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Derating of an induction machine under voltage unbalance combined with over or undervoltages

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ABSTRACT

This work deals with the load carrying capacity of an induction cage machine under voltage unbalance combined with over- or undervoltage. The effect of complex voltage unbalance factor (CVUF) angle on the derating factor is taken into consideration. The derating curves obtained with two different methods are compared. The machine efficiency, stator currents and temperature-rise distribution after applying the required derating factor are discussed. The results of experimental investigations and computer calculations are presented for two low-power induction motors of opposite properties. One of them has a comparatively weakly saturated magnetic circuit and is especially exposed to the risk of overheating for undervoltage. The other investigated machine has a comparatively strongly saturated magnetic circuit and is especially exposed to overheating in the conditions of overvoltage.

1. Introduction

Unbalance and voltage deviations commonly occur in power networks. The main causes of unbalance [1–3] are single phase loads present in power systems, unbalanced impedances of transmission lines and transformers, and non-uniform compensation of three-phases with capacitor banks. Further, voltage deviations result mostly from a voltage drop along a supply line and load power variation in a network. It should be noted that the introduction in the European Union of a unified low voltage level of 400/230 V (in place of the 380/220, 400/230 and 415/240 V ones used in different countries) means in practice permanent over- or undervoltage for some induction machines. Theoretically, this process has taken place in the years 1995–2008, but the newly admitted countries have much less time to adapt.

It is also worth mentioning that the most frequent case of voltage deviation is undervoltage, whereas overvoltage is considered a much rarer phenomenon. However, in some countries overvoltage often appears in off-peak periods [2,3]. Additionally, in some power systems permanent overvoltage has been observed. An example of a long-term overvoltage is presented in [4].

The voltage deviation and unbalance levels that AC motors should tolerate are defined in IEC standard 60034-1 [5]. According to the standard, a machine has to be capable of working continuously with its rated load torque for ±5% voltage deviation or 1% unbalance (VUF [1,6–9] = 1%). A three-phase motor also has to be capable of operating under 1.5% unbalance (VUF = 1.5%) "for a short period not exceeding a few minutes". It should be stressed that regulations concerning power quality in public networks permit a much higher voltage deviation and unbalance levels than those specified in IEC standard 60034-1 [5]. For example, in many European countries, according to the European voltage characteristic standard EN 50160 [10], the permissible long-term voltage deviation is ±10%, and the ratio of the negative-sequence voltage component [1] and the positive-sequence voltage component should not exceed 2%. The standard [10] also says that in some power systems the ratio is "up to about 3%". As a result, induction machines are often exposed to power quality disturbances significantly exceeding the levels defined in [5]. Both voltage deviation and voltage unbalance cause additional power losses in an induction machine, and consequently a reduction in its efficiency. The increase in power losses may be especially significant in the case of voltage deviation, which leads to serious machine overheating [11]. Further, for unbalanced supply the power losses in stator windings are non-uniformly distributed [8,12], which also may lead to local windings overheating [9]. It should be stressed that the thermal effect of voltage unbalance depends not only on the negative-sequence voltage component value but also on the angle between the negative and positive-sequence voltage components (the angle of the complex voltage unbalance factor [6,7,9] – CVUF angle). Depending on the CVUF angle (or the way of unbalancing [12]), the worst and the most favorable case of unbalance [7,9,13] can be distinguished. For machines investigated by the author, the additional windings temperature-rise is for the worst

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case of unbalance about 40–90% higher than for the most favorable case of unbalance [9].

A machine is exposed to serious overheating even if voltage unbalance or voltage deviation appears as a single disturbance. The situation is even worse when both power quality disturbances appear simultaneously. A cumulative effect of voltage unbalance and over- or undervoltage may lead to extremely high windings temperature [11,14]. For example, for the investigated machine Sg 132-S4 type, 3% unbalance (negative voltage sequence equal to 3% of the rated voltage; the worst case of unbalance) combined with 10% undervoltage causes a 37 K increase in windings temperature-rise, and for the machine TSg 100L-4B 3% unbalance (the worst case of unbalance) combined with 10% overvoltage causes a 29 K increase in windings temperature-rise [11]. According to the author's investigations [11], two extreme scenarios can be distinguished – the worst one and the most favorable one. The most favorable scenario takes place when the most favorable case of unbalance appears together with overvoltage for a machine with a weakly saturated magnetic circuit or the most favorable case of unbalance appears with combination of undervoltage for a machine with strongly saturated magnetic circuit. The worst scenario takes place when the worst case of unbalance appears with combination of undervoltage for a machine with a weakly saturated magnetic circuit or the worst case of unbalance appears together with overvoltage for a machine with a strongly saturated magnetic circuit. For the most favorable scenario the windings temperature-rise may be even less than for nominal supply. Further, the worst scenario will lead to failure of the insulation system in a comparatively short period of time (provided that the machine works with a full load). Even application of a higher class of insulation than resulting from the windings temperature-rise in nominal work conditions does not protect a machine against premature destruction [11].

In such undesirable supply conditions an induction machine cannot work with its rated load. In order to avoid overheating, a machine requires derating [6,7,9,12,13,15], i.e. lowering load power below the rating value. In the case of unbalance, the most popular method of derating is to determine the permissible load in such a way that the currents in any phase do not exceed their rated value (for simplicity, in the paper the derating method is called the CC method, i.e. the constant current method). A more precise method of derating is to determine the load in such a way that the windings temperature-rise can keep its value corresponding to the nominal work conditions [9,13,15] (in the paper the method is denoted as the CT method, i.e. the constant temperature method).

2. State of the art

Negative phenomena due to voltage unbalance, such as increase in power losses and windings temperature, reduction in efficiency, operational life, load carrying capacity and reliability, have been discussed in several papers [1–3,6–9,11–28]. It should be stressed that many of them focused on the percentage unbalance, omitting the angle between the positive-sequence and negative-sequence voltage components (or unbalance manner). To make the matter worse, in several works variations of positive-sequence voltage component were not taken into consideration. Consequently, "the results of these analyses on motor performance are not very reliable" Faiz et al. [16].

In the works concerning the derating of an induction machine, voltage unbalance is often considered as a single power quality disturbance – either the positive-sequence voltage component is assumed to be equal to the rated value [9,7] or voltage deviation resulting from the way of unbalancing is neglected [12,13]. For example, Rao and Rao [13] compared different methods of derating for induction machines with double-layer windings and proved that the CC method leads to underestimation of the derating factor. Kersting and Phillips [12] pointed out that unbalancing method has a significant impact on permissible machine load. Wang [7] investigated the effect of the CVUF angle on load carrying capacity, determined with the CC method. Derating curves obtained with the CT method for the most favorable and the worst case of unbalance were presented in the author's work [9].

The derating of an induction machine in the condition of unbalance appearing together with voltage deviation was analyzed by Faiz, Pillay, et al. [6,8,14,15]. In the work of Pillay et al. [15] the derating factor was determined with the CT method, on the basis of computer calculations. The derating curves versus voltage unbalance were presented for 10% overvoltage, 10% undervoltage and for the positive-sequence voltage component equal to its rated value. In [14] the calculated windings temperature-rise and estimated machine operational life for unbalance combined with voltage deviation were compared for the full load and reduced one. The effect of the CVUF angle or the way of unbalancing on the machine heating and derating factor were not taken into consideration. It is also worth mentioning that the machine efficiency and stator currents, after applying the required derating factor, were not analyzed. Further, in the works of Faiz et al. [6,8] the derating factor was determined with the CC method. The power losses and machine efficiency at full load and after applying the required derating factor were discussed. It is also worth mentioning that in the works of Faiz, Pillay, et al. [6,8,14,15] machines of different properties were not compared. Also, derating curves obtained with the CC and CT methods were not compared for a particular motor.

This work deals with the load carrying capacity of an induction machine under voltage unbalance combined with over- or undervoltage. The effect of the CVUF angle on the derating factor is taken into consideration. The derating curves obtained with the CT and CC methods are compared. The influence of the CC method on windings temperature-rise is discussed. The machine efficiency and stator currents after applying the required derating factor (determined with the CT method) are analyzed. The results of experimental investigations and computer calculations are compared for two low-power induction motors of opposite properties. One of them (Sg 132-S4 machine type) has a comparatively weakly saturated magnetic circuit and is especially exposed to the risk of overheating for undervoltage. The other investigated machine (TSg 100L-4B machine type) has a comparatively strongly saturated magnetic circuit and is especially exposed to overheating in the conditions of overvoltage.

3. The CT method of derating

The most precise method of derating is to determine the allowable load in such a way that the windings temperature-rise can keep its value corresponding to the nominal work conditions (the CT method of derating).

Below are the results of experimental investigations and computer calculations for two totally enclosed fan-cooled induction machines of rated power 3 kW (TSg 100L-4B machine type) and 5.5 kW (Sg 132-S4 machine type). Detailed information about the motors is provided in the author's work [11] and also in [29]. The laboratory stand is described in [9,11,27–29]. The computer calculations presented below were carried out with single phase equivalent circuits for the positive and negative-sequence [9,11] and the thermal model shown in Fig. 1. The model was described and experimentally verified in the author's works [9,11].