Theoretical and Experimental Investigation of the Supply Voltage Unbalance Effects on Squirrel Cage Induction Motors

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Abstract: Voltage unbalance is one of the power quality problems causing a lot of ill effects on induction motors. These are namely: Overheating, line-current unbalance, derating, torque pulsation, and inefficiency. The objective of the present work is to assess and quantify the effects of voltage unbalance on induction motors using both theory and experimentation. The analytical study is performed using the complex voltage unbalance factor model of this problem. The work deals specifically with the influence of the variations in the complex angle of the voltage unbalance factor on the stator and rotor currents, stator and rotor copper losses and total losses. The experimental investigation is carried out using an apparatus that measures currents, torque and power losses.

Keywords: Power quality; Voltage unbalance; Complex angle; Induction motor; Power losses

1. INTRODUCTION

Induction motors are widely used in industrial, commercial and residential systems due to various techno-economic advantages associated with them. Three-phase voltage unbalance is a frequently encountered power quality issue in weak power networks and in power systems that supply large single-phase loads. Voltage unbalance has detrimental effects on three-phase induction motors, including over heating, line-current unbalance, derating, torque pulsation, inefficiency, etc [1].

The ability of motors to support power system disturbances is a concern in nowadays industrial plants. A "disturbance-proof" system improves the reliability of the plant, particularly in the process industry where the failure of a motor can result in considerable downtime. Power quality disturbances are divided into three types; namely frequency disturbances, waveform disturbances (non-sinusoidal waveform) and voltage disturbances (unacceptable RMS value). The voltage disturbances include sags, swells and voltage unbalances. They cause failure and malfunction of much equipment such as electronic Adjustable Speed Drives (ASD's) and process control. Sag is a decrease of 10% up to 90% in RMS voltage or current at the power frequency during half cycle up to one minute. However, swell is an increase of 10% up to 90% in RMS voltage or current at the power frequency during half cycle up to one minute. [2,3].

Particularly, Voltage unbalance is regarded as a power quality problem of significant concern at the electricity distribution level. An excessive level of voltage unbalance can have serious impacts on mains connected induction motors. An unbalance in the line currents can lead to excessive losses in the stator and rotor that may cause protection systems to operate causing loss of production. Although induction motors are designed to tolerate a small level of unbalance they have to be derated if the unbalance is excessive. When the motor continues to operate under unbalanced voltage conditions, its efficiency will be reduced caused by both an increase in

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current and in resistance due to over-heating. As the resulting losses increase, the heat increases rapidly that may lead to a condition of uncontrollable heat rise called "thermal runaway". This results in a rapid deterioration of the winding insulation that will end up with failure of the winding [1,4,5].

An unbalanced voltage supply leads an increase in the motor's currents which forces the user to derate the motor. It is desirable to have a precise quantification of the current/voltage unbalance relationship before further analyses can be carried out.

Studies on the influence of voltage unbalance upon three-phase induction motors have been reported in literature, as the design, protection, operation, maintenance and lifetime estimation of the motor are closely related to the level of voltage unbalance to which the motor is to be subjected. The effects of unbalanced voltages on the performance of a three-phase induction motor have been studied widely. The influence of unbalanced on the efficiency [4],[6], power factor[4], derating in the machine [7],[8], temperature rise, and life reduction [9], increase of losses, and negative effects on the insulation [7],[9] and [10] are some contributions in the area. Some authors [4], [6] and [7], have concluded that the efficiency and power factor of the motor depend on the positive sequence voltage, the negative sequence voltage, the voltage magnitude and the voltage angle. Likewise, these authors show that the derating factor given by the NEMA standard is insufficient to evaluate the effects of unbalance voltage on the motor, because it is based only in NEMA definition. However, these authors do not give a mathematical relation that may be used to evaluate the efficiency and power factor.

There are two widely recognized definitions for voltage unbalance, the IEC (International Electromechanical Commission) definitions [11] and the NEMA (National Electrical Manufacturers Association) definitions [5]. The IEC definition is mathematically more rigorous compared to the NEMA definitions [12].

The method of evaluating the level of voltage unbalance is either the percent voltage unbalance (PVU) defined by the NEMA or the voltage unbalance factor (VUF) defined by the IEC. The PVU is the ratio of the maximum deviation from average voltage, to the average of three voltages, while the VUF is given by the ratio of the negative-to positive-sequence voltage. Both the PVU and the VUF are positive real quantities that reflect the level of voltage unbalance. Generally speaking, the PVU is convenient to field measurements because its calculation involves only the magnitudes of three-phase voltages. On the other hand, the calculation of the VUF requires both the magnitudes and phases of three-phase voltages to be known, which is more difficult in the field. However, the VUF conveys better physical interpretation of the cause of voltage unbalance, and is more useful in prediction and analysis of the effects of voltage unbalance on the motor [12] .

An extension of the VUF is the complex voltage unbalance factor (CVUF) that is defined by the ratio of the negative sequence voltage phasor to the positive-sequence voltage phasor. The CVUF is a complex quantity having the magnitude and the angle. Although the CVUF has not yet been widely used by practicing engineers, it has been proposed in some studies [13,14] due to its richness of information on unbalance. The effect of voltage unbalance on induction motors was studied and formulated using the CVUF in [13]. However, the author focused his analysis on the effect of the magnitude of the CVUF, and neither the physical meaning nor the effect of its angle was discussed. Furthermore, the works used the approximate equivalent circuit of the induction motor. Also, the authors of these works did not investigate the effect of the complex voltage unbalance angle on the induction motor.

In this work, the steady-state performance of an induction motor under voltage unbalance is studied and the emphasis will be placed on the effect of the angle of the CVUF. Particularly, the influence of the variations in the complex angle of the voltage unbalance factor on the stator and rotor currents, stator and rotor copper losses and total losses is dealt with. The effects of unbalanced voltages upon the line currents of the three phase squirrel cage induction motor from experimental point of view as well as a comparison with the theoretically estimated values are dealt with. This is useful to better model the line current variation due to an unbalance in the supply voltages.

2. DEFINITION OF VOLTAGE UNBALANCE

The level of voltage unbalance that is present in a system can be specified using two commonly used definitions. The first definition is widely used in European standards and is based on the Theory of Symmetrical Components. The second definition is used in USA and avoids the use of complex algebra

IEC definition

The definition of voltage unbalance used by academic community is the ratio of negative sequence voltage V_n to the positive sequence voltage V_p and is called Negative Sequence Voltage Unbalanced Factor. This definition is adopted by IEC 60034-26 [11] and is also known as the Voltage Unbalance Factor (VUF) or IEC definition.

$$VUF = \frac{V_n}{V_p} \tag{1}$$

For a set of unbalanced voltages V_{ab}, V_{bc}, V_{ca}, the positive and negative sequence voltages V_p and V_n are given by

$$V_p = \frac{V_{ab} + aV_{bc} + a^2 V_{ca}}{3} \tag{2}$$

$$V_n = \frac{V_{ab} + a^2 V_{bc} + aV_{ca}}{3} \tag{3}$$

Where $a = -0.5 + j0.866$ and $a^2 = -0.5 - j0.866$.

The VUF can also be expressed in a more user-friendly form than given by equation (1), which requires only the three line-line voltage readings V_{ab}, V_{bc}, V_{ca}.

$$VUF = \frac{V_n}{V_p} = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \tag{4}$$

Where

$$\beta = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)^2} \tag{5}$$

NEMA Definition

The NEMA Standard MG1.1993 [5] and the IEEE community use the following definition:

$$LVUF = \frac{\text{maximum voltage deviation from average voltage}}{\text{average voltage}} \tag{6}$$

This definition assumes that the average voltage is always equal to the rated value and avoids the use of complex algebra, and is called Line Voltage Unbalance Factor (LVUF) or NEMA definition

IEEE Definition

The IEEE definition of voltage unbalance is known as the Phase Voltage Unbalance Rate (PVUR) [7], is given by

$$PVUR = \frac{\text{maximum voltage deviation from average phase voltage}}{\text{average phase voltage}} \tag{7}$$

The IEEE definition is the same as the NEMA one; the only difference is that the IEEE uses the phase voltages rather than the line-to-line voltages. Here again the phase angle information is discarded since only magnitude is considered.

3. INDUCTION MOTOR MODELING UNDER UNBALANCED SUPPLY

Three phase unbalanced supply voltage can be modeled using the symmetrical component theory. Each set of positive and negative sequence voltages produce corresponding balanced currents in the induction motor, and the synthesis of the two sets of current vectors represents the actual currents produced in the three stator phases by the original unbalanced voltages.
The behavior of the machine due to the positive sequence voltage is essentially the same as for normal balanced operation [7]. Whereas the negative sequence currents set up reverse field, so that if the rotor slip is s with respect to the positive sequence field, it will be (2-s) relative to the negative sequence field. The motor behaves as the addition of two separate motors, one running at slip s with a terminal voltage of V_p per phase and the other running with a slip of (2-s) and a terminal voltage of V_n [9] . The equivalent circuits of the induction motor for each sequence are shown in fig. 1 and 2.

4. ANALYSIS OF INDUCTION MOTORS UNDER VOLTAGE UNBALANCE

Before carrying on with the study of the effects the voltage unbalance case has on the motor performance, it is worth investigating the normal case which is the balanced three phase supply. The performance measures of interest in the present study are namely the stator and rotor currents with their corresponding copper losses. At balance, these quantities turn out to be constant over all the range of angles. The values are shown in the first line of table 1.

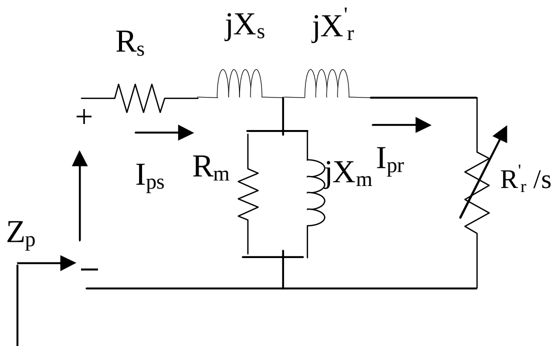


Fig. 1 Positive Sequence Equivalent Circuit

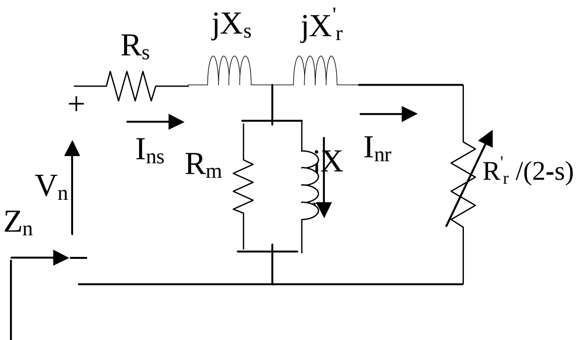


Fig. 2 Negative Sequence Equivalent Circuit

In the subsequent sections, the effects of having different voltage unbalance levels on the induction motor are investigated. Three percent voltage unbalance values are considered.

Case of 1% Voltage Unbalance

The variations of the stator and rotor currents along with stator and rotor copper losses for each phase versus the complex angle are shown in fig. 3 through 6. It is noticed that all quantities show a behavior that resembles an amplitude modulated sinusoidal waveform. For the stator currents, they are found to peak at some angles that are evenly spaced by 44° and they occur at different angles. The peak values are found to be 6.27 A compared to 6.205 A in the balanced case. In a similar way, the rotor currents exhibit amplitude modulated-like waveform. These currents peak at angles spaced again by 44° and at different angles.

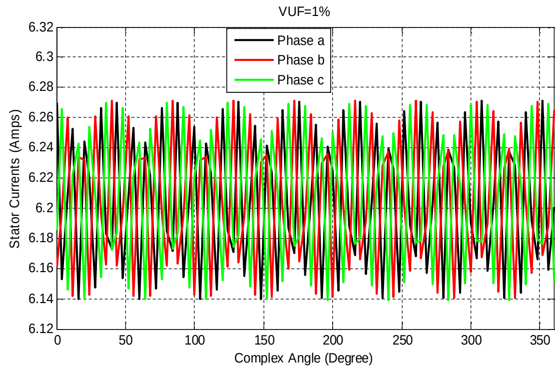


Fig. 3 Stator Currents versus complex unbalance angle with 1% voltage unbalance

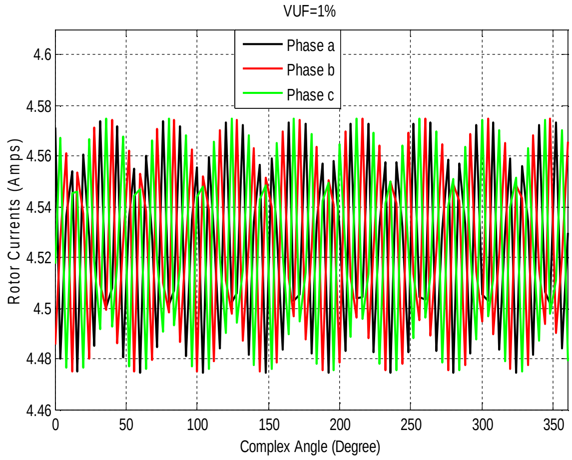


Fig. 4 Rotor Currents versus complex unbalance angle with 1% voltage unbalance

The peak value is at 4.574 A compared to 4.525 A. The behaviour of both stator and rotor currents impact the stator and rotor copper losses, respectively. Indeed, the two types of losses show an amplitude modulated-like behavior. The stator and rotor losses are found to peak at 279.6 W and 45.21 W compared to the balanced values of 279.5 W and 45.2 W, respectively.

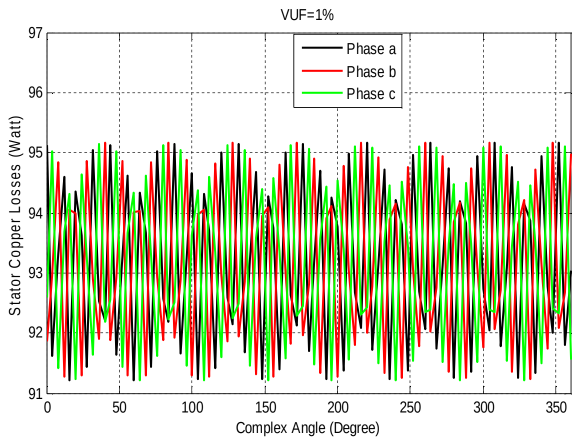


Fig. 5 Stator Copper Losses Versus Complex Unbalance Angle with 1% Voltage Unbalance

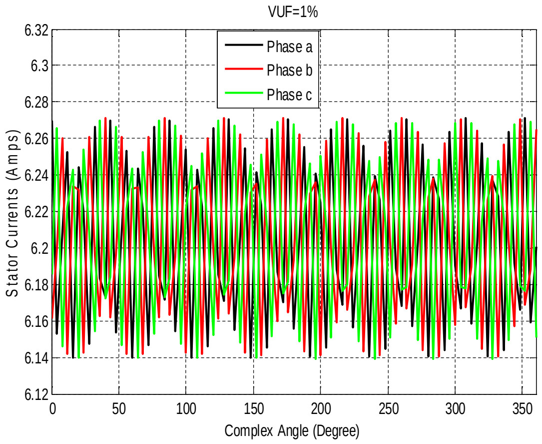


Fig. 6 Rotor Copper Losses Versus Complex Unbalance Angle with 1% Voltage Unbalance

Case of 3% Voltage Unbalance

The variations of the stator and rotor currents along with stator and rotor copper losses for each phase versus the complex angle are shown in fig. 7 through 10. It is noticed that all performance measures exhibit once more a behavior that resembles amplitude modulated sinusoidal waveform. For the stator currents, they peak at some angles that are evenly spaced by the same angle spacing 44° and they occur at different angles. The peak values are found to be 6.399 A compared to 6.205 A in the balanced case. In a similar way, the rotor currents peak at angles spaced also by 44° and at different angles. The peak values is at 4.672 A compared to 4.525 A. the behaviour of both stator and rotor currents revealed by the stator and rotor copper losses, respectively. Indeed, the two types of losses exhibit amplitude modulated-like behavior on their variations versus the complex angle. The stator and rotor losses are found to peak at 279.8 W and 45.25 W compared to the balanced values of 279.5 W and 45.2 W, respectively.

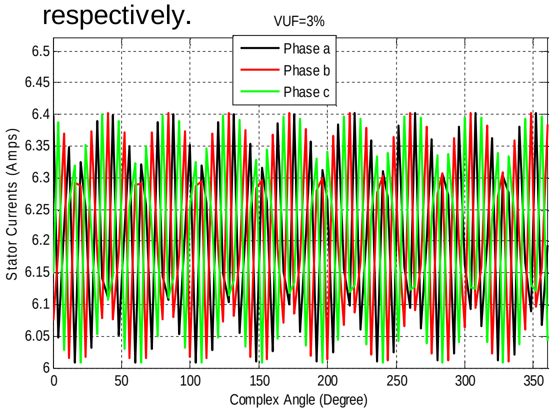


Fig. 7 Stator Currents versus complex unbalance angle with 3% voltage unbalance

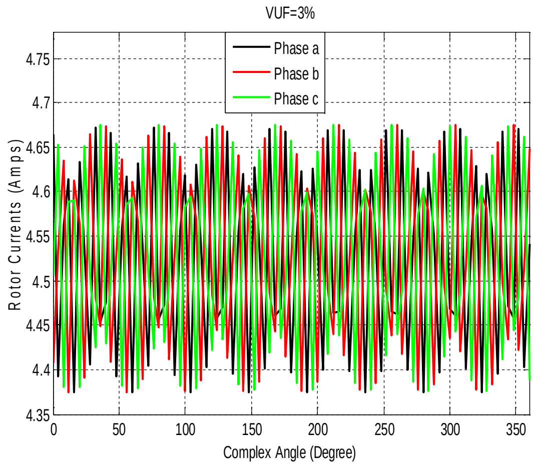


Fig. 8 Rotor Currents versus complex unbalance angle with 3% voltage unbalance

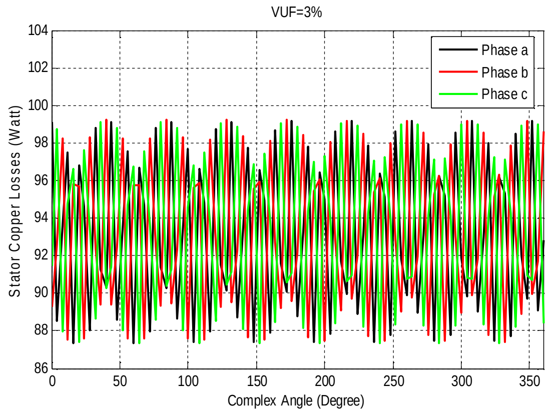


Fig. 9 Stator Copper Losses versus Complex Unbalance Angle with 3% Voltage Unbalance

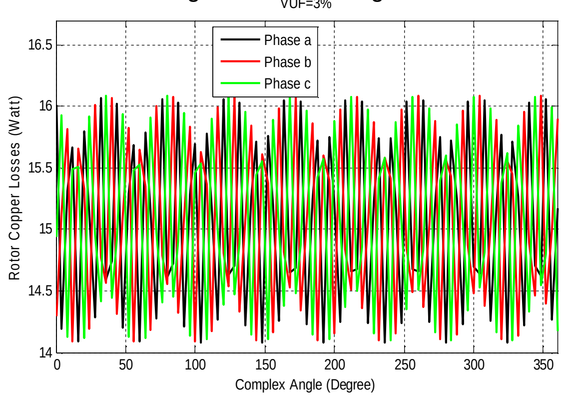


Fig. 10 Rotor Copper Losses versus Complex Unbalance Angle with 3% Voltage Unbalance

Case of 5% Voltage Unbalance

For this extreme case, the variations of the stator and rotor currents along with stator and rotor copper losses for each phase versus the complex angle are shown in fig. 11 through 14. It is noticed that all performance measures exhibit once more a behavior that is similar to an amplitude modulated sinusoidal waveform. For the stator currents, they peak once more at some angles that are evenly spaced by the same angle spacing 44° and they occur at different angles. The peak values are found to be 6.529 A compared to 6.205 A in the balanced case. In a similar manner, the rotor currents peak at angles spaced again by 44° and at different angles. The peak values is at 4.771 A compared to 4.525 A. the behaviour of both stator and rotor currents revealed by the stator and rotor copper losses, respectively. Indeed, the two types of losses exhibit amplitude modulated like behavior on their variations versus the complex angle. The stator and rotor losses are found to peak at 280.3 W and 45.34 W compared to the balanced values of 279.5 W and 45.2 W, respectively.

The previously presented results are all summarized in table 1. In the same table, the percent increase of the rotor and stator power losses versus the increase in voltage unbalance is also presented. It is noticed that losses do not have a clear relationship to the voltage unbalance level. In fact, the increase in percent voltage unbalance affects the power losses but no clear systematic behaviour of this increase is observed. The complex angle, on the other hand, is found to have no effect on the total stator and rotor copper losses for a given voltage unbalance level.

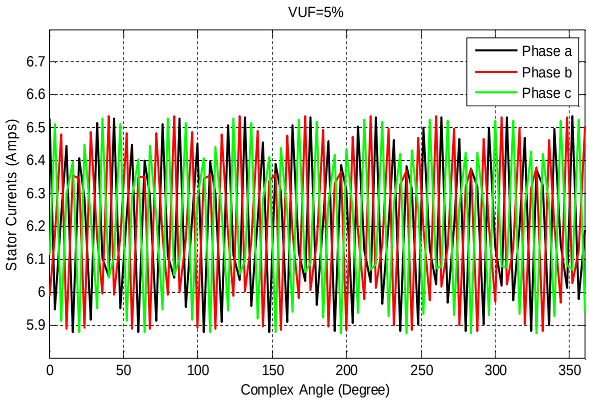


Fig. 11 Stator Currents versus Complex Unbalance Angle with 5% Voltage Unbalance

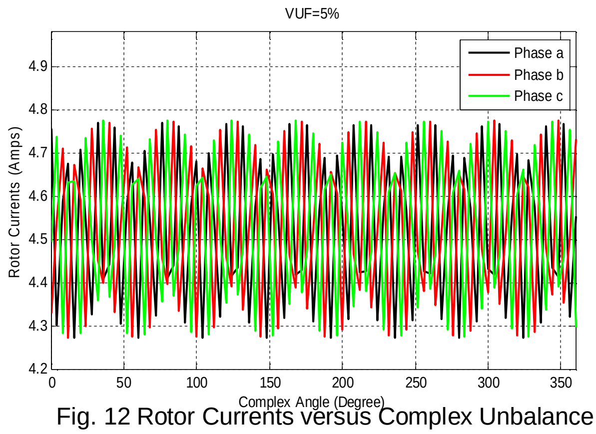


Fig. 12 Rotor Currents versus Complex Unbalance Angle with 5% Voltage Unbalance

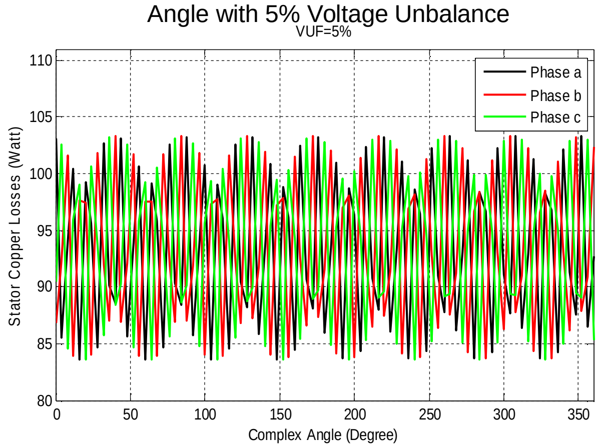


Fig. 13 Stator Copper Losses versus Complex Unbalance Angle with 5% Voltage Unbalance

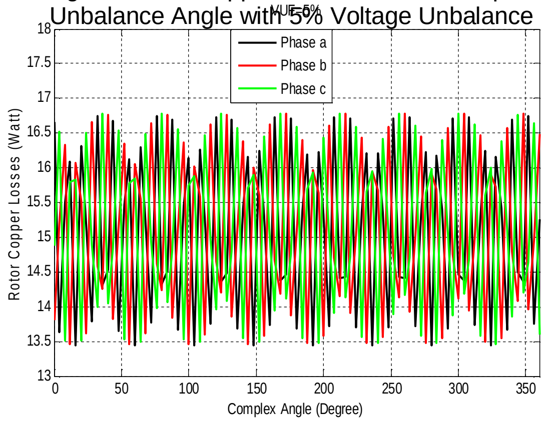


Fig. 14 Rotor Copper Losses versus Complex Unbalance Angle with 5% Voltage Unbalance

Table 1 Summary of the motor performance under different voltage unbalance levels along with the balanced case

	Stator Currents Max (Amps)			**Rotor Currents Max (Amps)**			**Stator Copper Losses Max (Watt)**			**Rotor Copper Losses Max (Watt)**			**Total Copper losses**	**increase %**
	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c		
VUF=0%	6.205	6.205	6.205	4.525	4.525	4.525	279.5	279.5	279.5	45.2	45.2	45.2	324.7	/
VUF=1%	6.27	6.271	6.27	4.574	4.574	4.575	95.13	95.17	95.13	15.4	15.4	15.4	324.8	0.031
VUF=3%	6.399	6.403	6.4	4.672	4.673	4.675	99.1	99.21	99.11	16.04	16.07	16.09	325.1	0.124
VUF=5%	6.529	6.535	6.53	4.771	4.772	4.775	103.2	103.3	103.2	16.75	16.76	16.78	325.7	0.31

5. EXPERIMENTAL RESULTS AND DISCUSSIONS

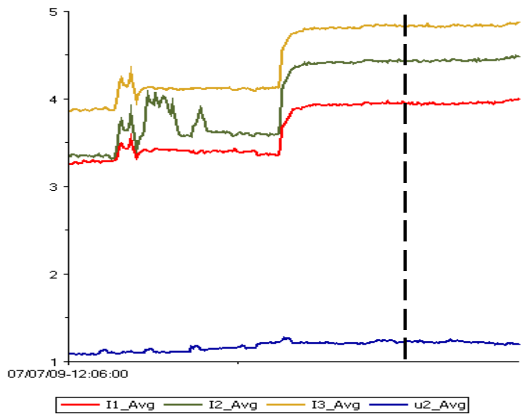
The experimental setup for conducting the measurements under voltage unbalance case is shown in fig. 15. The apparatus consists of 3 kW squirrel cage induction motor equipped with a braking system. The motor is fed by a three phase voltage supply. The measurement is done using the Power quality analyzer PQA824 of the HT ITALIA which is connected to the input three phase supply to give the input power, input voltage and input currents. The measuring apparatus consists also of a module to give the output power and the developed torque. The PQA824 meter permits a completely new approach to the world of electrical measures on network quality. In fact, this computer assisted instruments permit an easy and fast analysis of a huge quantity of data, which would be impossible with any other system. To have a better assessment of the results, a figure of merit that takes into account the differences between the measured and calculated currents is considered to be merely the mean square error (MSE) between the two set of data as:

$$\%\text{error} = \sum_{i=1}^{3} \frac{(I_{i\text{measured}} - I_{i\text{calculated}})^2}{I_{i\text{measured}}^2} \qquad (8)$$

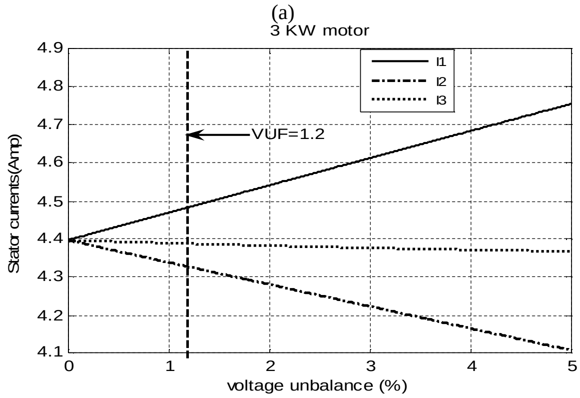
The experimental setup described earlier has been used to measure the line currents through varying the line voltages so as to give a certain voltage unbalance factor. The collection of data has been conducted for a given period of time not exceeding 4 minutes. It has been noticed that the average line currents increase proportionally with the voltage unbalance. As a further step and for a given voltage unbalance factor, the load has been increased from no load using the braking system. This increase in load causes a further increase in voltage unbalance as well as the line currents. However, the output power decreased with the load increase due to power losses. The different voltage unbalance factor values have been chosen arbitrarily to be within the NEMA interval limits (**<5%**).

In the first case, the line voltages have been varied to give a value of voltage unbalance of 1.2%. The line currents as measured by the PQA824 instrument as well as the unbalance factor are shown in fig. 16.a. the dashed line indicates the time where the samples of current values are considered for comparison. Fig. 16.b shows the theoretical variations of the line currents versus voltage unbalance obtained from a theoretical analysis using symmetrical components for the load corresponding to this voltage unbalance value. A simple projection for the corresponding voltage unbalance value leads to the theoretical line currents

Fig. 15 The experimental setup used in the measurements



(a)



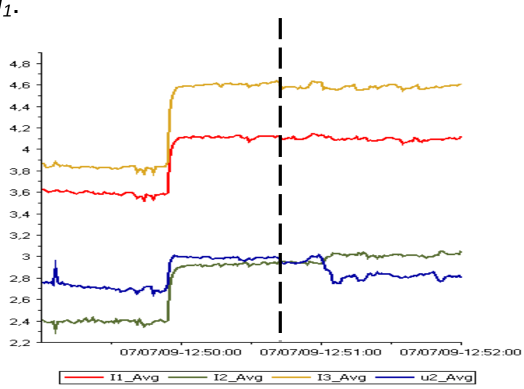
(b)

Fig. 16 The measured and theoretical data (VUF=1.2%)
(a) Measured data; (b) calculated data

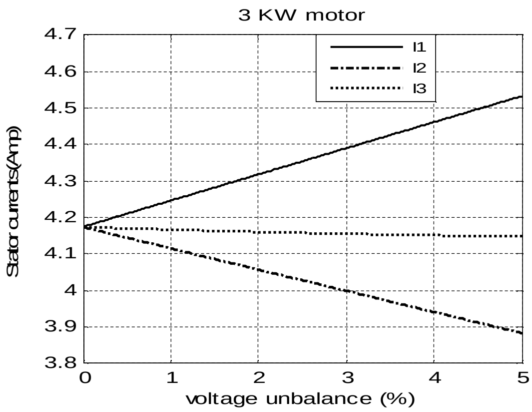
The results reveal differences in the experimental and theoretical line currents which are due to the simplistic use of the voltage unbalance definition that does not take into account the complex nature of this factor. However, the measured values fall within tolerable differences compared with the calculated ones as shown in the first column of table 2. The MSE for this case is found to be 0.0258 which is a very good value despite the differences in current values.

As a second case, a voltage unbalance factor of 2.8% has been set out. Fig. 17.a and Fig. 17.b show the PQA824 collected data and the theoretical values, respectively. Again, the values considered for comparison correspond to the instant shown by the dashed line in fig. 17.a.

The measured and calculated currents are shown in the second column of table 2. Again, differences between the two exist. These differences are again due to the non-use of the complex definition of the voltage unbalance factor. Furthermore, this case shows closer values especially for the current I_1.



(a)



(b)

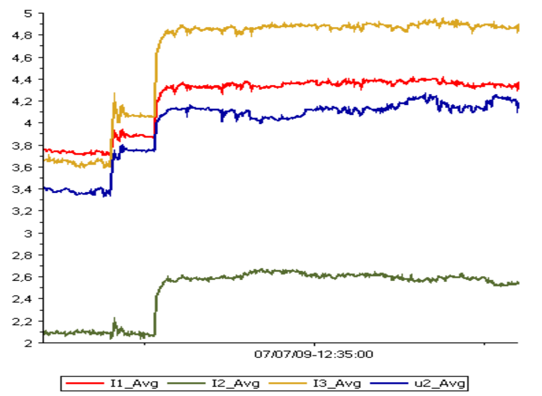
Fig. 17 The measured and theoretical data (VUF=2.8%)
(a) Measured data; (b) calculated data

However, for current I_2, the difference is almost 1A which in turn influences the MSE value for this case that is found to be 0.1229. As an even worst case, a value of voltage unbalance has been set up to be 4%. Both measured and computed theoretical values are shown in fig. 18.a and fig. 18.b, respectively. As a general remark, the situation is worse than the two other cases as the differences in currents get larger.

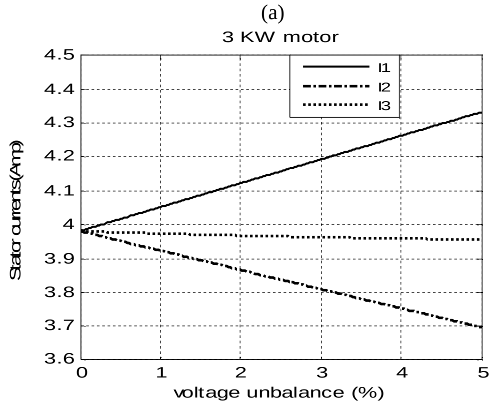
The results are summarized in the third column of table 2. Indeed, only the current I_1 fell within a tolerable difference that is an almost a perfect match. However, for the other currents, the difference is in the order of 1 A which is not acceptable. Indeed, the MSE for this case is found to be 0.1891.

Table 2 Summary of the measured and calculated currents

Voltage unbalance (%)	1.2	2.8	4
Measured currents	4.0	4.1	4.3
	4.5	3.0	2.7
	4.8	4.6	4.9
Calculated currents	4.595	4.306	4.263
	4.4533	3.992	3.753
	4.508	4.117	3.959
MSE	0.0258	0.1229	0.1891



(a)



(b)

Fig. 18 The measured and theoretical data (VUF=4%)
(a) Measured data; (b) calculated data

6. CONCLUSIONS

In this work, the effect of voltage unbalance on the performance of induction motors has been addressed using both theoretical and experimental approaches. The study has been carried out using the complex voltage unbalance that models both the magnitude and phase of the unbalance factor. The focus has been on the effect of the complex angle on the currents and copper losses. It has been found that for a given percent voltage unbalance, the phase stator and rotor currents and copper losses show behaviour that look like an amplitude modulated waveform with some peaks and troughs noticed along the angular spectrum. The total cooper losses turn out, however, to be not affected by the complex angle. On the other hand, the percent voltage unbalance has a direct effect on the total copper losses as the losses increase with the increase in voltage unbalance. An experimental investigation has also been carried out. The purpose has been to model as accurately as possible these effects so that predictions and further analyses can follow. The investigation recommends and favors the use of the complex definition of the voltage unbalance factor over the simplistic non-complex one. Only the effect of the voltage unbalance on the line currents has been considered due to the large collection of data that has been gathered. As a more thorough analysis, other influenced performance parameters should be considered including namely power losses and the developed torque all with the complex nature of the unbalance factor taken into account

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