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Precise derating of three phase induction motors with unbalanced voltages

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Abstract

Performance analysis of three phase induction motors under supply voltage unbalance conditions is normally conducted using the well-known symmetrical components analysis. In this analysis, the voltage unbalance level at the terminals of the machine is assessed by means of the NEMA or IEC definitions. Both definitions lead to a relatively large error in predicting the performance of a machine. A method has recently been proposed in which, in addition to the voltage unbalance factor (VUF), the phase angle has been taken into account in the analysis. This means that the voltage unbalance factor is regarded as a complex value.

This paper shows that although the use of the complex VUF reduces the computational error considerably, it is still high. This is proven by evaluating the derating factor of a three phase induction motor. A method is introduced to determine the derating factor precisely using the complex unbalance factor for an induction motor operating under any unbalanced supply condition. A practical case for derating of a typical three phase squirrel cage induction motor supplied by an unbalanced voltage is studied in the paper.

Keywords: Unbalanced voltage; Induction motor; Unbalance factor; Derating factor; NEMA; IEC

1. Introduction

Voltage unbalance exists in almost all three phase power system networks. The level of unbalance is considerably large in weak power systems and also those supplying large single phase loads. Based on the ANSI report [1], the voltage unbalance of 66% of the electrical distribution systems in the USA is less than 1% and that of 98% of the distribution systems is less than 3%, while in the remaining 2%, it is larger than 3%. The negative effects of voltage unbalance on the performance of three phase induction motors include: higher losses, higher temperature rise of the machine, reduction in efficiency and a reduction in developed torque [2]. Reduction of the rated power of the machine under unbalanced voltage is an important effect that was introduced in 1963 [3].

The efficacy of normal operation of a motor from an unbalanced supply depends directly on the degree of unbalance at the terminals of the machine. It is, therefore, essential that a suitable standard be used to quantify the degree of voltage unbalance. The NEMA and IEC standards introduce independent definitions for voltage unbalance, and one of these is normally used for the analysis of electrical machines.

2. Voltage unbalance definitions

2.1. NEMA definition

The voltage unbalance factor (VUF) at the terminals of a machine, based on the NEMA definition, can be expressed as [4]

$$\text{Unbalance } (\%) = \frac{\text{max. deviation from avg. voltage}}{\text{avg. voltage}} \times 100 \tag{1}$$

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where only the value of the line voltages have been considered in Eq. (1).

2.2. IEC or symmetrical components definition

The voltage unbalance factor at the terminals of a machine, based on the IEC definition, is as follows [5]:

$$\mathrm{VUF} = K_v\% = \frac{V_2}{V_1} \times 100\% \tag{2}$$

where V_1 and V_2 are the magnitudes of the positive and negative sequence components of the unbalanced voltages, respectively. Since the value of V_2 is also specified in this definition, the unbalanced condition is quantified more precisely. This definition is called "true" when compared to the NEMA definition [6].

It is clear that it does not suffice to use only the value of voltage unbalance (in both definitions) for the performance analysis of a motor under unbalanced supply conditions. This is due to the large number of permutations of the terminal voltages that could be assumed for the same degree of unbalance. For example, if the voltage unbalance is assumed to be 6%, this condition can result in an infinite number of cases for the terminal voltages of the machine, where each has a unique result [7].

Fig. 1 shows the terminal voltage variations for a 220 V three phase induction motor with 6% voltage unbalance at its terminals. As shown, the locus of the line voltages for the specified unbalance is the outer surface of a cylinder in a three-dimensional space. In other words, all points on this surface give a 6% voltage unbalance using the IEC definition. This indicates that in order to analyze the performance of a machine, all possible permutations of the line voltages must be taken in account, instead of just one. In Fig. 1, it appears that the axis of the cylinder is parallel with the axis of V_{bc}, but this is a visual error. In fact, this cylinder is located in three dimensions which are not along these three axes.

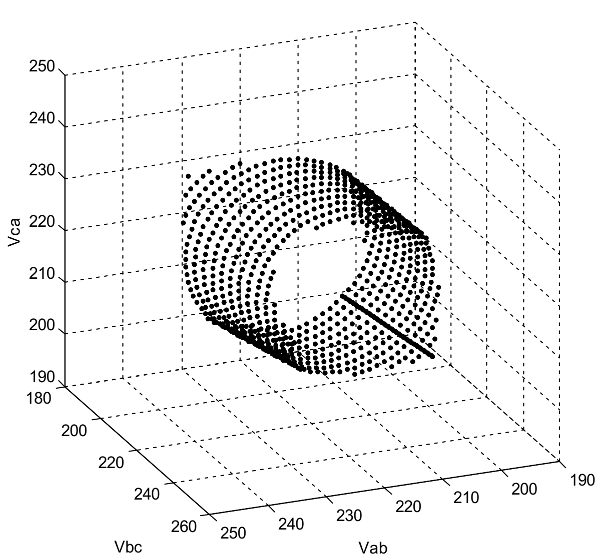

Fig. 1. Terminal voltages of three phase 220 V induction motor with 6% voltage unbalance.

Introduction of the complex voltage unbalance factor [8] reduces the range of variation of the terminal voltages for a given value of the VUF. This is due to the phase angle θ of the unbalance being taken into account in this definition in addition to the unbalance value. According to this third definition, the complex voltage unbalance factor (CVUF) can be expressed as follows:

$$\mathrm{CVUF} = \mathrm{VUF} < \theta = \left(\frac{V_2}{V_1}\right) < \theta \tag{3}$$

As an example, the variations of the terminal voltages of the aforementioned motor under a 6% voltage unbalance with phase angle $\theta = 120°$ has been shown in Fig. 1 by a straight line on the outer surface of the cylinder. This figure indicates that the range of terminal voltage variation of the motor is reduced from the points on the surface of the 3D cylinder into the points on a straight line.

This paper uses the IEC definition of symmetrical components for analysis of the motor performance.

3. Analysis of machine under unbalance conditions

In this paper, the performance of a three phase induction motor under unbalanced voltage imposed by the power system grid is studied. The phase currents, the deliverable power to the motor and the efficiency of the motor are proposed to analyze the influence of the power system and its unbalance. In order to analyze the performance of a three phase induction motor, symmetrical components analysis is normally used. In this method, positive and negative sequence equivalent circuits, as shown in Fig. 2, are utilized to calculate the different parameters of the machine under unbalanced voltage operation. A Y-connected three phase induction motor with the parameters given in Table 1 has been used for performance analysis of a motor under unbalanced voltage operation [8].

In the equivalent circuits of Fig. 2, subscripts s and r denote the stator and rotor, while 1 and 2 refers to the positive and negative sequences. If Z_1 and Z_2 indicate the input impedances of the positive and negative sequence equiva-

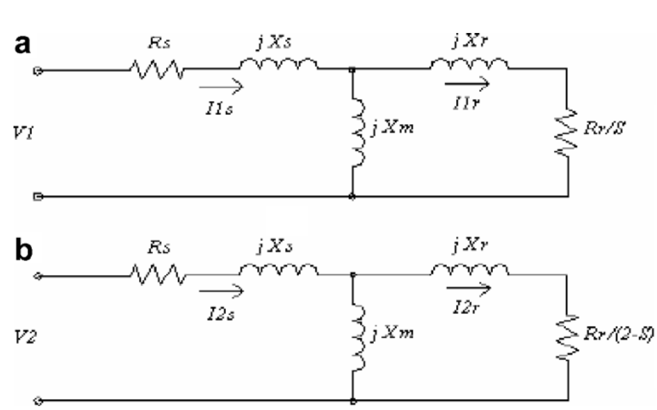

Fig. 2. Equivalent circuits of positive and negative sequences.