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A Linear Relation for Voltage Unbalance Factor Evaluation in Three-Phase Electrical Power System Using Space Vector

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***Abstract*—**The Voltage Unbalance Factor (VUF) index is recommended to evaluate system performance under unbalanced operation. However, its calculation requires complex algebra which limits its use in the field. Furthermore, one system cycle is required at least to detect unbalance using the VUF. Ideally unbalance mitigation must be performed within 10 ms for 50 Hz systems. In this work, a linear relation for VUF evaluation in three-phase electrical power system using space vector (SV) is derived. It is proposed to determine the voltage unbalance quickly and accurately and to overcome the constraints associated with the traditional methods of VUF evaluation. Aqaba-Qatrana-South Amman (AQSA) power system is considered to study the system performance under unbalanced conditions. The results show that both the complexity of calculations and the time required to evaluate VUF are reduced significantly.

***Keywords*—**Power quality, space vector, unbalance evaluation.

I. Introduction

THE performance of electrical power system degrades gradually in the presence of Power Quality (PQ) problems such as blackouts, harmonic distortion, transients, power frequency variations and voltage unbalance [1], [2]. Hence, treating these issues and evaluating system performance under these conditions is utmost concern to increase the power system efficiency.

The three-phase system is considered to be balanced whenever the three phase voltages and currents have the same amplitude and phase shift of 120° [3]. A primary cause for voltage unbalance is irregular distribution of single-phase loads over the three-phase system. Low voltage systems such as PCs and lightening are usually fed with single phase, also houses or apartments are organized in some layouts and connected as single-phase loads. Thus, maintaining balance over the three phases becomes difficult due to asymmetrical consumption of power [4]. Also, unbalance can result from inadequate design of electric transit and railroads and asymmetrical impedances of Transmission Lines (TL) and transformer windings [5].

Several publications and standards were introduced to evaluate voltage unbalance. In [6], the authors proposed three indices to assess the effect of voltage unbalance named as: Maximum Current Deviation (MCD), Combined Maximum Current Deviation (CMCD) and Effective Current Deviation. (ECD). However, these indices cannot be used alone in unbalance evaluation, they must be combined with other standard indices. Another factor that is introduced in [7] is the Voltage Unbalance Level (VUL) which assesses unbalance in time domain.

In terms of standard indices, IEEE Std.936-1987 defined voltage unbalance as: The difference between the highest and the lowest rms voltage, referred to the average of the three voltages [8]. Also, IEEE Std.112-1991 defined an index known as phase voltage unbalance rate (PVUR). It can be given as the ratio between the maximum deviation from the average of three phase voltages, and the average of these voltages [9].

Another index for voltage unbalance was defined by NEMA. It is known as Line Voltage Unbalance Ratio (LVUR) and defined as the ratio between maximum deviation from average voltage and the average of the three-line voltages [10]. Whereas, the true definition for voltage unbalance that is given by IEC and confirmed by IEEE Std.1159 [11] is the VUF, which can be defined as the ratio between negative sequence voltage and the positive sequence one [12]. Both LVUR and VUF are highly recommended for accurate unbalance assessment [6]. Furthermore, other developed indices are usually used in a combination with these indices.

The VUF describes the existence of negative sequence component in the system, thus it provides a better physical interpretation for voltage unbalance and its more useful for unbalance analysis. However, the main constraint that limits its use in field measurement is that it requires both the magnitudes and angles for the three phase voltages. Furthermore, a complexity is associated with its calculation because it requires complex algebra [13]. As a result, the calculation of VUF takes significant time with respect to the total ideal time allowed for unbalance mitigation which is 10 ms [14].

In this work, a technique to evaluate the VUF is proposed. A linear relationship between the SV amplitude and the VUF is derived. Thus, only the magnitudes of the three phase line voltages are required to calculate the SV and consequentially the VUF. This inherently simplifies the calculation of VUF. Furthermore, the time required for calculations is significantly reduced. A MATLAB/Simulink model that represents AQSA power system is built to test the proposed technique.

The paper is organized as follows: Section II introduces the basics of unbalanced three phase power system. Section III

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explains the traditional method used for VUF calculation. Then, the SV is introduced in Section IV. After that, Section V explains the proposed method and clarifies the relation between SV and VUF. Section VI discusses the results and finally, conclusions are introduced in Section VII.

II. Unbalanced Three Phase Power System

The functionality of Electrical power system diminishes when operating under unbalance conditions. Thus, the system performance must be analyzed and evaluated. Unbalanced three phase system components can be expressed as a set of balanced ones based on symmetrical components theory. This method reduces complexity in analyzing and visualizing the system under unbalanced conditions. Symmetrical components include positive, negative and zero sequence currents and voltages. The positive sequence represents system voltages which have equal magnitudes and 120° phase shifts. The negative sequence components are similar to the positive ones, except that they rotate in the opposite direction. Finally, the zero sequence voltages which are in phase and have equal magnitudes, this sequence does not contribute to system balance [15]. Generally, the system balance can be restored by discarding the negative sequence components. The following equations represent symmetrical components of phase (a) in terms of system three phase voltages [16]:

$$V_0 = ⅓ (V_a + V_b + V_c \tag{1}$$

$$V_1 = ⅓ (V_a + aV_b + a^2V_c) \tag{2}$$

$$V_2 = ⅓ (V_a + a^2V_b + aV_c) \tag{3}$$

where: $V_a, V_b \ and \ V_c$ represents the three phase unbalanced voltages. $V_0, V_1 \ and \ V_2$ represents the zero, positive and negative sequence components of the three phase voltages respectively and a: $1\angle 120° = e^{j\frac{2\pi}{3}}$.

In order to analyze system performance under unbalance conditions, AQSA power system was considered as a case study. A Simulink/MATLAB model that depicts the system was built. The system consists of generation station at Aqaba, then a transmission is performed for 245 km to Qatrana substation. Finally, the power is delivered to South Amman substation which is 83 km distant from Qatrana substation. The transmission line is represented by three Π to simulate system performance accurately. The unbalance is achieved by irregular distribution of single-phase inductive loads. The general layout for the system simulation is shown in Fig. 1.

III. Voltage Unbalance Factor

VUF is highly recommended for unbalance assessment. However, several constraints are accompanied with its use as discussed in the introduction. It represents the ratio between the negative and positive sequence voltage and can be calculated by the following equation:

$$\% \, VUF = \frac{V_2}{V_1} \, x100 \, \% \tag{4}$$

It is worth mentioning that, according to ANSI standard C84.1–1995, voltage unbalance in the electrical power system should not exceed 3%. Furthermore, the NEMA standard, i.e NEMA MG1-1993, recommends that the induction motor should be derated if the voltage unbalance exceeds 1% [17]. Thus, it is necessary to evaluate the VUF in order to apply suitable mitigation techniques.

IV. SV Calculation

The SV represents the total effect of the balanced three phase voltages by a single complex variable [18]. The SV $\bar{v}_s$ of the three phase voltages can be given as:

$$\bar{v}_s = \frac{2}{3}(v_a - \frac{1}{2}(v_b + v_c) + j\frac{\sqrt{3}}{2}(v_b - v_c)) \tag{5}$$

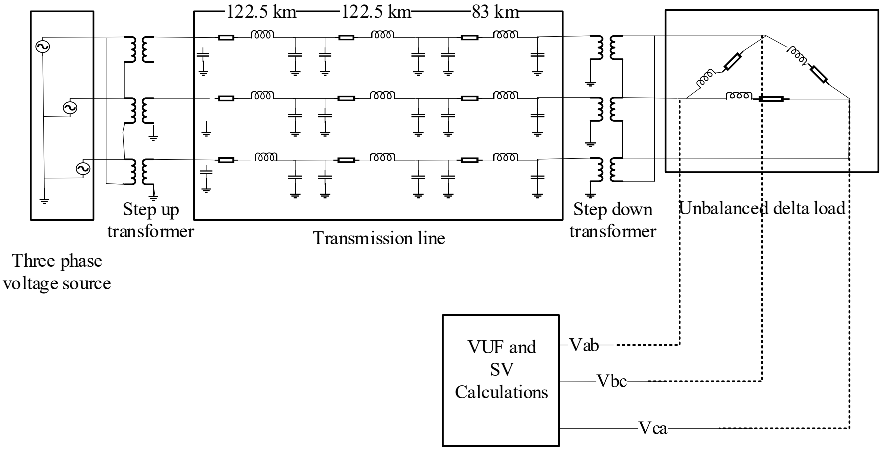

Fig. 1 AQSA power system simulation model general layout

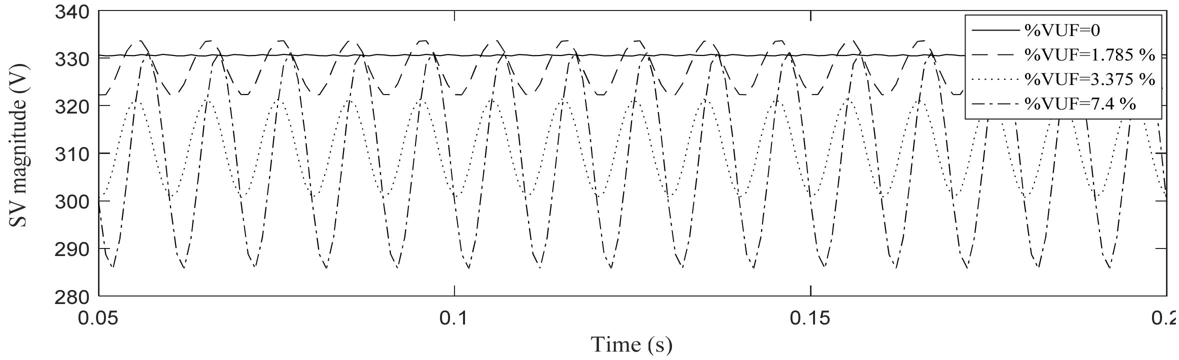

Fig. 2 SV signal at different VUF

The magnitude of $\bar{v}_s$ can be given as:

$$|\bar{v}_s| = \sqrt{{v_a}^2 + \frac{1}{3}(v_b - v_c)^2} \quad (6)$$

In calculations of SV signal only the magnitude of the SV is required. Therefore, complex algebra associated with traditional method is avoided.

V. VUF Evaluation Using SV Amplitude

In this work, a simplified method to calculate the VUF from the SV is proposed. In case of unbalanced three phase voltages, the SV magnitude is calculated according to (6). We found that the amplitude value of the resultant SV signal varies with the variations in the VUF. Fig. 2 shows the SV signal for balanced three phase system where VUF is zero. Also, it shows the SV signal for several unbalance cases where the VUF is 1.785%, 3.375% and 7.4%. It is obvious that as the VUF increase the amplitude of the SV signal increase.

VI. Results and Discussion

In order to derive a relationship between the SV amplitude and the VUF, 115 data point were obtained from the simulation model. Fig. 3 proves the proposed hypothesis and shows that the relation between the SV and VUF is linear according to the following equation:

$$\%VUF = 0.0034\, SV - 0.0037 \quad (7)$$

Also, it is worth mentioning that the regression factor is 0.99 which is very high and means that the suggested linear equation fits the data.

Table I shows the results for unbalance calculation by the derived equation and compares the results with data obtained using traditional method for 10 cases. Furthermore, the evaluation of VUF by calculating the ratio between the negative sequence voltage and the positive sequence one, takes 20 ms at least which is considered a very long time. Ideally the whole process for unbalance mitigation must be performed within 10 ms. In the proposed method, the amplitude of the SV signal can be found after 2.5 ms (one eighth system cycle) for systems with 50 Hz frequency, whereas the traditional method requires one cycle at least which is eight times of the proposed method. Fig. 4 shows that the time required for SV amplitude evaluation is 2.5 ms. The amplitude is 11.1 and the calculated VUF is 3.51 % whereas the true value is 3.48 % and the relative error is 0.8 %.

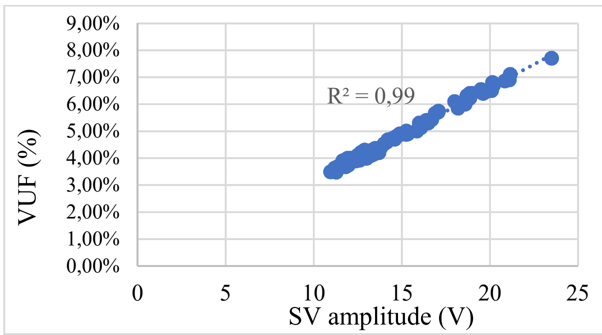

Fig. 3 The relationship between %VUF and SV amplitude

TABLE I
%VUF Calculation

%VUF (Ratio between negative and positive sequence)	SV amplitude	%VUF (proposed method)	Relative Error (%)
3.9	12.13	3.8755	0.628
5.14	15.42	5.027	2.198
6	17.75	5.8425	2.625
3.75	11.57	3.6795	1.88
3.8	11.6	3.69	2.895
4.02	12.58	4.033	0.323
5.83	17.12	5.622	3.568
6.64	20.25	6.7175	1.167
7	20.93	6.9555	0.636
7.43	22.9	7.645	2.894

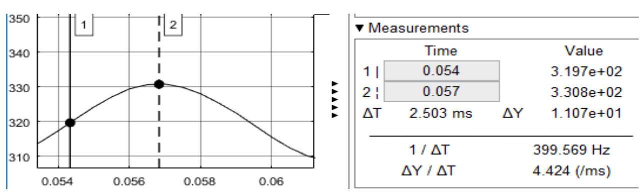

Fig. 4 Time required for VUF calculation using proposed method

VII. Conclusion

A method that simplifies the calculation of VUF was proposed. AQSA electrical power system was considered as a case study. We found that as the VUF increase, the amplitude of the SV signal increase. Therefore, A linear equation that relates the VUF with the SV was derived, thus complexities associated with calculations are eliminated. Furthermore, the time required to calculate VUF was reduced to 2.5 ms. The derived equation is system dependent, so we suggest that a more general equation can be derived in terms of system parameters.

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