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The use of the current complex factor to determine the precise output energy of the induction motor

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ABSTRACT

The Complex Voltage Unbalance Factor (CVUF) has been commonly used to assess the output torque of the induction motor. However, this approach has been criticized, as CVUF has been found to depend solely on the unbalanced supply voltage, while neglecting the machine parameters, although, as known, the machine parameters affect the performance of the induction motor during the unbalanced operation. This paper investigates a different method of calculating the Complex Current Unbalance Factor (CUF), using both voltage unbalance and machine parameters for a more accurate estimate of the output energy. This paper also analyzes the output torque as a function of CUF, while examining CVUF and the Complex Impedance Unbalance Factor (IUF) to reach to the most accurate unbalance factor. The paper provides a comparative analysis of the performance during the unbalanced operation between a cascaded set of induction motors and single large sized induction motor having the same rating and proves that the operation of a cascaded set of induction motors under balanced and unbalanced supply voltage is more efficient than of a single large sized induction motor.

1. Introduction

It is important to study the operation of the induction motor (IM) under unbalanced supply voltage for several reasons [1,2], including the power quality issue and the stability of the power systems [3–7]. The issue of induction motors operating under unbalanced supply voltage and its effects on efficiency, windings temperature, power loss, power factor, output torque, insulation life, derating factor, etc. have been already discussed in a number of studies [8–14]. Refs. [8,9] suggested that motor's derating factor and temperature rise curves rely upon both voltage unbalance factor and the magnitude of the positive sequence voltage. Refs. [10–12] tackled the issues of winding temperature, thermal loss of induction motor operating with over and under voltages, and differences in definition of voltage unbalance. Ref. [13] has set the derating factor using National Electrical Manufacturers Association (NEMA) definition, while, on the other hand, Ref. [14] determined the derating factor using the complex unbalance factor for an induction motor operating under any unbalanced supply condition. Refs. [15–17] examined the influence of voltage unbalance on the machine performance. In Ref. [15], different conditions of voltage unbalance were considered, IM performance was analyzed using both Voltage Unbalance Factor (VUF) and the magnitude of positive sequence voltage, while in Ref. [16], researchers proposed a power flow model and power circle diagram to be used in assessing the output energy during both balanced and unbalanced conditions. This model did not take into consideration machine parameters.

The Percent Voltage Unbalance Factor (PVUF), as defined by NEMA [13], and VUF, as defined by International Electrotechnical Commission (IEC) [18], take only into consideration the voltage magnitude, upon calculating the degree of unbalance. PVUF is the ratio of the maximum deviation from average voltage to the average of three voltages, while VUF is the ratio between the negative sequence voltage to the positive sequence voltage. PVUF and VUF only use the magnitude of the voltage unbalance, while neglecting the angle of unbalance factor; entailing inaccurate assessment of the output energy [19].

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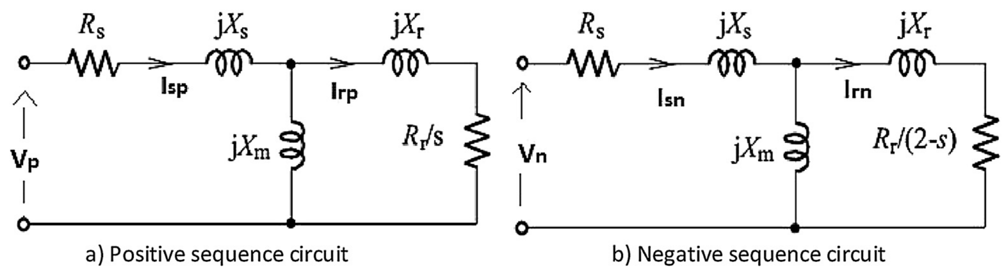

Fig. 1. Single-phase equivalent circuit of the motor.

Numerous prior research studies [4,5,14,17,19,26] used CVUF to evaluate the impact of unbalanced voltage on the steady state performance of IM. They all modified IEC definition of voltage unbalance by including the phase angle to VUF. CVUF count only on the voltage unbalance without taking into consideration the effect of the machine parameters in assessing IM output energy, though essential for the precise assessment of output energy [6,7]. This means that counting on CVUF entails inaccurate estimates of the output energy.

The aforementioned studies [4,5,14,17,19,26] emphasized that both the magnitude and angle of CVUF are sufficient to assess the performance of IM under unbalanced voltage. In other studies using VUF and the magnitude of the positive sequence voltage, IUF is used for assessing the performance of IM [25], relying only on the machine parameters. This paper is dedicated to finding the most accurate unbalance factor to determine the output energy of single large sized IM or cascaded set of induction motors, using both the machine parameters and the unbalanced voltage. The symmetrical component theory approach with MATLAB simulation was used to investigate the operation of induction motor under unbalanced conditions. MATLAB environment used to simulate the results, as this software tool used in a lot of successful research applications.

According to the aforementioned studies, the unbalance factor used to give a complete and precise assessment of IM under unbalanced voltage should measure the degree of unbalance in stator and rotor of IM, based on both unbalanced voltage and machine parameters. CUF meets these criteria, as this factor holds within two aspects: one related to the negative and positive currents passing through the stator windings, (Complex Current Unbalance Factor of the Stator (CUFS) and the second related to the negative and positive currents passing through the rotor windings (Complex Current Unbalance Factor of the Rotor (CUFR). CUF relies on both voltage unbalance and machine parameters, as CVUF and IUF, respectively. Relations between torque and unbalanced factors (CVUF, CUF, and IUF) have been proven and Torque – Speed characteristics of IM for different values of unbalanced factors have been discussed, along with the comparison of three unbalanced factors with speed.

Due to accurate results achieved by CUF, it applies to the cascaded induction motors (a set of small sized induction motors mechanically connected in cascade, which are more efficient than a single large induction motor whose rating equals the sum of the small sized cascaded induction motors [20]). The importance of cascaded induction motors comes from using the same in many industrial applications, such as deep well digging (oil wells).

2. Equivalent circuit of the induction motor supplied from sinusoidal asymmetrical voltages source

Fig. 1(a) and (b) illustrate, respectively, both positive and negative sequence equivalent circuits of the machine. Since IM is either connected in star without neutral or in delta, the zero sequence component is absent. Thus, negative sequence component becomes the primary cause of voltage unbalance [19]. The only difference between both circuits is the equivalent rotor resistance. Since the positive and negative sequence components are both symmetrical, the principle of superposition may apply to determine the overall performance of the machine [21,22].

In Fig. 1, R_s and X_s are the stator resistance and reactance, R_r and X_r are the stator referred rotor resistance and reactance, X_m is the magnetizing reactance, I_{sp} and I_{rp} are the stator and the rotor positive sequence current phasors, I_{sn} and I_{rn} are the stator and the rotor negative sequence current phasors, and S is the slip.

3. Symmetrical component analysis

Eqs. (1) and (2) give, respectively, the positive and negative sequence components of the supply voltage in polar form [20,23].

$$V_p = \frac{V_a + aV_b + a^2V_c}{3} = V_p\angle\beta \tag{1}$$

$$V_n = \frac{V_a + a^2V_b + aV_c}{3} = V_n\angle\beta + \theta_v \tag{2}$$

where ‘a’ equals 1.0 exp. (2π/3), Eqs. (3) and (4) give, respectively, the input impedances of positive and negative sequence circuits in Fig. 1a and b.

$$Z_{sp} = (R_s + jX_s) + \frac{\left(\frac{R_r}{s} + jX_r\right) * jX_m}{\frac{R_r}{s} + j(X_m + X_r)} = Z_{sp}\angle\Phi_p \tag{3}$$

$$Z_{sn} = (R_s + jX_s) + \frac{\left(\frac{R_r}{2-s} + jX_r\right) * jX_m}{\frac{R_r}{2-s} + j(X_m + X_r)} = Z_{sn}\angle\Phi_n \tag{4}$$

where Φ_p and Φ_n are, respectively, the angles of positive and negative sequence input impedances.

3.1. Current asymmetry

When a balanced three-phase voltage applies to asymmetrical three-phase loads, the current will be asymmetrical. Likewise, asymmetrical faults in power systems also lead to current asymmetry. Using Eqs. (1)–(4), the positive and negative sequences of the stator current are obtained from the following Eqs. (5) and (6), respectively.

$$I_{sp} = \frac{V_p}{Z_{sp}} = I_{sp}\angle\beta - \Phi_p \tag{5}$$

$$I_{sn} = \frac{V_n}{Z_{sn}} = I_{sn}\angle\beta + \theta_v - \Phi_n \tag{6}$$

3.2. Definition of the Complex Voltage Unbalance Factor (CVUF)

CVUF is the ratio of V_n to V_p and is calculated in Eq. (7):

$$CVUF = \frac{V_n}{V_p} = K_v\angle\theta_v \tag{7}$$

where K_v and $\theta_v$are the magnitude and angle of CVUF, respectively.