0 = \sum \bar{U}_{ph}$ and $3\bar{I}_{0,f/h} = \sum \bar{I}_{ph,f/h}$.

Let us assume for simplicity that $k_f = k_h$, then the second equation in (1) is turned to $3\bar{I}_{0,f} = 3\bar{I}_{0,h} + \bar{U}_b G_F$. The phasor diagram for this case can be found in Fig. 2(a) ($\Delta\bar{Y}$ is 1%, direction of zero sequence current is from the substation).

As it is possible to see, ϕ_0 of the healthy feeder is less than 90° ($|\bar{I}_{0,h}|\cos(\phi_{0,h}) > 0$) and vice versa for the faulty feeder ($|\bar{I}_{0,f}|\cos(\phi_{0,f}) < 0$). The traditional ground protection is based on this fact. It should also be noticed that such systems in Norway are overcompensated, therefore in further analyses $|\bar{Y}_L| > 3|\bar{Y}|$. After fault identification, a resistor can be connected in parallel with the coil that increases ϕ_0 in the faulty feeder and helps to facilitate the selection if watt-metric contribution is scarce.

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