INVESTIGATION INTO UNBALANCE PHENOMENA IN THE DISTRIBUTION NETWORKS USING POWER OSCILLATION INDEX

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ABSTRACT

Unbalance and harmonics are two major distortions in the three-phase distribution systems. In this paper an investigation into unbalance phenomena in the distribution networks using instantaneous space phasors theoryy, is presented. For system analysis a general power flow algorithm for three-phase four-wire radial distribution networks, based on backward-forward technique, is applied. Results obtained from several case studies using medium voltage test feeder with unbalanced load, are presented and discussed.

INTRODUCTION

Unbalance phenomena in the distribution systems have been in the researcher's focus last decades [1], [2], [3], [4], [5], and [6]. Problem of unbalance regime of DNs exists in both three-wire and four–wire DNs. The return current is due to both the unbalanced load and the non-linear characteristics of electrical equipment through the distribution feeder such as distribution transformers. The return current may be larger than the phase currents if three-phase loads are seriously unbalanced in some segments. Besides, it is observed that mean value of the 3-rd harmonic component (due to nonlinear equipment and loads) can be greater than that of the fundamental component (due to load unbalances). An unbalance power component was defined in the total apparent power in terms of the symmetric component [6], [7], [8], [9], and [10].

In this paper, a new method for investigation unbalance phenomena in distribution systems, using instantaneous space phasors theory, is presented. Power oscillation index (POI) introduced in [11], and effective power factor (PFe) are calculated in the network nodes for several unbalance loading conditions. The main objective of the research was to investigate correlation between load unbalance, power oscillation index (POI), effective power factor (PFe), and power losses for different type of neutral design of DNs and several unbalance scenarios.

Here it is assumed that load unbalance only affects the fundamental component of the neutral current. In case there is an evidence of presence of harmonics in DNs, the unbalance decomposition method [10] can be applied prior to loss analysis. The proposed methodology for investigation unbalance phenomena is of general usage since it can be applied for most of the existing DNs: medium voltage (MV); low voltage (LV); three-wire, four-wire, with (solidly) grounded neutral or isolated neutral wire. Results obtained from case studies using real life MV feeder are presented and discussed.

METHOD FOR UNBALANCE INVESTIGATION

The neutrals of distribution networks play an important role in power quality and safety problems [2], [3], and [4]. The design of neutrals varies widely from country to country and even from utility to utility within the same country [3].

Line Model

Model of a three-phase four-wire multi-grounded distribution line as the most complex one, is shown on Fig. 1 [12].

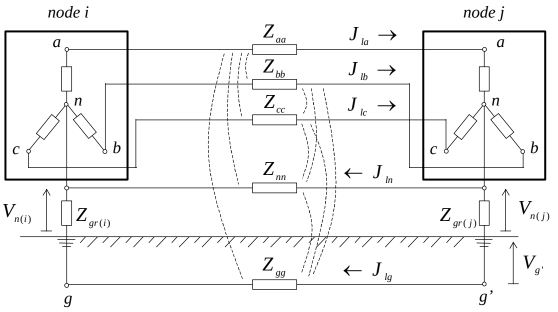

Figure 1 Model of a three-phase four-wire multi-grounded distribution line.

Power Flow Algorithm

For system analysis efficient and robust three-phase branch-oriented backward-forward procedure is applied. This method exploits 5x5-network representation, considering 3-phase wires, neutral wire and assumed ground wire [12].

Power Oscillation Index

The loss due to unbalance loading is complex function of loading level, loading unbalance, penetration level of non-linear loads, embedded generators, electrical equipments, neutral design, system of neutral grounding, network configuration, etc. The main objective of this research was to investigate correlation between load unbalance, power oscillation index (POI), effective power factor (PFe) and power losses for different type of DNs.

The three-phase effective power factor PF_e is the ratio of the average value of the real power and the effective apparent power [6], [11].

$$PF_e = \frac{<p> + P^0}{S_e} \quad . \tag{1}$$

The expression for the effective apparent power in terms of instantaneous space phasors is given by eq. (2),

$$S_e = \frac{3}{2}\sqrt{\left[<\left|\tilde{V}\right|^2> + \left(V^0\right)^2\right]\left[<\left|\tilde{I}\right|^2> + 8\left(I^0\right)^2\right]} \, . \tag{2}$$

The apparent instantaneous power in terms of sequence components, is given by eq. (3)

$$\begin{aligned}\tilde{S} &= \frac{3}{2}\left[\tilde{V}^+ + \tilde{V}^-\right]\left[\tilde{I}^+ + \tilde{I}^-\right]^* \\ &= \frac{3}{2}\left[\hat{V}^+ e^{j\left(\omega t + \phi_V^+\right)} + \hat{V}^- e^{-j\left(\omega t + \phi_V^-\right)}\right] \\ &\quad \left[\hat{I}^+ e^{-j\left(\omega t + \phi_I^+\right)} + \hat{I}^- e^{j\left(\omega t + \phi_I^-\right)}\right]\end{aligned} \tag{3}$$

which may be expressed as

$$\tilde{S} = \tilde{S}^+ + \tilde{S}^- + \tilde{S}^{\pm} + \tilde{S}^{\mu} \, , \tag{4}$$

where

$$\tilde{S}^+ = \hat{V}^+ \hat{I}^+ e^{j\left(\phi_V^+ - \phi_I^+\right)} = P^+ + jQ^+ \, ,$$

$$\tilde{S}^- = \hat{V}^- \hat{I}^- e^{j\left(\phi_v^- - \phi_i^-\right)} = P^- + jQ^- \, ,$$

are the constant positive and negative-sequence conventional complex powers.

The real power $\Re e\left\{\tilde{S}\right\}$ and imaginary power $\Im m\left\{\tilde{S}\right\}$ oscillate with double fundamental frequency with zero average values due to the interaction of the voltage and current positive and negative sequence components expressed in the terms

$$\tilde{S}^{\pm} = \hat{V}^+ \hat{I}^- e^{j\left(2\omega t + \phi_V^+ + \phi_I^-\right)} \, , \tag{5}$$

$$\tilde{S}^{\mu} = \hat{V}^- \hat{I}^+ e^{-j\left(2\omega t + \phi_V^- + \phi_I^+\right)} \, , \tag{6}$$

whose amplitudes grow with the system unbalance.

The average values $<\Re e\left\{\tilde{S}\right\}>$ and $<\Im m\left\{\tilde{S}\right\}>$ are due the remaining terms of (4) which are the real and imaginary parts of the conventional complex power

$$\bar{S} = <\Re e\left\{\tilde{S}\right\}> + j<\Im m\left\{\tilde{S}\right\}> \, , \tag{7}$$

where

$$<\Re e\left\{\tilde{S}\right\}> = \bar{p} = P^+ + P^- \tag{8}$$

is the three-phase positive plus negative sequence active power and

$$<\Im m\left\{\tilde{S}\right\}> = \bar{q} = Q^+ + Q^- \tag{9}$$

is the three-phase positive plus negative sequence reactive power.

Power oscillations in three-phase power systems do not depend only on the unbalance of voltages and currents, but also on the harmonic contents of those quantities.

The evaluation of the power oscillation can be quantified through the definition of a power quality index, named Power Oscillation Index, *POI*, introduced in [11] and given by eq. (10)

$$POI = \frac{\Re e\left\{\tilde{S}\right\}_M}{<\Re e\left\{\tilde{S}\right\}>} \, , \tag{10}$$

where the numerator is the maximum value of the real power oscillation and the denominator is its average value.

TEST NETWORKS

In this research the test network is the IEEE 34-bus radial distribution network [13], Fig. 2. Base voltage of the network is V_b = 24.9 kV, and the reference voltage in the root node is V_{ref} = 25.647 kV. Simplifying, the autotransformer 24.9/4.16 kV/kV in the original IEEE 34-bus test feeder is replaced with the line and the network is modeled with the single voltage level. The automatic voltage regulator is also not represented. The injections for the IEEE 34-bus DN are given in ref. [13].

The following test networks considering neutral design are used:

A1. Four-wire three-phase IEEE 34 feeder with isolated neutral;

A2. Four-wire three-phase IEEE 34 with multi-grounded neutral (grounding resistance R_{gr} = 1Ω in the following nodes: 3, 8, 10, 14, 16, 21, 30, 31, 32, R_{gr} = 1 Ω in substation HV/MV) [12]; and

B. Three-wire three-phase IEEE 34 line.

Mutual and self impedances of phases *a*, *b*, *c* and neutral in cases A1 and A2 (elements of the fourth row and fourth column of the 5x5 matrix) are calculated using *Carson's* equations, considering the ground as a perfect conductor.

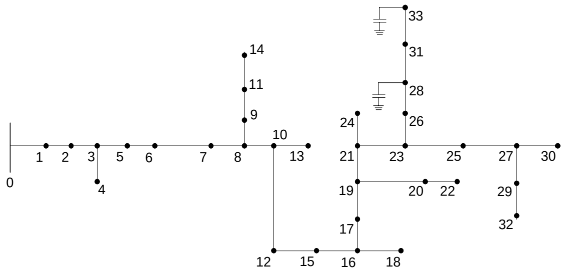

Figure 2 IEEE 34-bus MV test feeder

APPLICATIONS

The methodology for investigation into the unbalance phenomena is tested on numerous MV and LV real-life DNs. In this paper, the methodology is applied on IEEE 34 test feeder. Also the effects of different design of neutral and system grounding on system losses due to unbalance loading are investigated.

Case Study

The following case studies are performed:

Case 1 Balanced loading;
Case 2 Unbalanced loading according to the ref.[13], and
Case 3 Unbalanced loading according to the phase participation scheme 40, 30, 30 % (x=0.6), and 50, 25, 25 % (x=0.5).

Results

Fig. 3 shows several cycles of the real power oscillation at node 10 in the 3–wire IEEE 34 test network B, case 2. Fig. 4 shows effective power factor in the 3-wire IEEE 34 test feeder with unbalance loading x=0.6. Fig. 5 and Fig. 6 show power oscillation index in the 3-wire and the 4-wire IEEE 34 test feeder with multi-grounded neutral wire, and unbalance loading x=0.6, respectively. On comparing Figures 4 and 5 it must be observed that the PFe does not depend only on the power oscillation, but also on the reactive power. However there is a meaningful correlation between the PFe and the POI: the variation of the PFe is mainly due to real power oscillation expressed by POI.

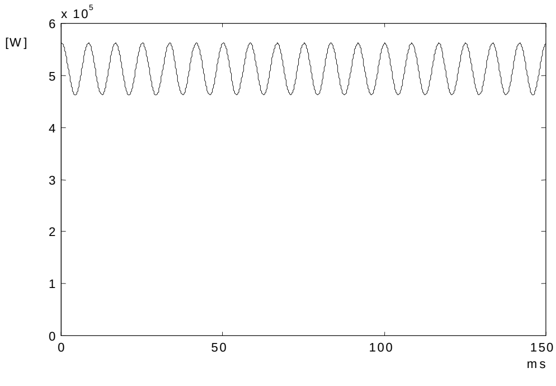

Figure 3 Real power oscillations at node 10 of 3-wire IEEE 34.

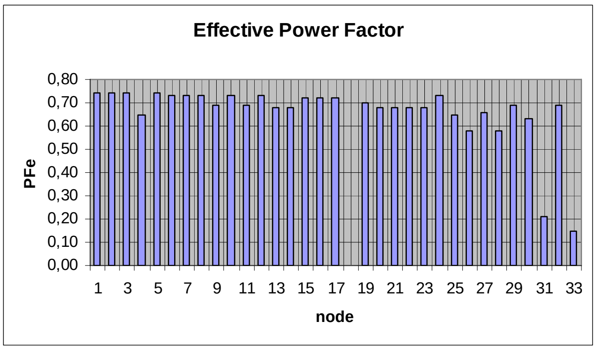

Figure 4 Effective power factor in the 3-wire IEEE 34 test feeder and unbalance loading x=0.6.

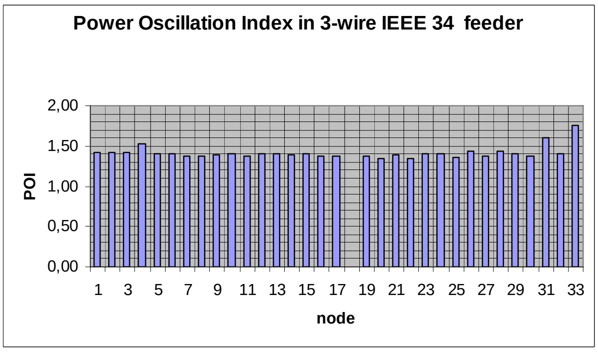

Figure 5 Power oscillation index in the 3-wire IEEE 34 test feeder and unbalance loading x=0.6

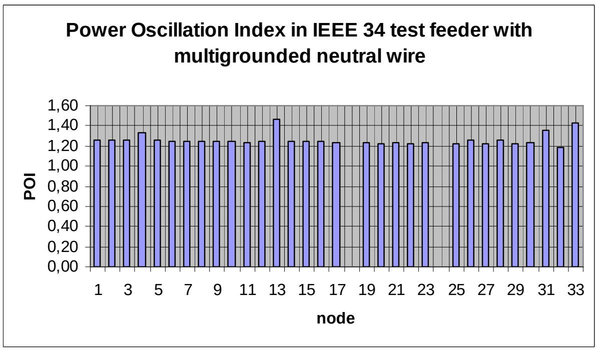

Figure 6 Power oscillation index in the IEEE 34 test feeder with multi grounded neutral wire and unbalance loading x=0.6.

Conclusion Remarks

The following conclusions about unbalance phenomena can be made based on the performed simulations:

- Power Oscillation Index (POI) is very sensitive on the unbalance loading; In case of balance loading and 3-wire system, the average value of the power oscillation index POI_{avg}=1; In loading case 2, POI_{avg}=1.36, while in case of unbalance loading (x=0.6), POI_{avg}=1.41;
- There is a relation between the effective power factor PFe, and the unbalance reflected on the power oscillation index POI in the network nodes: while the effective power factor PFe decreases, the POI

increases;

- Power oscillation index POI shows more sensitivity regarding the load unbalance comparing to the effective power factor PFe: For example, in section 10-12 of the 3-wire IEEE 34, effective power factor stay constant, PFe=0.99, in both balanced and unbalanced loading conditions; On the other side POI changes from 1 to 1.07;
- Power oscillation index POI is sensitive on the design of the neutral wire: In the 3-wire feeder under unbalance condition (x=0.6), the average value of power oscillation index is POI_{avg} =1.41. In the 4-wire feeder with multi grounded neutral wire and the same load conditions, the average value of power oscillation index is POI_{avg} =1.24. It seems that multi-grounded neutral wire in unbalance conditions acts towards decreasing the oscillating power.
- High level of load unbalance induces significant real power oscillation producing greater losses while serving the same demand. Contribution of heavy unbalance loading (x=0.5) to the total losses in considered DNs was more than 50 %;
- Total power losses also depend on the neutral design and grounding scheme. The losses in the 4-wire system with isolated neutral, 4-wire system with multi-grounded neutral, and 3-wire system and standard loading conditions were 6.31 %, 6.16 % and 6.09 % respectively.

CONCLUSIONS

In this paper an investigation into the unbalance phenomena in the distribution networks using instantaneous space phasor theory is presented. Real power oscillation as well as power losses in the DNs increase with the load unbalance. Real power oscillation and total power losses also depend on the neutral design and grounding scheme.

It is suggested that the real power oscillation be taken as one more element in analysis of real-life distribution systems. The proposed methodology for investigation of unbalance phenomena is of general usage since it can be applied for most of the existing DNs: medium voltage (MV); low voltage (LV); three-wire, four-wire, with (solidly) grounded neutral or isolated neutral wire.

The multi-grounded neutral wire in heavy unbalance conditions acts towards decreasing the oscillating power. It is suggested that multi-grounding of the neutral wire be applied in the MV distribution network areas with heavy unbalance conditions, as it is the case in the low voltage networks. In addition, the proper network reconfiguration should take into account load balancing, even being a non-controllable issue.

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