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Impacts of the representation of mutual coupling between feeders in distribution systems

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ABSTRACT

The mutual coupling between parallel feeders affects the power flow solution for distribution systems. By analyzing these effects, the unbalanced operation of distribution systems is better understood and the analyses are useful for distribution planning. This paper presents analytical evaluations of the impacts of mutual coupling between feeders in multiphase power flow analysis. Detailed explanations are presented, and several tests are performed to prove the results. The impacts of the mutual coupling representation are tested in relation to the distance between feeders, current intensity, unbalanced load, feeder geometry, parallel section size, and other sensitivities. The impacts considering the presence of voltage regulators are also studied. Tests were performed on a modified IEEE 13 system, a modified IEEE 34 system, and a neutral-to-earth-voltage (NEV) test feeder.

1. Introduction

In recent years, several researchers have been working on better representations of distribution systems to improve electrical system analyses. Factors related to voltage profile accuracy, representation of the imbalance of loads, accurate losses calculation, and more adequate system models are fundamental concerns. A correct model of components and the utilization of more efficient tools in these systems evaluation are fundamental and have become more necessary [1].

The electromagnetic coupling or mutual coupling that occurs between two or more parallel feeders must be considered in distribution system studies. This type of parallel configuration is commonly employed in electric power utilities, and feeders can share the same poles over long distances. Usually two or more feeders can share a single pole from the substation to the point of branching to serve different service areas. This situation can occur in any portion of the distribution system [2].

The mutual coupling that occurs between two different feeders can considerably affect the system performance, and its extent depends on the configuration of the transmission or distribution network and the design characteristics such as the separation distance between the conductors or the geometry of the feeders. In addition, the load imbalances can affect the feeder performance. These factors may have a significant impact on the system voltage profile [3,4], especially in the presence of some combined characteristics. Therefore, it is important to analyze the issues of feeder coupling and load imbalances together.

In transmission systems, the effect of mutual coupling has been well studied in the protection of double circuit transmission lines [5,6]. However, in distribution systems, the coupling between feeders is usually ignored in the majority of the analysis methods. It is difficult to find a paper in the literature that thoroughly deals with this. This can be seen in the insufficient references to the subject and the few papers that use the NEV test case system proposed by the IEEE PES Distribution System Analysis Subcommittee (DSASC) [1,7]. One of the objectives of the NEV test case is to enable the study of the effects of mutual coupling in distribution systems; however, it seems that only few methods can deal with this system [1].

The coupling between phase conductors of the same feeder has always been considered since the first proposed three-phase power flow solution methods for distribution systems, but some works do not explicitly consider the coupling between the phase conductors and the neutral conductor. For example in [8,9], the Kron reduction method was applied to embed the effects of the neutrals in the phase cables. In [10,11], methods were proposed that explicitly represent the neutral conductor and its magnetic couplings. The magnetic coupling is treated in other works. The main techniques for magnetic field mitigation at power frequency were analyzed in [12]. In [13], it was shown that the geometry of the conductors is important, and a method was proposed to minimize the stray magnetic field.

More recent works [14–21] present methods that allow representing the coupling between cables or feeders. For example, methods that can represent several types of distribution networks, including the coupling between feeders and neutral cables, have been presented in [14,15], but

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the impact of that representation was not analyzed. Fault location problems have been discussed in distribution systems in the presence of parallel feeders [16]. In [17], current distribution and losses in underground cables were studied, and three methods were used to calculate the effects of mutual couplings between conductors. In [18], the mechanism that results in uneven voltage drops was examined, as well as the impacts of unbalanced line configurations with different phase loading levels on network voltage imbalance. In [19], the effects of mutual coupling and transposition of phase conductors on the maximum photovoltaic penetration levels were studied in a distribution feeder. In [20] and [21], models to represent the coupling between the medium voltage and the low voltage network were defined, it was concluded that in some situations coupling must be performed; however, tests were performed only on a simple system. However, in the cited papers, several aspects of parallel feeders representation were not explored and only simple test systems were used.

Considering the importance of the issue and its possible impacts in distribution system analyses, this study evaluates the impacts of mutual coupling between feeders in multiphase power flow analysis. Analytical explanations are presented, and several tests are performed to prove the obtained results. The impacts of the mutual coupling representation were tested in relation to the distance between feeders, current intensity, unbalanced load, feeder geometry, and parallel section size. The impacts of voltage regulators on distribution systems with mutual coupling between feeders were also analyzed. By analyzing these effects, the unbalanced operation of distribution systems is better understood and the analyses are useful for distribution planning. The tests were performed on a modified IEEE 13-bus system, a modified IEEE 34-bus system, and the NEV test feeder. Detailed analyses and analytical explanations of the presented issues are the major contributions of this work. The use of DSASC systems [7] to allow replication of the results is also of considerable importance.

2. Mutual coupling between medium voltage parallel feeders

2.1. Representation of feeders in parallel

Double (or more) feeders in parallel are very common near substations [2]. Usually the feeders run in parallel from a hundred meters to a few kilometers. To illustrate, in Fig. 1, two couple of feeders are presented in parallel on each side of the street and in Fig. 2, five feeders are presented in parallel. Both are coming out of a substation. It is emphasized that the higher current values are found at the beginning of the feeders.

The schematic of a pole with two feeders with a flat configuration of the cables is shown in Fig. 3, the first feeder (Fd1) is composed of the phases *a-b-c* and the second feeder is composed by the phases *a′-b′-c′*. The mutual impedances of the feeder 1 (MIF) are given by $Z_{a,b}$, $Z_{a,c}$, and $Z_{b,c}$. The mutual impedances of the feeder 2 are given by $Z_{a',b'}$, $Z_{a',c'}$, and $Z_{b',c'}$. The mutual impedances between feeders (MIBF) are given by $Z_{a,a'}$,

Fig. 1. Two feeders on the same pole - Real DS.

Fig. 2. Five feeders in parallel - Real DS.

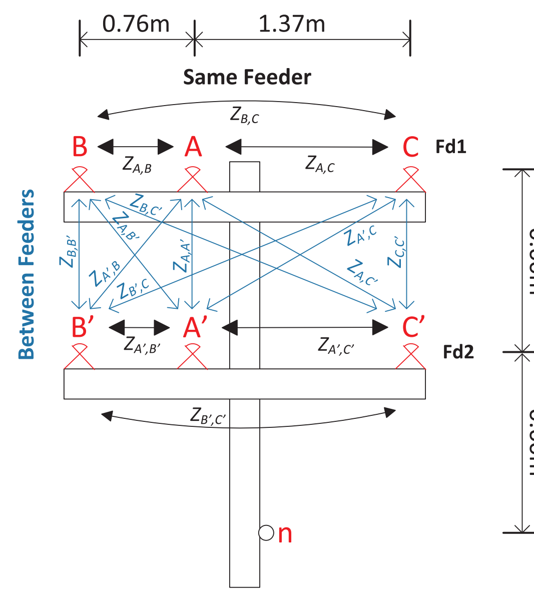

Fig. 3. Two feeders on the same pole.

$Z_{a,b'}$, $Z_{a,\acute{c}}$, $Z_{b,a'}$, $Z_{b,b'}$, $Z_{b,c'}$, $Z_{c,a'}$, $Z_{c,b'}$, and $Z_{c,c'}$. The mutual impedances between the neutral and the feeders are not drawn in Fig. 3 for easier viewing, but the idea of representation is similar.

There are several methods for calculating the impedance values of the transmission lines and of the distribution feeders in literature. In this paper a simple method derived from the *De* method will be used. This method presents good results when used in distribution feeders [2]. The self and mutual impedances are given by Eqs. (1) and (2) respectively. The parameters were calculated considering the soil resistivity equal to 100 Ω·m and frequency of 60 Hz. These equations are not limited to only two feeders.

$$Z_{xx} = (r_c + r_d) + j0.07537\left(\ln\frac{1}{GMR_x} + 6.74580\right)\Omega/\text{km} \tag{1}$$

$$Z_{xy} = r_d + j0.07537\left(\ln\frac{1}{D_{x,y}} + 6.74580\right)\Omega/\text{km} \tag{2}$$

where

Z_{xx} is the self impedance of cable x, in Ω/km;
Z_{xy} is the mutual impedance between cables x and y, in Ω/km;
r_c is the resistance of cable x, in Ω/km;
r_d is the earth resistance given by 0.05919 Ω/km (100 Ω·m, 60 Hz);
GMR_x is the geometric mean radius of the cable x, in meters;