PROBABILISTIC ESTIMATION OF VOLTAGE UNBALANCE IN DISTRIBUTION NETWORKS WITH ASYMMETRICAL LOADS

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ABSTRACT

The paper presents a method for the detection of areas affected by voltage unbalance in distribution networks and presents the results graphically by "Heat Map". Voltage unbalance causes overheating of equipment, increased losses and general reduction in efficiency of power system equipment and user devices. This results in additional economic costs for both Distribution Network Operators (DNOs) and consumers. This paper uses three-phase full Newton-Raphson load flow method and Monte Carlo simulations to probabilistically estimate the voltage unbalance level at all buses in the network under unbalanced loading conditions. The usage of "Heat map" graphical representation of the results facilitates easy identification of the areas of the network that are affected the most by unbalance. Proposed methodology is demonstrated on a real 24 bus network with actual network parameters.

INTRODUCTION

Voltage unbalance refers to phenomenon when three phase voltages are not equal in magnitude or the phase shift between voltages of any two phases is not 120°, or both. This long-term power quality phenomenon principally leads to overheating of power system equipment and end-user devices, consequent accelerated thermal ageing, reduction of efficiency, increased network losses and general reduction in efficiency of network and devices connected to it. Ultimately this results in additional maintenance and/or replacement costs for both Distribution Network Operators (DNOs) and customers [1].

The main cause of voltage unbalance is asymmetrical loading. Voltages at HV substations, i.e., at connection points between transmission and distribution network, are generally regulated and balanced. So the major source of unbalance in the network is typically at lower distribution level voltages. Although the transmission lines in distribution network are not fully transposed, the small unbalanced impedances due to short line lengths do not introduce any significant systemic unbalance in the network. The large number of single phase loads connected to distribution network whose operation and connection status varies with time causes changes (often unpredictable) in demand that could and often results in

unbalanced voltages in three phases [2]. The unbalanced load at network buses, therefore, forms the major source of unbalance in the network.

The focus of this research is on probabilistic modelling of asymmetrical load as it is the main source of unbalance, and assessing the propagation of the unbalance through the network in order to identify the areas of the network that are most affected by the unbalance and where potential consequences of unbalance could lead to significant financial loss to network operator and end users. DNOs are required to ensure that the level of unbalance in the network stays below certain threshold to guarantee normal operation of the system equipment and customer devices and to reduce losses in the network. Once a source of unbalance appears in the network, the induced unbalanced three-phase power propagates to the whole network [3]. However, due to the limited monitoring in the network, real-time levels of unbalance may not be available. To overcome the shortage of incomplete data set, probabilistic estimation of unbalance can provide the likely distribution and propagation of unbalance. Using the load flow parameters derived from probabilistic estimation, the detection of weak areas as well as the prediction of level of voltage unbalance at different buses is available, which can help DNOs to develop appropriate mitigation strategy according to the location and degree of unbalance.

This paper employs statistical daily loading curves for different types (domestic/commercial/industrial) of loads along with normally distributed power factors to model load asymmetry, in order to represent load uncertainty in the network. The overall level of unbalance in the network is then estimated using the full Newton-Raphson three-phase load flow results. Finally, the areas of the network affected by the unbalance and the degree of this effect are clearly illustrated using multicoloured "heat map".

QUANTIFYING VOLTAGE UNBALANCE

This section introduces the method of quantifying the level of voltage unbalance and the related standard limitation.

Three-phase Load Flow

For the purpose of quantifying voltage unbalance in the network, a three-phase full Newton-Raphson load flow analysis is carried out. Similar to single-phase load flow,

three-phase load flow employs line impedances, voltage magnitudes and voltage angles to derive the power flows in the network. However, variables of three-phase load flow are considered on three-phase basis. The three-phase load flow equations for powers injected in bus i from bus k (k=1, 2, 3 …) are as follows[4]:

$$P_i^p = V_i^p \sum_{k=1}^{n} \sum_{m=1}^{a} V_k^m \left[G_{ik}^{pm} \cos(\theta_{ik}^{pm}) + B_{ik}^{pm} \sin(\theta_{ik}^{pm}) \right] \quad (1)$$

$$Q_i^p = V_i^p \sum_{k=1}^{n} \sum_{m=1}^{a} V_k^m \left[G_{ik}^{pm} \sin(\theta_{ik}^{pm}) - B_{ik}^{pm} \cos(\theta_{ik}^{pm}) \right] \quad (2)$$

Where Y=G+jB denotes the line admittance matrix between each two buses, θ denotes the admittance angle, and p and m can be either a, b or c phase.

Symmetrical components are used to decompose the three-phase voltages derived from three-phase load flow into positive sequence component (V_1 or I_1), negative sequence component (V_2 or I_2) and zero sequence component (V_0 or I_0). Transformation from the phase domain to the sequence domain is achieved using the transform (3) [5]. Among these three symmetrical components, positive and negative sequence voltage are essential to the study of unbalance as the propagation of zero sequence component through the network is limited by transformer winding connections and network grounding.

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \times \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (3)$$

Where $a = e^{j120°}$.

Voltage Unbalance Factor (VUF)

The Voltage Unbalance Factor (VUF), defined by (4) as the ratio of negative (V_2) and positive (V_1) sequence voltages, is the most widely used and recommended (e.g., EN50160 [6]) measure of voltage unbalance in the network.

$$VUF = \frac{V_2}{V_1} \times 100\% \quad (4)$$

As zero sequence power flow in the network is much more restricted and therefore has much smaller effect than negative sequence power flow, it is not included in this definition of VUF.

Standard EN 50160 [6] defines that, during each week, 95% of the 10-minute average VUFs should be less than 2% in LV and MV netowrk, and less than 1% in HV network. Furthermore, it should not exceed 4% at any time. In engineering practice, DNOs usually do not consider mitigation for unbalance until VUF exceeds 2%. In many cases however, the full monitoring data for comparison with the standard are not available, or at least

not at all buses in the network; hence lacking the full observability of unbalance in the network. This however is essential to verify the range of VUF variation at different buses as it may exceed 2% [3].

METHODOLOGY

Test Network

Fig. 1 shows a 24-bus test network consisting of fourteen 33kV (labelled green) and ten 11kV buses (labelled red). The network is part of real UK distribution network. All parameters of the network are given in [3]. The test network is supplied from the external grid through bus 1. The power source is considered to be entirely balanced. Every 11kV substation serves a local load while 33kV buses have no direct loads connected to them. All transformers have delta earthed-star (Dyn11) winding connection, which blocks zero sequence flows. All the transmission lines connecting buses are assumed symmetrical and fully transposed.

Fig. 1. 24-bus network.

Load Variation

Load Classification
To create close-to-realistic time-varying loads, statistical daily loading curves for domestic, commercial and industrial loads are employed in these studies. Because of different peaks and changing trends of the three types of customers, loads in the network are classified into three classes and each class is treated separately. (Note: In real network, every bus supplies a mixture of two or three different load classes. In this study, however, for simplicity and without any loss of generality, individual loads at buses are considered as single-class loads, i.e., each load bus supplies either a residential, a commercial or an industrial load, but not a mix of those.) According to the size of connected loads, buses are categorized into three groups, listed in Table 1.

Daily Loading Time Zones
As a result of different agreements for supply and demand

of electrical energy at different time of a day, the system presents time-varying parameters of power flow that affect the evaluation of unbalance. By considering daily loading curves in the VUF estimations, results can be more accurate and realistic. For the purposes of this study, the twenty-four hours of a day are divided into three-hour slots, namely, eight time zones. Fig. 2 shows the average winter loading (the sum of all three types of loads) of the network for eight time zones (only weekdays of one week are considered) during the day.

Load Type	Bus Number
Residential	18, 21
Commercial	16, 17, 19, 20, 22, 24
Industrial	15, 23

Table. 1. Categories of load classes (types of customers) connected at different buses
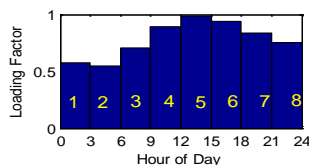
Fig. 2. Daily loading curve for the network.

The individual loading factors for different time zones are normalised with respect to the maximum value (Time Zone 5). The loading factors for individual load classes are calculated in the same way and shown in Table 2.

TIME ZONE	TOTAL	DOMESTIC	COMMERCIAL	INDUSTRIAL
1	0.575	0.57	0.53	0.597
2	0.551	0.52	0.55	0.554
3	0.705	0.71	0.66	0.725
4	0.894	0.69	0.85	0.929
5	0.983	0.65	1	1.000
6	0.942	0.78	0.98	0.936
7	0.833	1	0.88	0.798
8	0.752	0.91	0.72	0.755

Table. 2. Daily loading factor for the network.

Power Factor Variation

In order to model the unbalanced operation of a network, after applying daily loading factors, one or several or all loads may be adjusted to become potential sources of unbalance. To generate unbalanced loads in the load flow loops, the power factors of three phases of each load are varied assuming constant real power demand of each phase. Three base values of power factor, 1.0, 0.95 and 0.8, corresponding to lighting load, general load and induction motor load respectively, are selected to model load asymmetry [3]. By keeping the active power constant

and changing the reactive power in accordance with the selected power factor, the apparent powers of three phases are different from each other, hence leading to an asymmetrical loading condition. Furthermore, in order to create large amount of unbalanced loading scenarios probabilistically, a normal distribution is employed to estimate the possible variation of power factor in each phase. By taking the aforementioned 1, 0.95 and 0.8 as the mean values for the normal distributions, random values are created within corresponding ±20% (±3σ) ranges. All values above 1.0 are discarded (see Fig. 3). Although some of the generated values may be out of the ±3σ range, they are of low probability (0.2%) and can be considered as extreme loading conditions [3].
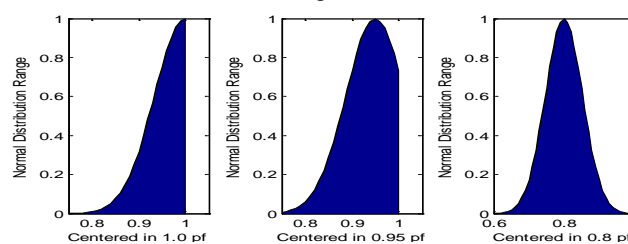

Fig. 3. Normally distributed power factor values.

For one run of three-phase load flow calculation, the power factors for three phases of one, or all loads, are randomly selected from the three normal distributions in Monte Carlo simulation. The load flow calculation is repeated for 500 different combinations of power factors. During the 500 Monte Carlo simulations, it is checked and ensured that the loading level of each phase of each load and every single load flow are different.

RESULTS AND DISCUSSION

After carrying out large number of simulations with different loading levels and different locations of sources of unbalance, the following principles about the propagation of unbalance are discovered.

As the power supply is assumed to be entirely balanced, the proximity of a bus to the power source helps diminish unbalance. Without considering the power regulation from the supply end, the resultant overall level of unbalance in the network is proportional to the size of the source. That is to say, large unbalanced load facilitates more sever unbalance and wider propagation of unbalance throughout the network. This conclusion also relates to the changing demand in customer load. During the peak demand period, VUFs of all buses are higher than at any other time, i.e., there is a higher risk of exceeding unbalance limit of 2% or 4%. The comparison of VUFs of minimum loading time zone (Time Zone 2) and maximum loading time zone (Time Zone 5) is shown in Fig. 4 using box diagrams. It is clear that in Time Zone

2, only bus 15 and to certain extent bus 23 are at risk of exceeding unbalance limit while there are four buses exceeding 4% instantaneous limit in Time Zone 5 and many more potentially exceeding 2% limit.

Heat Map (see Fig. 5) provides a visual understanding of the degree of unbalance in the network and the correlation between VUFs and the locations of buses. By using the mean values of 500 loops for 24 buses with ten sources of unbalance, heat map for the network for Time Zone 5 emphasizes the most affected area by showing it in orange colour. The yellow colour indicates the area where VUF exceeds the weekly 2% limit and where there might be some noticeable negative effects on customers' devices. The heat map clearly indicates propagation and severity of unbalance in the network. It identifies the areas with high VUF and points out to network operator where mitigation measures should be applied.
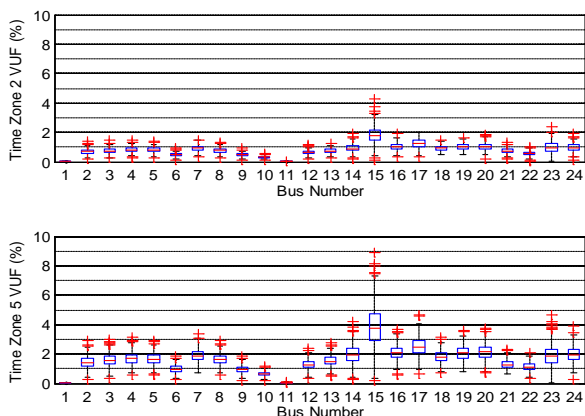
Fig. 4. Distributions of VUFs in Time Zone 2 and 5.
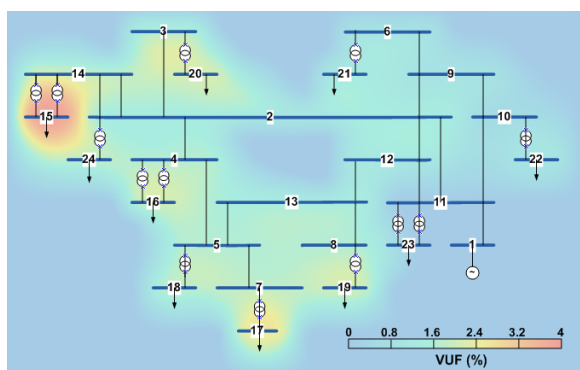
Fig. 5. "Heat map" of the network indicating the areas affected by unbalance.

By studying the effects of individual unbalance source in the network, geographical location becomes a significant concern. It is noticed that the neighbouring buses to the source of unbalance have similar behaviour, i.e., similar VUF, as the source bus (if they were not regulated by balancing source). In addition, there are districts of the network with similar level of unbalance depending on the

location of the source of unbalance. For example, once a source of unbalance appears in one district, it leads to bigger increase in the VUFs of buses in the same area, rather than buses in any other areas. The sub-division of the network into different areas of influence is shown in Fig. 6. For example, a voltage unbalance source in area 5 will mostly influence buses within area 5.
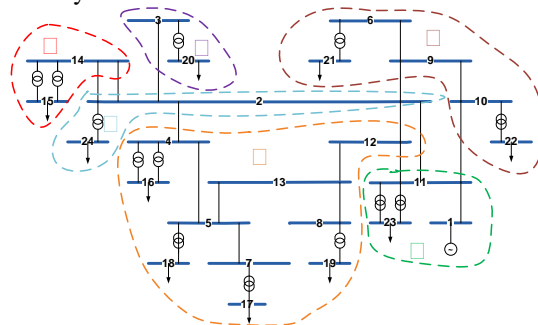

Fig. 6. Area sub-division according to individual performance of the buses of the network.

CONCLUSION

The variation in power factors of individual loads and the utilisation of daily loading curves help to generate close-to-realistic probabilistic loading of the network for voltage unbalance studies. After Monte Carlo simulations using the proposed methodology, the degree and propagation of unbalance in the network can be estimated and weak area in the network (with respect to voltage unbalance) can be identified. Developed heat-map presentation of the results facilitates easy tracking of unbalance through the network and identification of areas where mitigating solutions should be applied.

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