EVALUATION OF DISTRIBUTION SYSTEM LOSSES DUE TO LOAD UNBALANCE

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Abstract – Distribution network losses can vary significantly depending on the load unbalance. Here, an analysis of distribution system losses is presented that considers load unbalance and the effect of explicitly represented neutral wire. A general power flow algorithm for three-phase four-wire radial distribution networks, based on the current summation backward-forward technique is applied. Loss analysis results obtained from three-phase four-wire medium and low voltage test feeders with unbalanced load scenarios are presented and discussed considering: a) original phase and neutral wires resistances; and b) resistances obtained by performing Kron's reduction.

Keywords: Distribution networks, losses, load unbalance, power flow, three-phase four-wire

1 INTRODUCTION

Since system losses represent a considerable cost for utilities, its evaluation and reduction have been recognized as of interest by researchers. There are many distribution network devices responsible for energy loss, the most important being the primary and secondary lines, due mainly to overloaded low voltage (LV) feeders and unbalanced loads.

Unbalance is a common occurrence in three-phase distribution systems. However, it can be harmful to the operation of the network, its reliability and safety. Furthermore, measurements show that real power losses increase due to unbalanced loads. Thus, a distribution system unbalance phenomenon has been the focus of research in recent decades [1]-[3]. This problem in distribution networks exists in both three-wire and four-wire systems due to the fact that loads are switched on and off by end users [1].

In medium voltage (MV) distribution networks in North America, unbalance is due to the presence of single-phase laterals and a large number of single-phase customers. In Europe, although the MV distribution system is developed as a three-wire or four-wire system and most of the MV customers are three-phase, unbalanced load problems also arise.

Therefore, considering the importance of loss analysis, the objectives of this work are to evaluate losses due to load unbalance and highlight potential mistakes in loss analysis. It is assumed here that a load unbalance affects only the fundamental component of the neutral current since the harmonic power losses are, in general, small compared to the fundamental active power losses and could be considered as almost negligible [4]. An expanded power flow algorithm for three-phase four-wire radial distribution networks, based on current summation backward-forward technique [5], is applied.

Results obtained utilizing medium and low voltage distribution feeders are presented and discussed.

2 LOSS EVALUATION

In general, after solving the respective three-phase (four-wire or three-wire) power flow of a given distribution network, line section loss calculation can be performed utilizing one of the following procedures:

- Using the original resistances of the wires in the I^2R formula. Thus, losses on phase a, b and c losses can be computed. In addition, after the calculation of neutral currents (performed after solving the three-phase three-wire power flow), neutral wire losses can be computed. The sum of them gives the total losses. Here, phase losses, neutral wire losses and total losses are correct.

- Using the difference between input and output power ($S_{in} - S_{out}$) in each phase. The sum of the phase losses (a, b and c) gives the total losses, and it is not possible to compute the neutral losses. In this procedure the value of total losses is correct, but the losses in each phase are incorrect [6].

When four-wire line sections are represented by a reduced 3x3 matrix (performing Kron's reduction) in order to use a three-phase three-wire power flow algorithm (such as [7]), phase voltages and currents will be obtained with acceptable accuracy [8]. Nevertheless, if the resistances values from the reduced 3x3 matrix are used for calculating losses into the I^2R formula, one will obtain erroneous results.

Since the neutral wire is explicitly represented in the utilized power flow technique [5], neutral currents are calculated directly. Thus, with all current values, power losses can be computed by using the original phase and neutral wire resistances in the I^2R formula.

System losses are calculated under various scenarios, from balanced loads (considered here, as the first unbalance scenario) to the highest load unbalance allowed by the analyzed system. In that way, the impact of load unbalance on system losses can be clearly visualized.

3 TEST NETWORKS

The proposed methodology for evaluation of power losses due to load unbalance is applied on MV and LV distribution networks. In this paper the following networks are used:

LV-29: 29-bus real-life four-wire three-phase LV feeder from Bragança Paulista city, SP-Brazil (data supplied by Grupo Rede) (Figure 1). The total demand is 17.7 kW, and the loads are distributed along the network (the most distant node is 170 m from the root node). Line-to-line base voltage is $V_b = 210.0$ V;

IEEE-34: 34-bus IEEE four-wire three-phase MV feeder (Figure 2) [9]. The total demand is 1770 kW, and 72% of the loads are concentrated 56 km away from the root node (with the most distant node 59 km away). Line-to-line base voltage is $V_b = 24.9$ kV.

The networks operate with isolated neutral wire and have radial topology. The load data for the LV-29 test network is given in [5]. The original IEEE-34 test feeder is simplified by replacing the autotransformer (24.9 kV/4.16 kV) with a line and the network is modelled at the single voltage level. The automatic voltage regulator is also not represented.
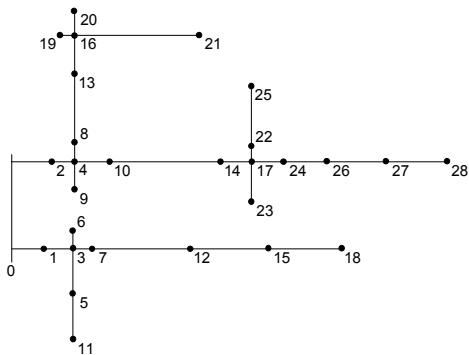

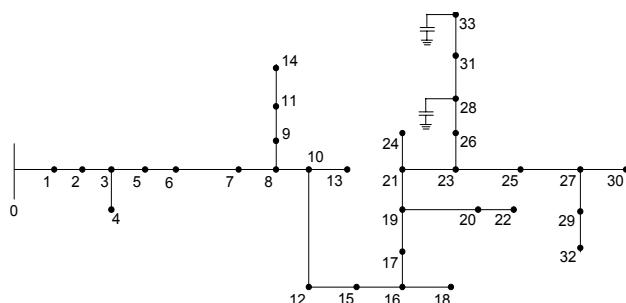**Figure 1:** LV-29 distribution network

Figure 2: IEEE-34 test feeder.

Impedances for the four-wire model are calculated considering a ground resistivity of 100 Ω-m and using the formulation in [5].

4 APPLICATIONS

In this work, the three-phase four-wire power flow algorithm [5] is applied on the MV and LV distribution networks presented previously. The presentation is focused on the discrepancy of loss calculation when a) original phase and neutral wire resistances and b) reduced matrix resistances (representation of four-wire line sections performing Kron's reduction) are used in the I^2R formula. The load was modelled as constant power.

The following types of unbalance are considered:

Unbalance Type A: Firstly the overall network load is balanced for the three phases. Subsequently, a percentage of the *b*-phase load is increased, while the same value is decreased in phase *c*. In this way, the total network load remains constant under each unbalance scenario.

Unbalance Type B: Firstly the overall network load is balanced for the three phases. Afterward, a percentage of the load of phase *b* is decreased, while the decrease is twice this value in phase *c*. This kind of unbalance reduces the total network load under each unbalanced scenario.

4.1 Analysis of LV Distribution Network

Figures 3 to 5 present real power losses for the LV-29 distribution network. Figure 3 shows results of the loss analysis for the LV-29 distribution network when the unbalance type A (constant demand) was applied. It is noticed that despite demand being maintained, total losses calculated by the explicit four-wire approach increased by 4.1% for a 15% unbalance as compared to a fully balanced system (EQ.). This is mainly because the neutral wire is being considered. When the reduced matrix approach is used, overall losses compared to the correct procedure are much larger for the balanced scenario (by 21.5%), whereas with the impact of unbalance they are less pronounced.
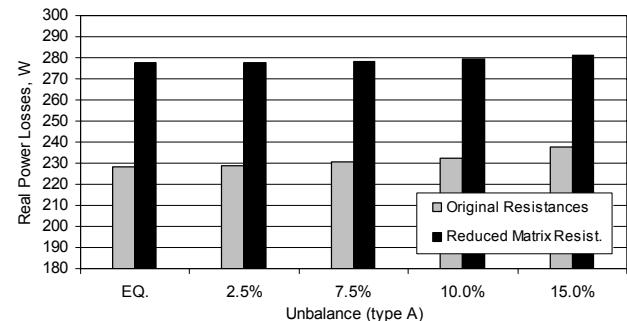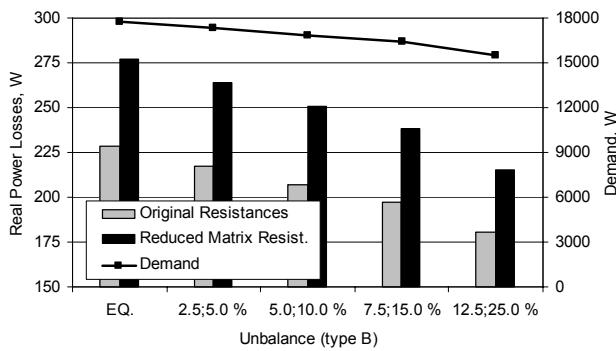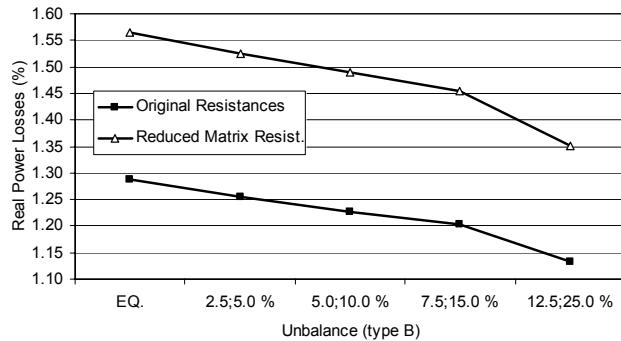

Figure 3: Real Power Losses for the LV-29 distribution network with unbalance type A.

Results of the loss analysis obtained by applying unbalance type B (variable demand) for the same distribution network are shown in Figures 4 and 5. Using the reduced matrix resistances leads again to larger losses (20.9% in average for considered unbalance scenarios) than using original resistances. Due to the decrease in demand under each unbalance scenario, the amount of losses also decreased. Losses computed with original resistances diminished 21% at the last unbalance scenario, which in terms of demand (17.7 kW) means from 1.29 (balanced loads) to 1.13% (Figure 5).
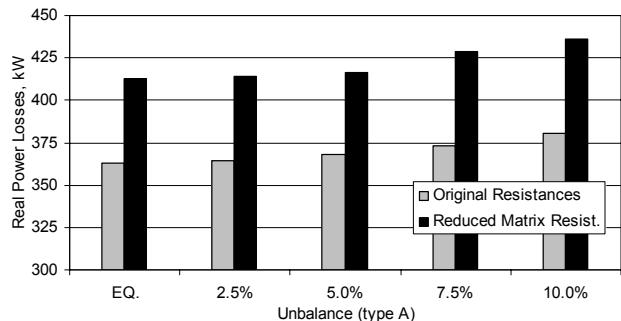
Figure 4: Real Power Losses for the LV-29 distribution network with unbalance type B.

Figure 5: Percentage of Real Power Losses respect to the demand for the LV-29 distribution network with unbalance type B.

## 4.2 Analysis of MV Distribution Network

Figures 6 to 8 present real power losses for the IEEE-34 distribution network. Results of loss analysis for the IEEE-34 distribution network applying the unbalance type A are shown in Figure 6. Total losses calculated with original phase and neutral wires resistances increased 4.9% (last unbalance scenario) compared to the balanced load scenario. Using reduced matrix resistances into the I^2R formula produces much larger results (13.8% at the first unbalance scenario increasing to 14.5% at the last unbalance scenario) than the correct procedure.
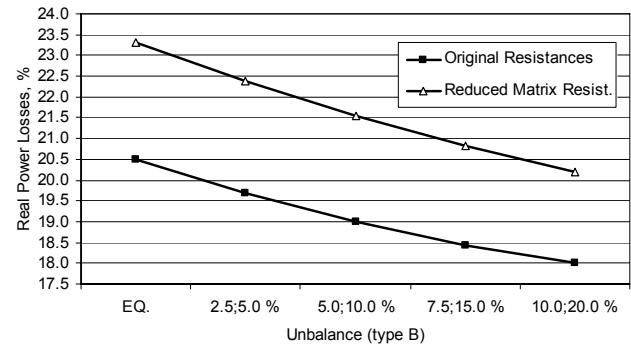

Figure 6: Real Power Losses for the IEEE-34 distribution network with unbalance type A.

Figures 7 and 8 show the results of loss analysis obtained by applying unbalance type B for the same network. Using reduced matrix resistances leads again to larger losses (13.3% greater in average) than using

original resistances. Losses computed with original resistances diminished 12.2% at the last unbalance scenario compared to the EQ. scenario. This represented, in terms of demand, a reduction from 20.5% to 18% (Figure 8).
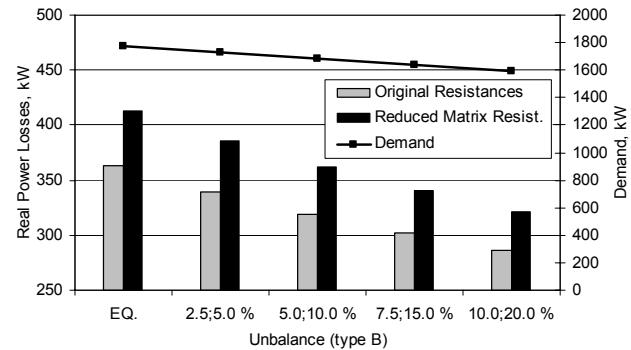
Figure 7: Real Power Losses for the IEEE-34 distribution network with unbalance type B.

Figure 8: Percentage of Real Power Losses respect to the demand for the IEEE-34 distribution network with unbalance type B.

It should be noted that the percentage losses (Figure 8) in the IEEE-34 distribution network are significantly greater than in the LV-29 network. The main reason for this situation is that load concentration in the IEEE-34 is far away from the root node. Moreover, the exclusion of the autotransformer and voltage regulators from the original IEEE-34 network allowed larger voltage drops and losses as well.

Based on the performed simulations the following observations can be made:

- Different unbalance scenarios considering a given demand (unbalance type A) showed that total power losses in distribution networks increase with the load unbalance.
- Usage of reduced matrix resistances for calculating losses into the I^2R formula leads to results much larger than using original wires resistances.

Figure 9 shows phases *a*, *b* and *c* and neutral wire losses for the IEEE-34 network considering unbalance type A and using original wires resistances. This decomposition of the total power losses (Figure 6) is useful to evidence how neutral wire losses affect indeed the overall value of losses in unbalanced load scenarios.

Neutral losses account for 0.03% at balanced scenario and 2.4% at the last unbalance scenario.
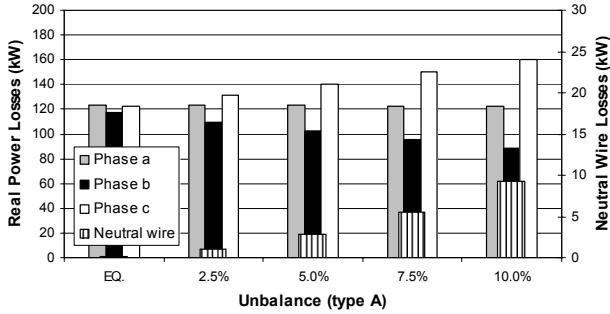
Figure 9: Phase and neutral wire losses for the IEEE-34 distribution network with unbalance type A.

It is also noticed in Figure 9 that phase losses are not equal at the balanced load scenario. This occurs because the topology of the IEEE-34 test feeder is not uniform, i.e., presents some single-phase line sections which unavoidably produce more unbalance at each considered unbalance scenario. Moreover, another minor unbalance occurs because of the coupling between phases that appears since there is no transposition, which is reflected in the line impedance matrix as mutual impedances.

Though it is an indirect procedure, neutral currents could be computed from phase currents obtained with a three-phase three-wire power flow algorithm. With these values it is possible to calculate phase and neutral wires losses by using the I^2R formula and original wires resistances. Nevertheless, it is important to notice that some three-phase three-wire power flow algorithms (e.g. power summation based algorithms [10] and [11]) require loss calculation within their iterative process which means that the final power flow solution will not be reliable if reduced matrix resistances were used [8].

5   CONCLUSIONS

In this paper we presented a loss analysis in distribution systems considering different load unbalance scenarios. A general power flow algorithm for three-phase four-wire radial distribution networks, based on backward-forward technique was applied. This approach improves loss calculation due to the explicit representation of the neutral conductor, which should be considered since unbalance is a common every-day occurrence in three-phase distribution systems.

High levels of load unbalance produced greater losses while the same demand is maintained at each unbalance scenario. This means that network reconfiguration considering load balancing is highly recommend in order to diminish overall system losses.

Usage of reduced matrix resistances (representation of four-wire line sections performing Kron's reduction) into the I^2R formula is a procedure that should be avoided since leads to incorrect results.

The selection of the load model to be used in the analysis plays an important role in the overall loss calculations. Constant admittance load model leads to lower amounts of losses and provides higher levels of unbalance than the constant power load model within the same specified tolerance [5].

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