International Journal of Engineering Research and Development
e-ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 12, Issue 12 (December 2016), PP.65-70

Prediction of Voltage Unbalance Employing Space Vector Property

Jasim Ghaeb[1], Jalel Chebil[2]
[1]*University of Philadelphia, Department of Mechatronics Engineering, Amman, Jordan.*
[2]*University of Sousse, ISTLS, Department of Technology and Engineering in Transport, Sousse, Tunisia.*

Abstract:- This paper examines the voltage unbalance in discrete manner. The system sinusoidal cycle is sampled at a particular sampling period, and the three instantaneous values of voltages are measured at these samples. These instantaneous values together with their space vector are employed by the proposed Algorithm for Voltage Unbalance Prediction (AVUP) to predict if there is any voltage unbalance. The simulated results show the high performance of AVUP for predicting of voltage unbalance.

Keywords:- Voltage unbalance, Space vector, Power quality, Power systems, Symmetrical components..

I. INTRODUCTION

A balance electrical power system contains only positive sequence components of voltage, current and impedance. The generators in the stations of power systems are constructed in the way to produce balanced three-phase sinusoidal voltages, of equal magnitudes and equal individual separation. However, at the utilization points the three-phase voltages may become unbalance due to the following causes [1, 2, and 3]:

1. Unregulated distribution of single-phase load connected through the three-phase power system,
2. Asymmetrical transformer winding impedances spreading among the three-phase power system,
3. Asymmetrical transmission impedances caused by incomplete transposition of transmission lines, and
4. Inappropriate design of utility of single-phase transaction and railroads.

Many utilities do not care about their voltage unbalance because the adverse results are not immediately realized, and the voltage unbalance is observed only when there is a complaint [4]. There are many problems associated with the voltage unbalance such as more energy losses, heating, possibility of system instability and negative effects on the equipment [5]. A reduction of efficiency or failure of an induction motor may occur when it is operating under unbalanced voltage conditions [6 and 7]. Kersting and Phillips proved that the losses of rotor and stator circuits of induction motor are increased with high voltage unbalance [8]. The operating of converter under unbalanced voltage conditions produces uncharacteristic triple current harmonics, such as 3rd and 9th order, in the input. In addition, it also produces the characteristic harmonics (5th, 7th, 11th etc.) [9].

Many authors [4, 10, 11 and 12] have proposed formulas for voltage unbalance factor assessment with the following improper assumptions:

1. They assumed that there is a voltage unbalance and made their calculations for the percentage voltage unbalance factor (VUF), but they did not determine if there is a voltage unbalance or not.
2. They made their calculations for the percentage voltage unbalance factor depending on the assumed RMS voltages, not on the real measured values.

There are many definitions for the voltage unbalance. The National Electrical Manufacturers Association (NEMA) define the voltage unbalance as the maximum deviation from the average of three line voltages, referred to the average of three line voltages [13]. According to IEEE Std.936-1987, the voltage unbalance is defined as the difference between the highest and lowest RMS voltages, referred to the average RMS of the three voltages [14]. Another definition of voltage unbalance is given by IEEE Std.112-1991: it is the deviation from the average of three phase voltages, referred to the average of three phase voltages [15]. The recently confirmed true definition is given by IEEE Std.1159-1195: it is the ratio of negative- sequence voltage and positive- sequence voltage. The author of [11] concluded that the two definitions; IEEE Std.936-1987 and IEEE Std.112-1991; give significant different results referred to the true definition IEEE Std.1159-1195.

Many techniques have been proposed to correct the voltage unbalance of electrical supply system. It is impossible to keep exact balance due to the continuous connection and disconnection of the single-phase loads and unregulated distribution between the three phases [16]. The methods of voltage unbalance correction were trying to distribute single-phase loads equally across the three- phase supply [17]. Broadwater et al. proposed to change the system configuration to balance the electrical distribution system using manual and automatic feeder switching operations [5]. A proper selection of distribution of transformers helps in keeping a balanced supply system [9]. The voltage unbalance correction can be achieved by means of the static Volt- Ampere Reactive (VAR) compensation [12, 18 and 19]. When there is an unbalanced load change, reactive power is added or absorbed by the reactive compensator to balance the load and then the three phase voltages.

Before calculating the voltage unbalance factor, it is necessary to determine if the power system is balanced or not. In this work, a discrete prediction of voltage unbalance is achieved through employing the property of Space Vector (SV) to provide enough time of system sinusoidal period for calculations and control of voltage unbalance. This results in fast response of correction.

The paper is organized as follows. The voltage unbalance in three-phase supply is discussed in Section 2, and the theory of space vector is given in Section 3. The proposed technique for prediction of voltage unbalance is presented in Section 4. Section 5 discusses the results and Section 6 concludes the paper.

II. UNBALANCED THREE- PHASE VOLTAGE

In the three-phase electric power system, the load elements are arranged in either star or delta connection and supplied by three line currents [20]. In the electrical power system, the voltage unbalanced means unequal voltage magnitudes at fundamental frequency, fundamental phase angle deviation and unequal levels of harmonics between the three phases [4]. The American Standard C84.1-1995 confirmed that the maximum voltage unbalance of electrical supply systems should not exceed 3% [21]. The International Electro-mechanical Commission (IEC) recommended that the maximum voltage unbalance should not exceed 2% [16]. Fig. 1 shows the three line currents (ia, ib, ic) of three-phase supply, which are drawn by the unbalanced load.

If there is an unbalanced change in the load, the three line currents become unbalance, leading to three unbalanced load voltages. These unbalanced voltages can be divided in three components: positive-sequence, negative-sequence and zero-sequence components. For getting back the balance condition, it is necessary to discard the negative-sequence component or the positive-sequence component.

For a stable system, it is necessary to watch if any unbalanced load change has occurred, and the correction has to be done in very short time. In this work, a prediction of voltage unbalance in discrete manner is achieved, employing the property of space vector. This achievement will speed up the response of controller which is used in voltage unbalance.

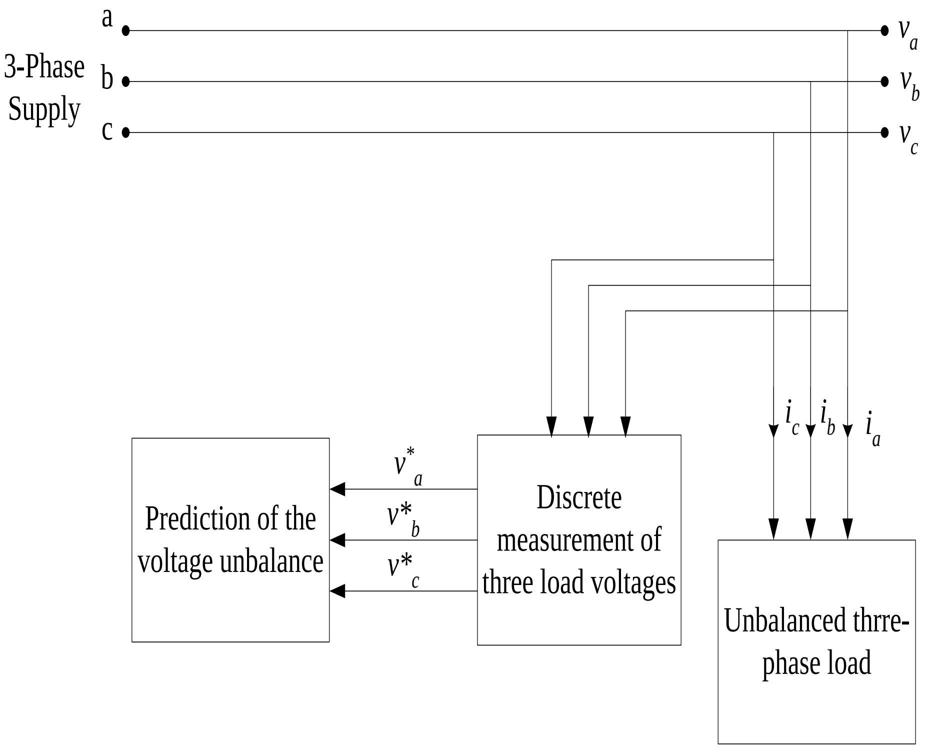

Fig. 1: Three-phase supply with unbalanced load.

III. SPACE VECTOR THEORY

The space vector is the transformation of effect of balanced three instantaneous values into a single complex variable [22]. For the balanced three- phase voltages, the time domain of voltage va is assumed:

$$v_a = \sin\omega t \tag{1}$$

Its space vector is:

$$\bar{v}_a = \sin\omega t = v_a \tag{2}$$

The three voltages are balanced, therefore, space vector of two voltages: v_b and v_c are:

$$\bar{v}_b = av_b \tag{3}$$

$$\bar{v}_c = a^2 v_c \tag{4}$$

The space vector for three voltages is:

$$\bar{v} = v_a + av_b + a^2 v_c \tag{5}$$

where a= exp(j 2π/3)

By substituting 'a' and 'a^2' in (5), we get:

$$\bar{v} = \frac{3}{2}v_a + j\frac{\sqrt{3}}{2}(v_b - v_c) \tag{6}$$

After scaling (6) by (2/3), the equation becomes:

$$\bar{v}_s = v_a + j\frac{1}{\sqrt{3}}(v_b - v_c) \tag{7}$$

IV. PREDICTION OF VOLTAGE UNBALANCE

Unbalanced voltages in three- phase system cause adverse effects on the electrical power system and equipment. In this work, the system sinusoidal cycle is divided into many samples. The three instantaneous values of voltages are measured at these samples and kept for voltage unbalance prediction. The property of the space vector together with the discrete measurement of the three instantaneous values of voltages is employed to prognosticate the voltage unbalance at discrete manner.

A. Algorithm for Voltage Unbalance Prediction (AVUP)

At any instant, the sum of three instantaneous values of balanced voltages is zero. However, for some cases the sum of the instantaneous values is zero even though the system is unbalanced. For instance, the three instantaneous values of an unbalanced case of: va= 300V, vb= -300V and vc= 0V, give a sum of zero although the three voltages are unbalanced.

If the property of space vector is employed to measure the voltage unbalance, the measured space vector magnitude (VSM) has to be fixed and equal the reference one (Vsref) for all samples, to guarantee the balance case. However, it may occur that the measured space vector magnitude (Vsm) is less or greater than the reference one and the three voltages are still balanced. Therefore, to measure the voltage unbalance, it is necessary to include both conditions; the instantaneous values of voltages and the space vector magnitude, as proposed by the Algorithm for Voltage Unbalance Prediction (AVUP), which is given in Fig. 2.

The two logic conditions used in the AVUP are as follows:

1. Sum of instantaneous values of voltages is equal or not equal to zero
2. Comparison between the measured and the referenced space vector magnitude

These two conditions form a binary number of 2-bits which represent four states: 00, 01, 10 and 11. The Most Significant Bit (MSB) of the binary number represents the state of condition (1) and the Least Significant Bit (LSB) represents the state of condition (2). A binary number '1' stands for the equality in condition (1) or condition (2), and the binary number '0' stands for the inequality in condition (1) or condition (2). A detailed description of each state is shown below:

- State (11) indicates that the sum of instantaneous values of three voltages is zero and the magnitudes of measured space vector and reference one are equal. Therefore, the three voltages are balanced.

- State (00) indicates that the sum of instantaneous values of three voltages is not zero and the magnitudes of measured space vector and reference one are not equal. Therefore, the three voltages are unbalanced.

- If state (10) is fulfilled, the load change may be occurred in the way to give a balanced condition, but Vsm is less or more than Vsref. Therefore, the algorithm has to go through path (1), to verify this possibility.

- State (01) is invalid, because the MSB of binary number '0' proves that the system is unbalanced (because the sum of instantaneous values of three voltages is not zero). Therefore, the LSB of binary number has to be '0' and Vsm$\neq$ Vsref.

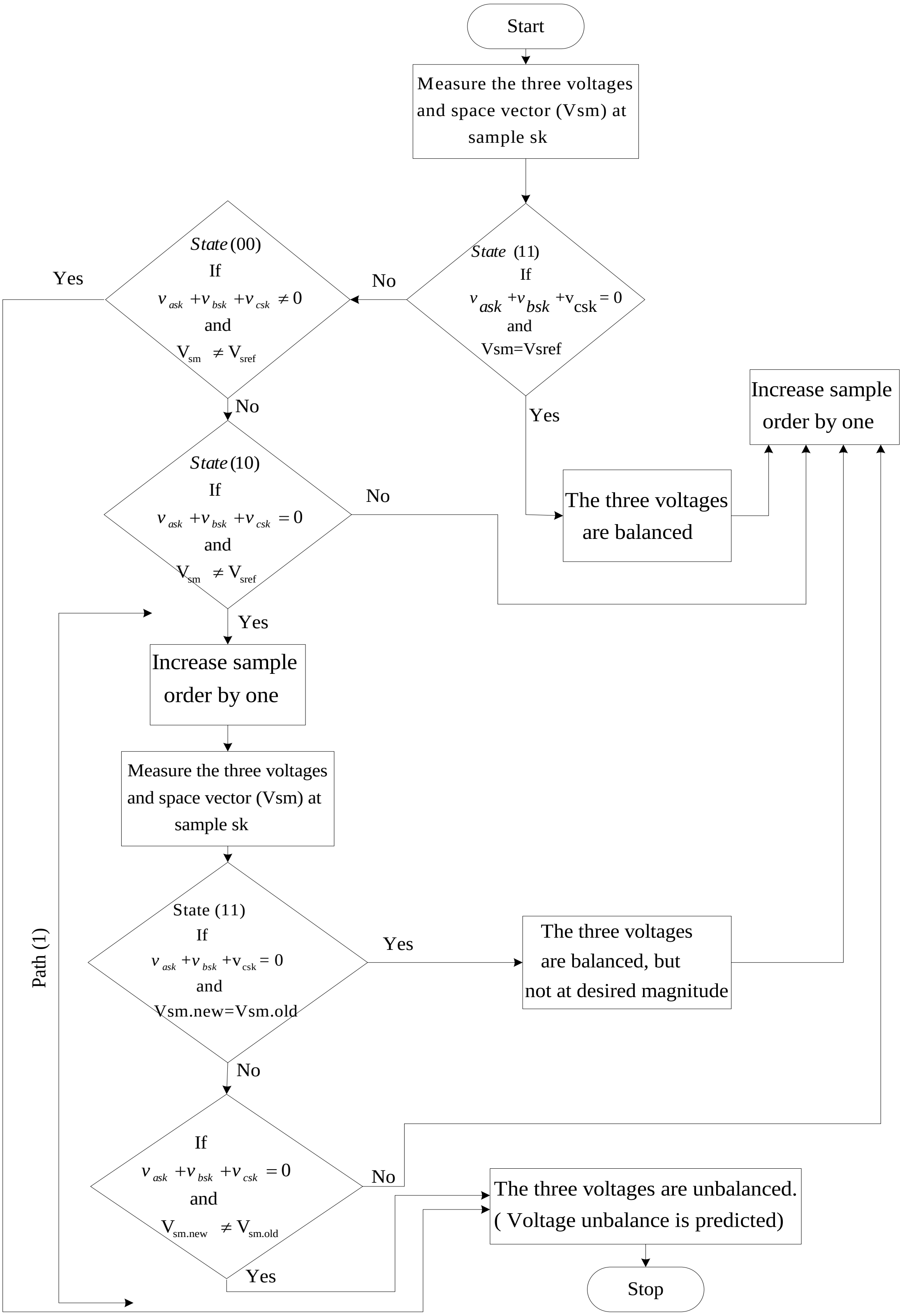

Fig. 2: Algorithm for Voltage Unbalance Prediction (AVUP)

V. RESULTS AND DISCUSSIONS

In the AVUP, the discrete values of the balanced voltages are recorded for a complete cycle, to use them in calculating the reference value of space vector. For this simulation, the reference value of space vector is taken as 100V. For different changes of three- phase voltages, the AVUP algorithm is used to predict the voltage unbalance, and the simulated results are shown in Table I. In the first and second cases, the change occurred in such a way to produce a balance and unbalance voltage respectively , it is found that in both cases the two conditions of AVUP produce the correct result. In case (3) and case (4), the true result of voltage unbalance is not detected by condition (1) of AVUP, but it is detected by condition (2) of AVUP. In case (5), the true result is the voltage balance but with voltage magnitude less than the desired one. Therefore, the AVUP has to go through path (1), as shown in Fig. 2. It can be concluded that for measuring the voltage unbalance accurately, it is necessary to include both conditions as proposed by the AVUP algorithm.

Table I: Simulated Results of Voltage Unbalance Prediction

Case-number	Instantaneous values of three voltages after the change			True result	Sum of instantaneous values of three voltages	Space vector magnitude (Vsm) (Vsref=100V)
	v_a	v_b	v_c			
1.	95.10V	-74.31V	-20.79V	Voltage Balance	0	100V
2.	80.90V	-77.65V	-11.49V	Voltage Unbalance	14.74V	95.88V
3.	80.50V	-35.10V	-45.40V	Voltage Unbalance	0	80.71V
4.	94.10V	-55.07V	-39.03V	Voltage Unbalance	0	94.55V
5.	64.72V	-73.08V	08.36V	Voltage Balance but at less voltage magnitude	0	80V

VI. CONCLUSIONS

In this work, a discrete prediction of voltage unbalance is achieved to provide enough time of system sinusoidal period for calculations and control of voltage unbalance, results in fast response of correction. An Algorithm for Voltage Unbalance Prediction (AVUP) is proposed. The AVUP uses the sum of three instantaneous values of voltages and space vector magnitude to predict the voltage unbalance accurately.

REFERENCES

[1]. R. Bergeron, Voltage unbalance on distribution systems—Phase", Canadian Electrical Association, Montreal, Quebec, Project no. 231 D 488, 1989.

[2]. R. F. Woll, "Effect of unbalanced voltage on the operation of poly-phase induction motors", IEEE Trans. Industry Applications, vol. IA-11, no.1, pp. 38–42, 1975.

[3]. A. von Jouanne and B. B. Banerjee, "Voltage unbalance: Power quality issues, related standards and mitigation techniques", Electric Power Research Institute, Palo Alto, CA, EPRI Final Rep, 2000.

[4]. A. Jouanne, B. Banerjee " Assessment of voltage unbalance", IEEE Trans. Power Delivery, vol. 16, no.4, pp. 782–790, 2001.

[5]. R. P. Broadwater, A. H. Khan, H. E. Shaalan, and R. E. Lee, "Timevarying load analysis to reduce distribution losses through reconfiguration", IEEE Trans. Power Delivery, vol. 8, no. 1, pp. 294–300, 1993.

[6]. J. W. Williams "Operation of 3 phase induction motors on unbalanced voltages" AIEE Trans. Power App. Syst., vol. PAS-73, pp. 125–133, 1954.

[7]. Gafford, W. C. Duesterhoeft, and C. C. Mosher "Heating of induction motors on unbalanced voltages", AIEE Trans. Power App. Syst., vol. PAS-78, pp. 282–297, 1959.

[8]. W. H. Kersting and W. H. Phillips "Phase frame analysis of the effects of voltage unbalance on induction machines", IEEE Trans. Industry Applications, vol. 33, no. 2, pp. 415–420, 1997.

[9]. D. R. Smith, H. R. Braunstein, and J. D. Borst "Voltage unbalance in 3- and 4 wire delta secondary systems", IEEE Trans. Power Delivery, vol. 3, no. 2, pp. 733–741,1988.

[10]. J. A. L. Ghijselen, A. P. M. Van den Bossche " Exact Voltage Unbalance AssessmentWithout Phase Measurements", IEEE Trans. on power systems, vol. 20, no. 1, 2005.

[11]. M. Bollen "Definitions of voltage unbalance" IEEE Power Eng Rev., vol. 22, no. 11, pp. 49–50, Nov, 2002.
[12]. T. J. E. Miller, Reactive Power Control in Electric Systems. New York: Wiley, 1982.
[13]. Motors and Generators, NEMA Standards Publication no. MG 1-1993.
[14]. IEEE Standard Dictionary of Electrical and Electronics Terms, IEEE Std.100-1996.
[15]. P. Pillay and M. Manyage "Definitions of voltage unbalance", IEEE Power Eng. Rev. Mag., vol. 5,pp. 50-51, May 2001.
[16]. EPRI Power Electronics Applications Center "Input performance of, ASDs during supply voltage unbalance", Power quality testing network PQTN Brief no. 28, 1996.
[17]. A. von Jouanne and B. B. Banerjee" Voltage unbalance: Power qualityissues, related standards and mitigation techniques", Electric Power Research Institute, Palo Alto, CA, EPRI Final Rep., 2000.
[18]. A. Campos, G. Joos, P. D. Ziogas, and J. F. Lindsay "Analysis and design of a series voltage unbalance compensator based on a three-phase VSI operating with unbalanced switching functions", IEEE Trans. Power Electronics, vol. 9, no. 3, pp. 269–274,1994.
[19]. J.-H. Chen, W.-J. Lee, and M.-S. Chen "Using a static var compensator to balance a distribution system ", IEEE Trans. Industry Applications, vol. 35, no. 2, pp. 298–304, 1999.
[20]. J. Grainger and W. Stevenson, Power system analysis. McGraw- Hill, Inc, New York, pp. 422-432, 1994.
[21]. Electric Power Systems and Equipment-Voltage Ratings (60 Hertz), ANSI Standard Publication no. ANSI C84.1-1995.
[22]. V. Peter, Vector control of AC machines, New York: Oxford University Press, 1990.