Available online at www.sciencedirect.com
ScienceDirect
Energy Conversion and Management 49 (2008) 761–770
ENERGY CONVERSION & MANAGEMENT
www.elsevier.com/locate/enconman

Effect of unbalanced voltage on windings temperature, operational life and load carrying capacity of induction machine

P. Gnacinski *

Gdynia Maritime University, Department of Ship Electrical Power Engineering, Morska Street 83, 81–225 Gdynia, Poland

Received 4 December 2006; accepted 16 July 2007
Available online 4 September 2007

Abstract

This paper investigates the influence of the CVUF angle on the windings temperature rise and the derating factor of an induction machine supplied with unbalanced voltage. The effect of simultaneous voltage unbalance and harmonics on its operational life is analyzed as well. The results of calculations and experimental investigations are presented for two induction cage machines of rated power 3 and 5.5 kW.

Keywords: Induction motor; Temperature; Complex voltage unbalance factor; Voltage unbalance

1. Introduction

One of the most common energy receivers is an induction cage machine. Its feature is high reliability and durability. However, the proper condition of work of an induction cage machine is an appropriate voltage quality – it should be supplied with balanced, sinusoidal voltage of the appropriate frequency and rms value. Any disturbances in the supply network – frequency or rms voltage value deviations, unbalance and voltage waveform distortions lead to an increase in windings temperature [1,2] and, consequently, faster aging of the insulation system and shortening the operational life. One of the disturbances resulting in a significant increase in windings temperature is voltage unbalance.

The influence of voltage unbalance on three phase induction machines can be analyzed with symmetrical components [3,4] – negative sequence and positive sequence components. Their ratio, known as the voltage unbalance factor – VUF, describes the voltage unbalance percentage (although other definitions of voltage unbalance percentage [4–7] are commonly used):

$$\mathrm{VUF} = \left|\frac{U_-}{U_+}\right| 100\% \tag{1}$$

where U_- is a negative sequence voltage component and U_+ is a positive sequence voltage component.

A more precise parameter describing unbalance is the complex voltage unbalance factor [3] – CVUF:

$$\mathrm{CVUF} = \frac{U_{\mathrm{L}-}}{U_{\mathrm{L}+}} = k_u, \quad \angle\theta_u \tag{2}$$

or

$$\mathrm{CVUF} = \frac{V_-}{V_+} = k_V, \quad \angle\theta_v \tag{3}$$

where $U_{\mathrm{L}-}$ is a negative sequence of a line voltage component, $U_{\mathrm{L}+}$ is a positive sequence of a line voltage component, V_- is a negative sequence of a line to neutral voltage component and V_+ is a positive sequence of a line to neutral voltage component. The k_u and k_v parameters describe the magnitude and θ_u and θ_v the angle of the CVUF. Between the angles, the following dependence exists [3]:

* Tel.: +48 58 6901382; fax: +48 58 6901261.
E-mail address: piotrg@am.gdynia.pl

0196-8904/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2007.07.033

$$\theta_u = \theta_v - 60^o \quad (4)$$

The angle θ_u is an angle between the negative and positive sequence components of the line voltage. It also describes the voltage unbalance manner.

2. State of the art

Numerous works concerning unbalance focus on the effect of voltage unbalance percentage on an induction machine while neglecting the angle between the positive sequence and negative sequence components and the possible variation of the positive voltage component. This approach has been criticized recently.

In Ref. [8], the study performed for two different methods of voltage unbalancing showed that not only the voltage unbalance percentage but also the manner in which voltage was unbalanced has an effect on the power losses distribution and the derating factor (determined so that the stator currents hold the rated value in the worst affected phase).

In Ref. [4], the approach based on emphasizing only the voltage unbalance percentage was strongly criticized. In Ref. [9], the effect of unbalanced voltage on the currents, machine efficiency, losses and their economic aspect was presented. The influence of the CVUF angle on the effect of the unbalanced supply was analyzed in Ref. [3]. The work was concerned with currents, allowable slip and derating factors of an induction machine fed with unbalanced voltage. It should be noted that the deratings curves were presented for two cases – the most favorable one and the worst one. The curves were determined so that the currents could keep their rated values in the worst affected phase. It is also worth mentioning that this study is considered "one of the most complete investigations in the derating of the motor" [9].

The effect of voltage unbalance on windings temperature and/or induction machine durability was published in Refs. [1,5–7,10–13]. In none of them was the influence of the CVUF angle on the thermal effect of the unbalanced supply analyzed. The measured temperature rise distribution in an induction machine supplied with unbalanced voltage were shown in Ref. [1]. In the work of Refs. [5,6], the measured efficiency, power factor and windings temperature rise for various cases of voltage unbalance of the same percentage and economic analysis of the extra costs due to voltage unbalance were presented. The windings temperature rise was measured in an indirect way – with the measurement of windings resistance.

In Ref. [7], the derating curves were presented for an induction machine supplied with unbalanced voltage with the combination of over and under voltages. In Ref. [10], the thermal loss of life was discussed for voltage unbalance appearing simultaneously with voltage rms value deviation. It should be noted that for the purpose of identification of the applied thermal model, the investigated machine was driven with a DC motor and one of the phase windings was supplied with DC current. During the calculation of thermal resistances, the power losses in the rotor windings are not taken into consideration (during the test the working conditions of the rotor windings were similar to those in a short circuited synchronous generator. It is also worth mentioning that supplying the stator windings with DC current can be used for braking induction machines).

In Ref. [11], the influence of simultaneous voltage unbalance and harmonics on the operational life of an induction machine was analyzed on the basis of the results of calculations. In the applied thermal model, the end windings, similarly as the slot windings, were considered as a whole – they were not divided into three phase windings. In the stator windings, only two heat sources were taken into consideration – one in the end windings and one in the slot windings. The losses in the end windings due to unbalance were added to the source, modeling the total losses in the end windings, and the losses in the slot windings due to unbalance were added to the heat source, modeling the total slot windings losses. The model does not take into account the fact that at full load, the power losses in the worst affected phase winding (of an induction machine fed with unbalanced voltage) may be even $2 \div 3$ times higher than the power losses in the least affected phase windings [9]. For loads less than nominal, the difference is still greater. As a result of such power losses distribution, some phase windings may be significantly overheated, whereas others can have a lower temperature rise than in the balanced supply conditions (see results of the research). Consequently, the maximal increase in the end windings temperature rise due to voltage unbalance (in the worst affected phase winding) is significantly higher than the average one for all three phase windings. Additionally, in the applied thermal model, the effect of windings temperature on power losses was omitted. To sum up, the thermal model in Ref. [11] enables calculation of only the average increase in the end windings (or slot windings) temperature rise due to voltage unbalance. The effect of voltage unbalance on the operational life time of an induction machine would have been assessed more accurately if the maximal increase in the end windings temperature rise due to voltage unbalance instead of the average one had been taken into consideration.

The effect of simultaneous voltage unbalance and voltage waveform distortion on operational life and its economic aspects was analyzed in Ref. [12]. In Ref. [13], the influence of simultaneous voltage unbalance and waveform voltage distortions on the reliability of an induction machine was investigated. In both these works, in the applied thermal models, the windings were not divided into three separate phase windings.

Preliminary investigations of the influence of the CVUF angle on the thermal effect of voltage unbalance are included in the author's work [14] with Mindykowski, Tarasiuk and Rupnik: Evaluation of the influence of an electrical power quality deterioration on operation of the selected devices in ship electrical power networks. A final report on