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Effects of sequence voltage components on torque and efficiency of a three-phase induction motor

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ABSTRACT

For quantifying voltage unbalance, some standards adopt the index provided by the ratio between the negative and positive sequence component magnitudes. In these documents, the use of an indicator that includes the zero sequence component is not obligatory. This article presents the results from evaluations of the effects of the zero, negative and positive sequence voltage components on the torque and efficiency of a three-phase induction motor. These evaluations are performed through laboratory experiments and the application of incremental sensitivity analysis. The results of this investigation allow for, among other things, identifying the consequences of the absence of the zero sequence component in unbalance quantification.

1. Introduction

Voltage unbalance is a phenomenon in power quality that occurs in electric systems when there is no equality among the magnitudes of the three-phase voltage and/or phase shifts different from 120°. Depending on their intensities, the negative and zero sequence components resulting from the existence of voltage unbalance can cause noxious effects on the performance of electrical equipment, such as the Three-Phase Induction Motor (TIM) [1].

Some standards and recommendations like the IEEE 1159-1995 [2], IEC 61000-4-30 [3], NRS 048-2 [4] and PRODIST [5] adopt the index which is a result of the ratio between the negative and positive sequence components in module (VUF_2) for quantifying voltage unbalance. However, there are many studies in scientific literature that contest its use, affirming that this ratio is not sufficiently reliable to evaluate winding losses, input power, temperatures, power factor, derating factor, currents in the stator windings or torque of the TIM. This happens mainly because different unbalanced voltage combinations culminate in the same value of this indicator.

Indeed, in Ref. [6], the authors applied eight types of unbalance conditions on a TIM, in order to show the difference between the effects observed in a motor subjected to some voltage phasors which lead to the same amount of VUF_2. The use of the positive sequence component module together with the VUF_2 value was suggested to mitigate the quantification unbalance problem. In Ref. [7], the effect of unbalanced voltage on the losses and efficiency of a three-phase squirrel cage induction motor have been investigated. It was concluded that for the same voltage unbalance condition, a derated motor may have a higher efficiency than a non-derated motor. Employing the electric model of the TIM, the authors from Ref. [8] investigated the variations caused by unbalances in current, efficiency and in the input power of a motor coupled to a centrifugal pump. According to them, it is important to know the exact nature and extent of voltage unbalance for a better understanding of efficiency. In Ref. [9], the operating performance of a three-phase induction motor-pump system subjected to voltage and load variations (obtained by means of experimental tests) was presented. In accordance with the authors, it is very necessary to study the operational performance under variable conditions. In Ref. [10], the influence of the unbalance factors on the total copper losses, efficiency, power factor, input power, output torque, peak currents, and derating factor of the operating motor was evaluated. Based on their investigations, it was concluded that only the VUF_2 is sufficient

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to determine (i) the total losses in the motor windings, (ii) the input power, (iii) the power factor, and (iv) the output torque. However, the phase angle of the unbalance factor must be included for accurate prediction of peak current and peak copper losses of the phase windings and derating factor of the motor. In Ref. [11], the use of the voltage magnitudes arithmetic mean as an indicator for evaluating the performance of a motor subjected to unbalanced voltages was proposed. In this study, it was shown that for the same VUF_2, there is a variety of V_1 that culminates in a wide range of torques, so the usage of VUF_2 with V_1 reduces these variations considerably. The effects of coupled machines operating under voltage unbalance on the electromagnetic torque have been investigated in Ref. [12]. Exhibited among other results was that, small size coupled machines presents a superior performance when compared with a big size induction motor. Shown in Ref. [13] is a study of the effects of the voltage unbalance on the torque, efficiency and on the input and output power of a TIM. The authors concluded that the torque increases with the elevation in the positive sequence voltage, and the presence of the negative sequence component increases the variation range of torque, efficiency, input and output power to a given value of V_1. The results showed that VUF_2 is not a good index to relate the unbalance to the effects on torque and efficiency. The electrical model of the TIM was used in Ref. [14] in order to investigate the effects of unbalanced voltages on the line currents, losses, efficiency and power factor. The authors affirmed that the positive sequence voltage must be considered together with the percentage of the VUF_2.

From the evaluation of these studies, it is observed that numerous articles available in the literature employ computational results of the performance of a TIM for the identification of a possible solution to the fact that different unbalanced voltage combinations culminate in the same value of VUF_2. Therefore, it is possible to conclude that there is a lack of experimental studies dedicated to the evaluation of the behavior of the torque and efficiency in function to the sequence components involving a large amount of unbalanced conditions.

Moreover, another drawback to the referred standards is that they do not adequately deal with the use of an indicator which quantifies the zero sequence voltage unbalance. In fact, studies related to the effects of the zero sequence component on TIMs have not been identified so far in the literature. It is noteworthy that in the case where the motor is not connected in grounded wye (Y), the voltage unbalance coming from the zero sequence component does not provoke effects on the machine.

Considering the aforementioned aspects, came the idea for developing this study which has the objective of evaluating the effects of the positive, negative and zero components on the torque and efficiency of the TIM. In order to put this purpose into practice, a databank with 1444 conditions of voltage unbalance, which are applied on both the experimental tests and the sensitivity analysis, is used. To make a comparative evaluation between the results obtained through sensitivity analysis and laboratorial tests possible, equations that allow the verification of the average variations in efficiency and torque in function to changes in the three symmetrical components values are elaborated.

The results of this investigation allow for, among other things, (i) the evaluation of how the torque and efficiency of a TIM behave in the presence of the zero, negative and positive sequence components, and (ii) the identification of the consequences of the absence of the zero sequence component on unbalance quantification.

Presented initially is a theoretical foundation including some quantification indices for voltage unbalance, equations of the torque and efficiency of the TIM based on the equivalent circuits and the sensitivity analysis theory. Then, in the section that follows, an experimental evaluation of the TIM and the results obtained

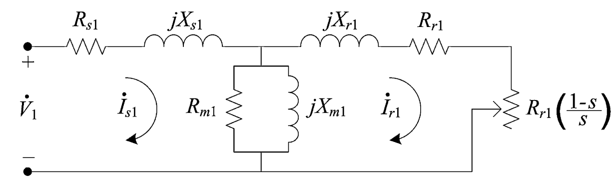

Fig. 1. Single-phase equivalent for the positive sequence.

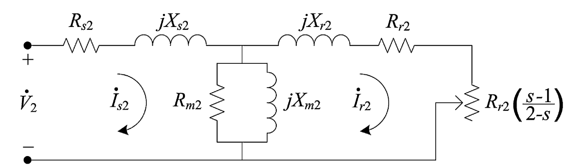

Fig. 2. Single-phase equivalent for the negative sequence.

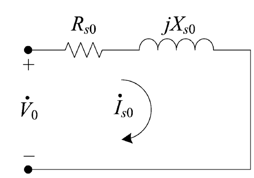

Fig. 3. Single-phase equivalent for the zero sequence.

from the sensitivity analysis are exhibited. Finally, the conclusions reached in this study are addressed.

2. Theoretical foundation

The three methods commonly used for quantifying voltage unbalance are: symmetrical components, the ANSI and NEMA, and CIGRÉ [2]. This study is founded entirely on symmetrical components. Mathematically, this last method is the same as the first. In this study, the definitions of indicators shown in (1), (2), (3) and (4) are used to analyze the effect of sequence components on a TIM.

$$VUF_2 = |\dot{V}_2/\dot{V}_1| = V_2/V_1 \quad (1)$$

$$VUF_0 = |\dot{V}_0/\dot{V}_1| = V_0/V_1 \quad (2)$$

$$CVUF_2 = \dot{V}_2/\dot{V}_1 = (V_2/V_1)\angle\theta_2 \quad (3)$$

$$CVUF_0 = \dot{V}_0/\dot{V}_1 = (V_0/V_1)\angle\theta_0 \quad (4)$$

In Eq. (1)–(4), the phasors of the zero, positive and negative sequence components are respectively given by $\dot{V}_0$, $\dot{V}_1$ and $\dot{V}_2$. The magnitude of the zero, positive and negative sequence components are given by V_0, V_1 and V_2. VUF_2 and VUF_0 are respectively the negative and zero sequence voltage unbalance factors. Finally, $CVUF_2$ and $CVUF_0$ represent the negative and zero complex voltage unbalance factors.

2.1. Tim equivalent circuit

The three-phase induction motor using a wye connection with a path to neutral can be modeled by a set of three single-phase equivalent circuits: positive, negative, and zero sequences. These circuits are presented in Figs. 1–3.

In the electrical model of the TIM, R_S and X_S are the stator resistance and the leakage reactance of the stator. X_r and R_r are the rotor resistance and the leakage reactance of the rotor. R_m is the core loss resistance. X_m is the magnetizing reactance. $\dot{I}_s$ and $\dot{I}_r$ are the currents in the stator and rotor, respectively, and s is the slip. $R_r(1-s)/s$ is the resistance which represents the load. Indices 0, 1,