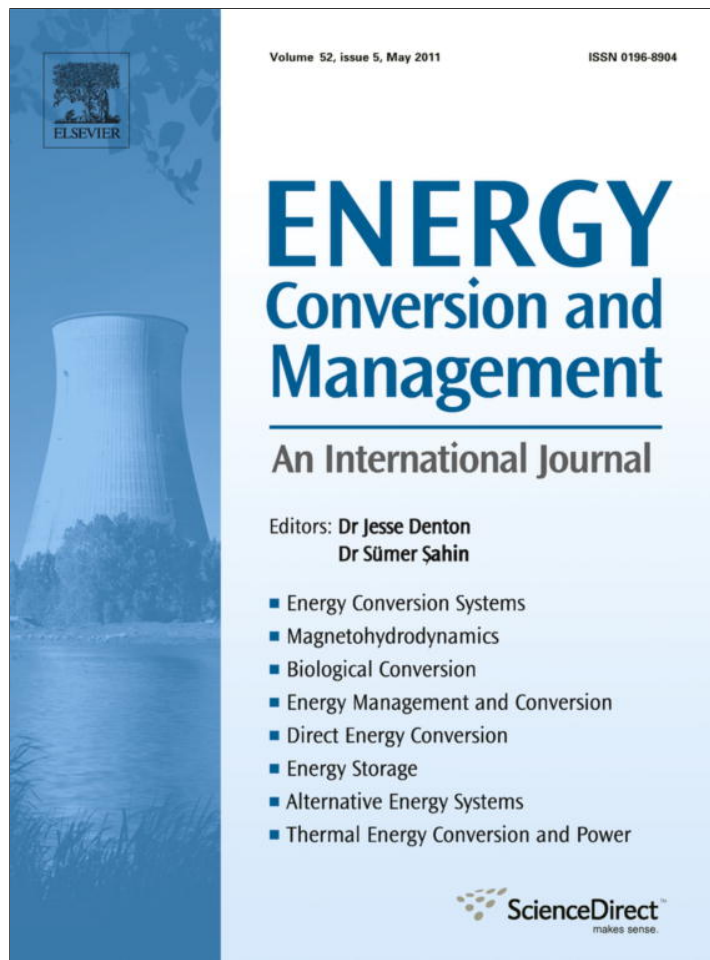


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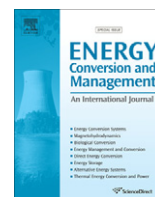
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Analysis of voltage unbalance effects on induction motors with open and closed slots

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ABSTRACT

This paper aims to complement studies concerning the influence of voltage unbalance on the performance of induction motors. We use sequence equivalent circuits to determine the increase of losses in the induction motor. We take into account the dependence of the rotor negative-sequence reactance with the load state and the increase in rotor resistance with the negative-sequence currents. Variations in the negative-sequence impedance are related with the structural characteristics of the rotor. We analyze motors with open and closed rotor slots, because the impedance of rotors with closed slots grows considerably when the load is less than rated, producing lower negative-sequence currents and lower losses. Increased rotor impedance in closed slot motors protects these motors against problems due to unbalanced supply voltage. For both type of rotors, we analyze motor derating factor based on voltage unbalance and increases in total losses and rotor losses.

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1. Introduction

Voltage unbalance affects the performance of induction motors (IM). Negative sequence voltages produce, in the air gap of the IM, a flux that rotates against the rotor's direction of rotation. This negative sequence flux produces torque pulsations, power pulsations, and highly unbalanced currents on the stator windings [1]. Torque and power oscillations result in increased vibrations [2] that may damage the IM [3]. Additionally, vibration due to voltage unbalance may be miss-attributed to bearing failure. Similarly, high negative-sequence currents may be miss-attributed to stator winding failure [4]. In these cases a healthy IM may be taken out service.

High negative-sequence currents cause overheating and hot spots in the stator windings of the IM [2]. To avoid overheating, the National Electrical Manufacturer Association (Standard NEMA MG 1-2003, revision 1-2004, Motors and Generators) and the International Electrotechnical Commission (IEC Standard 60034-1) provide derating factors for the output power that depend on voltage unbalance factors (k_v).

There are many papers discussing the limitations of these standards [1,5–7]. One of the troubles is that the voltage unbalance factors defined by the standards are non-injective. This means that different voltages may result in the same voltage unbalance factor.

Also, the derating factors defined by the standards are unique for all types of IM. This general definition may overprotect some IMs and may not be enough for others. Policarpo et al. [7] show

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that the derating factors of the output power set by the standards are too conservative, when the total losses of the IM are taken into account. On the other hand, Reineri et al. [8], provide an example where the derating factors are not enough to protect an IM with wound rotor.

Bibliography on voltage unbalance proposed different methods to estimate derating factors for IMs. In [9] the derating factors are obtained with the rated stator current of IM as the maximum allowable current. Wang [10] proposes using derating factors obtained in the same way but using complex voltage unbalanced factor. Gnacinski [11] proposed to determinate the maximum load in such a way that the windings temperature is limited to the value corresponding to rated working condition, but this method requires a very detailed model of the IM.

In this paper we propose a method to compute the IM's losses taking into account the effect of unbalanced voltages. To take into account the effect of voltage unbalance, we use a single phase equivalent circuit for the positive and negative sequences of the IM and we consider the skin effect in the sequence resistances of the rotor. The model also takes into account the negative-sequence reactance variations with IM's load.

The relationship between the negative-sequence impedance and the motor load depends on the rotor having open slots (OS) or closed slots (CS) [2,12].

IMs with closed-slot rotors have lower efficiency than IMs with open slot rotors but, they are widely used because they are simple to build.

At low load levels, when the iron on the rotor slots is not saturated, the negative-sequence impedance of closed-slot rotors is significantly larger than at rated load. We consider this effect

because IMs with closed rotor slots are widely used in medium and low voltage systems, in which power quality problems are more common.

2. Effects of unbalanced voltages on the IM

Voltage unbalance leads to large negative-sequence currents in the IM. Negative-sequence currents in IMs produce several adverse effects, such as increased copper losses in the stator and in the rotor, and oscillations in torque, speed and power.

Increased copper losses generate local temperature increases on the IM windings that lead to premature insulation failure. However, higher copper losses in the stator are not necessarily accompanied by a significant increase in stator currents and therefore cannot be detected by some overcurrent protections.

In the rotor, the problems are more severe because the negative-sequence resistance is greater than the positive-sequence resistance. This creates localized warming of the rotor circuits in a short period of time.

The negative-sequence resistance of the rotor is between 3 and 15 times greater than its positive-sequence resistance [13] because, the frequency of operation is almost two times the positive-sequence frequency.

For squirrel cage type rotors, the negative-sequence resistance is typically five times its positive-sequence resistance.

Depending on the structural characteristics of the IM, the negative-sequence reactance of the rotor may change significantly with the load.

In squirrel-cage rotors with open slots (Fig. 1a), the rotor negative-sequence reactance does not vary significantly because the leakage flux has a high reluctance path through the air for any loading condition of the IM.

In IMs with closed-slots squirrel-cage rotor (Fig. 1b) the iron that covers the bars is not saturated for low load levels. Thus for low load, leakage flux encounters a lower reluctance path than for rated load. These reluctance changes result in a larger rotor negative-sequence leakage reactance during low load conditions [2,12].

The different behavior of the rotor negative-sequence reactance with the state of load produces in the rotor with closed-slots smaller negative-sequence currents than in the case of rotor with open-slots. Then, a lower negative-sequence current produces a lesser increase of rotor losses.

Finally, the IMs with rotor windings, which have open rotor slots, are most affected by increased losses because the windings' insulation deteriorates with higher than normal temperatures.

3. IM model

3.1. Sequence equivalent models for IMs

In this analysis we considered the positive- and negative-sequences equivalent circuits of the IM [14]. These circuits allow analyzing the effects that voltage unbalance has on the IM [15,16].

The positive-sequence current defines the main rotating field and the direction of rotor rotation. The frequency of the positive-sequence current in the IM's rotor is given by $(s)f$ where f is the supply frequency and s is the slip.

The positive-sequence equivalent circuit is shown in Fig. 2.

The frequency of the negative-sequence current in the IM's rotor is given by $(2 - s)f$. This negative-sequence current produces a field rotating against the main field. The negative-sequence field produces oscillations in the torque and power of the IM at twice the supply frequency. The negative-sequence equivalent circuit is shown in Fig. 3.

3.2. Equivalent circuit parameters

There are different ways to find the parameters of the IM [17–20] depending on the available data and equipment.

We obtained the parameters of two 5.5 kW IMs with squirrel-cage rotors using the no-load and locked-rotor tests [21]. One

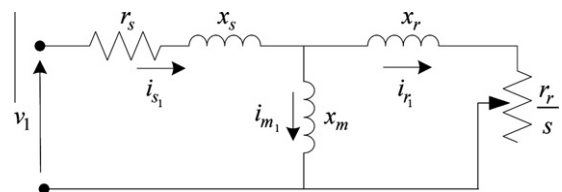


Fig. 2. Positive-sequence equivalent circuit.

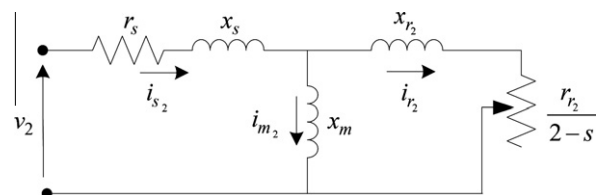


Fig. 3. Negative-sequence equivalent circuit.

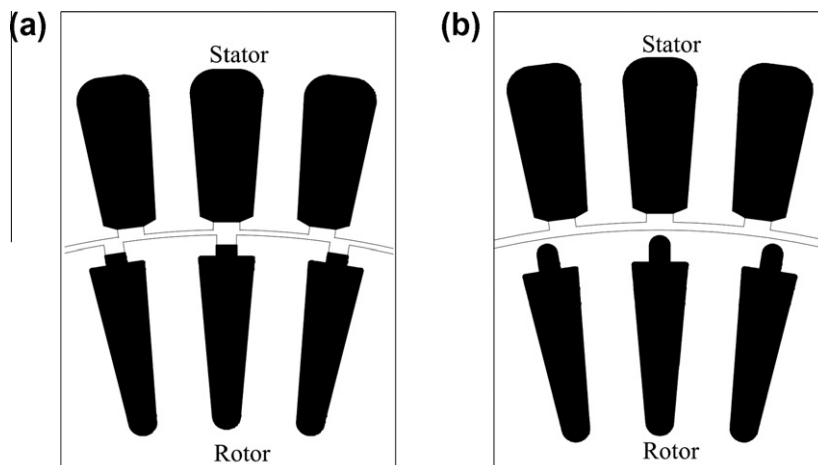


Fig. 1. Rotors with open (a) and closed slots (b).

machine was equipped with a closed-slots rotor, the other was equipped with an open-slots rotor. The technical data and positive sequence parameters of the IMs are shown in Table 5 of Appendix A.

We obtained the negative-sequence parameters for both IMs by applying unbalanced voltages to the IMs under different load conditions. We measured the sequence voltages and currents and calculated the negative-sequence impedances of the IMs.

The variation of negative-sequence resistance and reactance with the load is shown in Figs. 4 and 5.

Assuming that the stator's resistance remains constant for both sequence-systems and that the sequence magnetization reactance is much greater than the leakage impedance, the negative-sequence resistance of the motor is obtained as shown in:

$$r_{r2} = (r_{\text{measured}} - r_s)(2 - s) \quad (1)$$

Applying Eq. (1) to the data shown in Fig. 4, we obtained Table 1.

Using the positive-sequence rotor resistance as base value, we obtained the per unit negative-sequence rotor resistance shown in Table 2.

Table 2 shows that, at full load, the negative-sequence resistance is approximately 4.5 times greater than the positive-sequence resistance. The table also shows that, for loads smaller than 0.25 p.u., the negative-sequence resistance of the closed-slot rotor is up to 10 times greater than the positive-sequence rotor resistance.

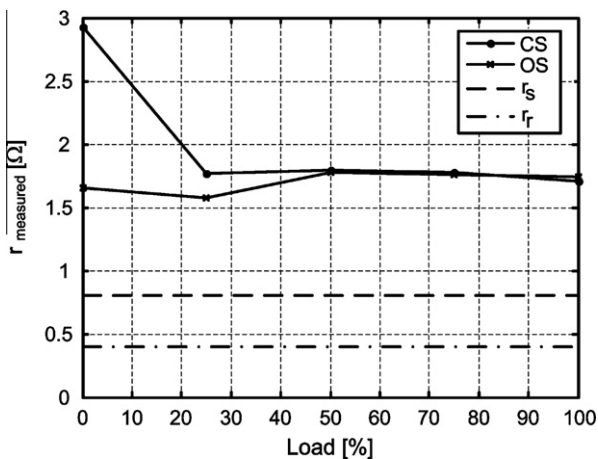


Fig. 4. Negative-sequence resistance as a function of the loading condition.

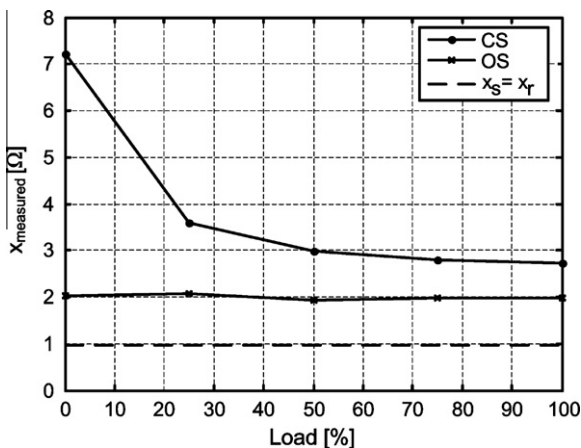


Fig. 5. Negative-sequence reactance as a function of the loading condition.

Table 1
Negative-sequence rotor resistance.

r _{r2} /load (%)	0	25	50	75	100
CS (Ω)	4.26	1.93	1.98	1.95	1.80
OS (Ω)	1.71	1.55	1.95	1.90	1.87

Table 2
Per unit negative-sequence rotor resistance.

r _{r2} /load (%)	0	25	50	75	100
CS (p.u. of r _r)	10.7	4.83	4.94	4.87	4.5
OS (p.u. of r _r)	4.28	3.87	4.87	4.75	4.68

Table 3
Negative-sequence rotor reactance.

x _{r2} /load (%)	0	25	50	75	100
CS (Ω)	6.25	2.62	2.01	1.83	1.76
OS (Ω)	1.07	1.12	0.96	1.01	1.02

Fig. 5 shows that, for the rotor with open slots, the negative-sequence leakage reactance of the rotor is similar to the positive-sequence one. Table 3 shows that, for closed-slot rotors, the negative-sequence leakage reactance grows significantly for low load levels.

4. Experimental validation of the model and its parameters

We performed an experimental validation of the model by monitoring the stator currents of the IM for different levels of voltage unbalance and loads.

The test setup shown in Fig. 6, consists of three autotransformers to feed the IM under test. We adjusted the turns ratio of each autotransformer independently to obtain different voltage unbalance levels. The IM under test is coupled to another IM driven by a commercial torque-controlled variable-speed drive that acts as a variable load.

We measured two phase currents and two line voltages to calculate the sequence currents and voltages to estimate the sequence impedances.

Fig. 7a and b shows the positive-sequence current of IMs with closed and open slots we obtained in the tests. Fig. 7c and d shows the results obtain by using the proposed model.

It is interesting to note that the positive-sequence currents are not significantly affected by the voltage unbalance.

The negative-sequence currents considerably increase with the level of voltage unbalance. Fig. 8a and b shows the negative-sequence currents for different voltage unbalance levels we obtained in the test. Fig. 8c presents the negative-sequence currents we obtained using the analytical model of the IM with the closed-slots rotor. Finally, Fig. 8d shows the results obtained from the model of the IM with open slots.

Fig. 8 shows that the negative-sequence current increases considerably with the level of unbalance. The figure also shows that in the IM with the closed-slots rotor, the increase in the negative-sequence rotor impedance with the decreases load produces a significant reduction in the negative-sequence currents. By contrast, in the IM with open slots the leakage reactance does not vary with the load and then, the negative-sequence currents are not significantly affected by changes in load.

Figs. 7 and 8 show that the model matches the behavior of the IMs closely.

5. Admissible power on IMs with voltage unbalance

Excessive winding temperature reduces winding insulation life [22]. Keeping losses at, or below, nominal values help avoiding

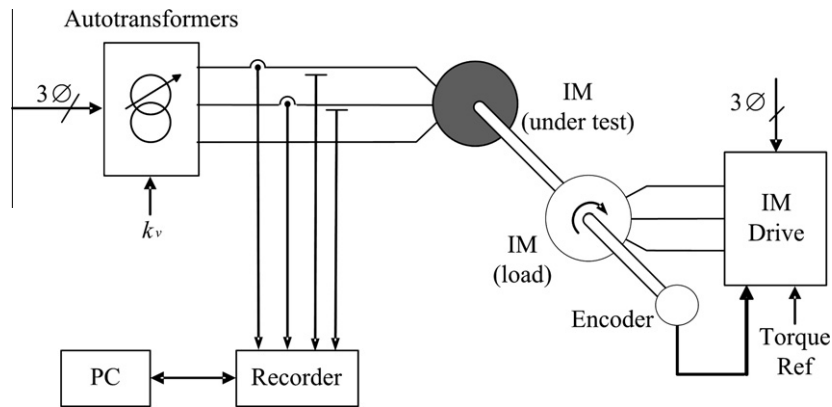


Fig. 6. Laboratory setup.

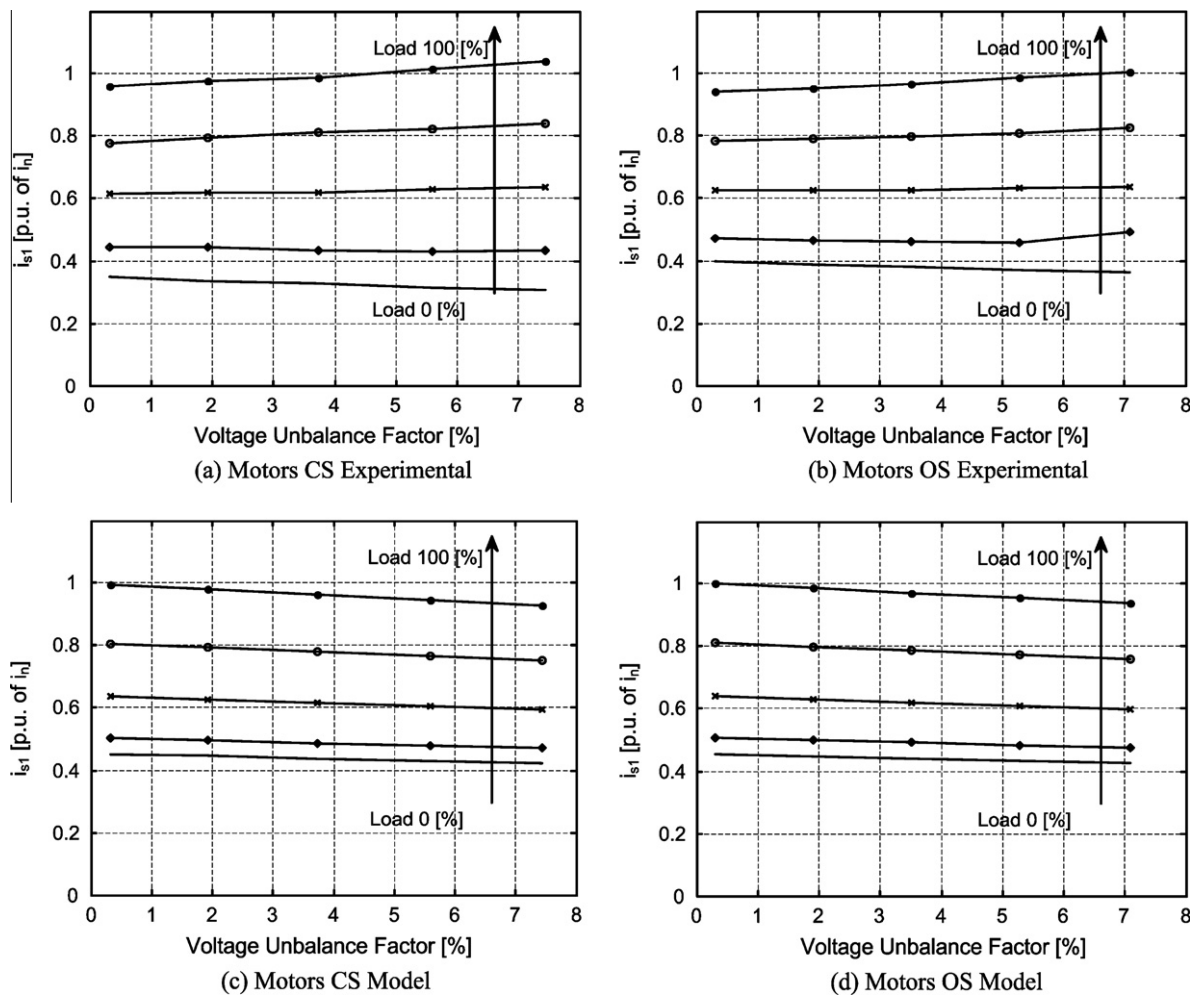


Fig. 7. Test and model positive-sequence currents obtained for the motors with open and closed rotor slots.

excessive temperatures [7]. To protect the stator's windings of a squirrel cage IM, we recommend keeping the total losses of the IMs below the nominal value. For wound rotor IMs, we recommend keeping the rotor losses below the rotor nominal losses value because the rotor winding is typically the more vulnerable than the stator winding.

5.1. Losses in the IM

From the equations that show the behavior of the IM and the equivalent circuits of the IM, we obtain the output power as the

sum of the positive sequence power and the negative sequence power:

$$P_M = P_{m1} + P_{m2} \quad (2)$$

where

$$P_{m1} = 3(i_{r1})^2 \left(\frac{1-s}{s} \right) r_r \quad (3)$$

$$P_{m2} = 3(i_{r2})^2 \left(\frac{s-1}{2-s} \right) r_{r2} \quad (4)$$

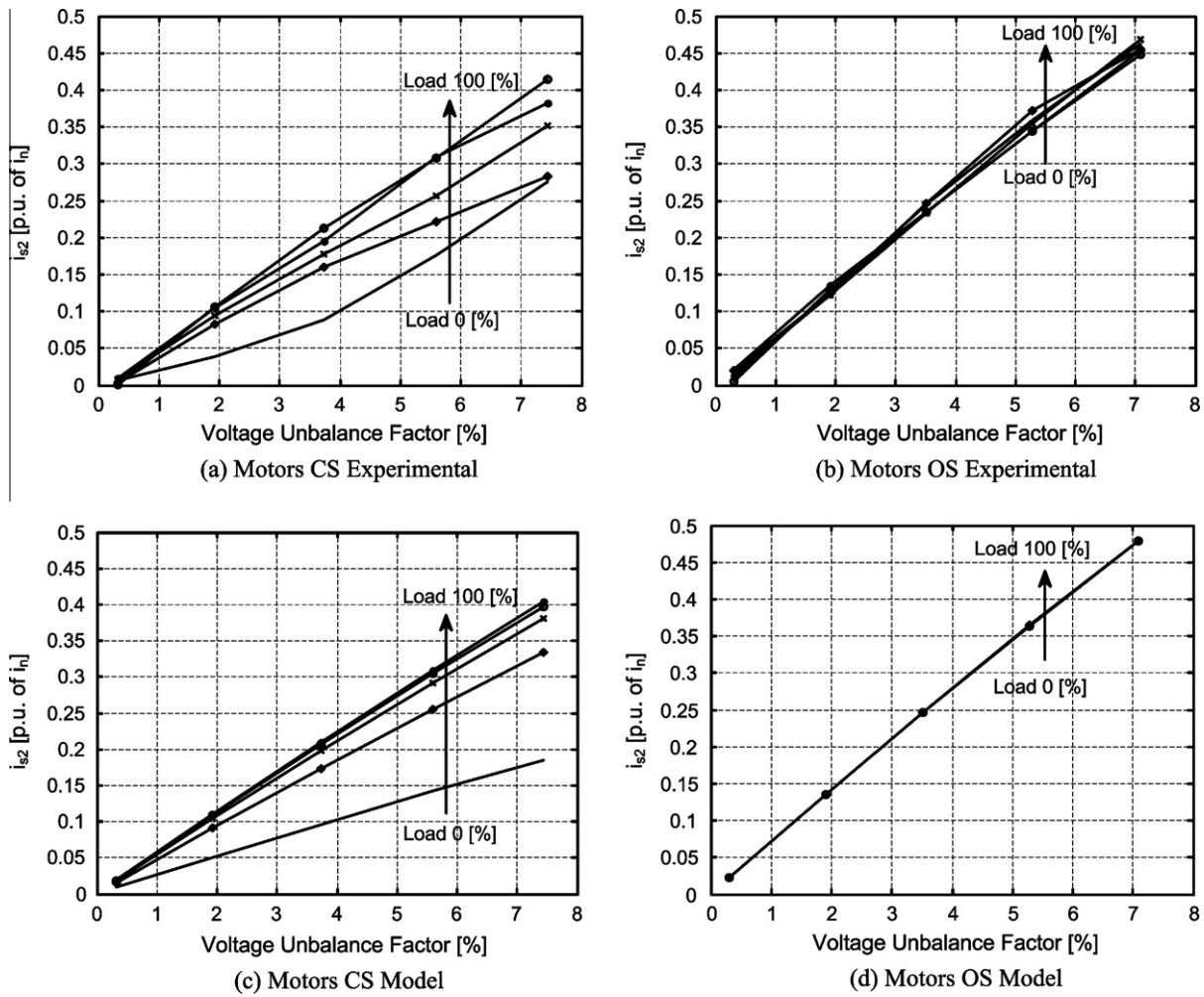


Fig. 8. Test and model negative-sequence currents obtained for the motors with open and closed rotor slots.

The analysis of the Eqs. (3) and (4) shows that for normal slip, the negative sequence power opposes to the effect of the positive sequence power. Then, the negative sequence power produces a reduction in the total mechanical power available at the shaft.

The losses of the IM are the sum of the ohmic losses, the iron losses, the friction losses and the additional losses. In this paper we assume that the iron losses, the losses due to friction and the additional losses are constant, and we calculate the ohmic losses as according to:

$$P_{ohmic} = P_r + P_s \quad (5)$$

where

$$P_s = 3(i_{s1})^2 r_s + 3(i_{s2})^2 r_s \quad (6)$$

$$P_r = 3(i_{r1})^2 r_r + 3(i_{r2})^2 r_r \quad (7)$$

are the ohmic losses in the stator and rotor respectively.

5.2. Derating factors and voltage unbalance

To obtain derating factors for different voltage unbalance conditions, we keep the positive sequence voltage constant and we vary the negative sequence voltage from 0% to 10%. Additionally, we adjust the mechanical power provided by the IM to keep the losses at its nominal value. The ratio of the mechanical power obtained un-

der these conditions and the rated mechanical power of the machine is the machine derating factor.

This method involves applying voltages larger than rated as the voltage unbalance rises. Nevertheless, it shows that the increase in losses is caused by the voltage unbalance and not by a voltage lower than rated.

5.3. Analysis methodology

In this paper we assume, as proposed in [14], that the maximum mechanical power the IM can provide is limited by the rated losses of the IM. This assumption holds under steady state conditions and for any voltage unbalance condition.

Using the equivalent circuit of the IM we obtain the total losses for the entire operating range of the motor under unbalanced voltage conditions. With these data and the rated IM power we obtain the rated level of total losses using Eq. (5).

By increasing the voltage unbalance, we redraw the curve of total losses in the entire operating range. Then, we obtain the maximum power available at the shaft for the rated losses. Fig. 9 shows a simplified flow diagram of the used methodology.

A graphical analysis of the IM of 5.5 kW with closed-slots squirrel-cage rotor can be seen in Fig. 10. This figure shows that the losses level increase with the voltage unbalance.

For wound rotor IM's, the same procedure can be applied using the rotor losses instead of the total losses.

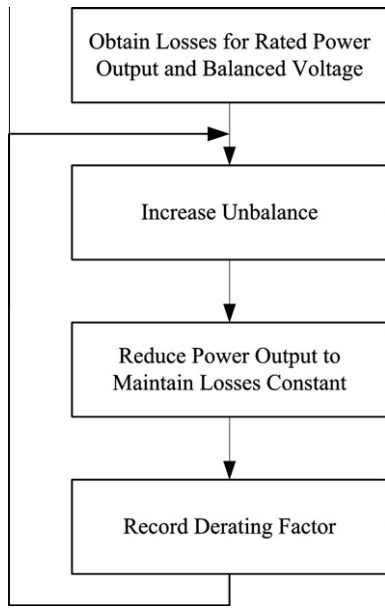


Fig. 9. Flow diagram of the proposed methodology.

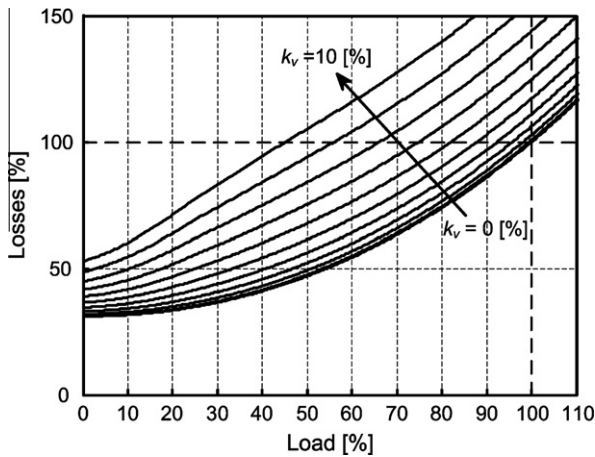


Fig. 10. Increase in total losses with the voltage unbalance level.

5.4. Test cases

In this paper we studied two 5.5 kW IMs, one of them has a closed-slots rotor and the other an open-slots rotor.

In both cases, the positive sequence parameters of the IMs are shown in Table 5 of Appendix A.

We assume that the stator's parameters and the magnetization reactance remain constant for both sequence-systems. The rotor's negative-sequence parameters depend on the type of slots of the IM.

In the first case, we analyze the IM with closed-slots squirrel-cage rotor. Table 4 shows the rotor's impedance parameters used for the different loading conditions.

In the second case, we analyze an IM with open-slots squirrel-cage rotor. The negative-sequence rotor resistance was taken as 4.5 times the resistance of positive sequence. Also, the negative-

Table 4
Impedance of closed-slots rotor negative-sequence referred to positive-sequence.

Impedance/load (%)	0	25	50	75	100
r_{r2} (p.u. of r_r)	10	4.5	4.5	4.5	4.5
x_{r2} (p.u. of x_r)	6.49	2.72	2.09	1.90	1.83

sequence leakage reactance is considered equal to the positive-sequence one.

6. Results

In this section we present the derating factors for the IMs under test. Figs. 11 and 12 show the derating factors to be applied to keep the losses at rated level (DF).

These figures also show the derating factors to be applied to keep the ohmic losses in the rotor at the rated level (DF_{rotor}). The results are compared with the derating factors provided by the NEMA and IEC standards.

6.1. IM with closed-slots squirrel-cage rotor

Fig. 11 shows the results for the case of an IM with closed-slots rotor. The derating factors to keep the losses at rated level are larger than those that have been proposed by the standards. However the results are different when the derating factors are applied to maintain the ohmic losses in the rotor at the rated level. With the last analysis, the derating factors are similar than those that have been proposed by the standards.

6.2. IM with open-slots squirrel-cage rotor

Fig. 12 shows the results for the case of an IM with open-slots rotor. The derating factors to keep the losses in the rated level

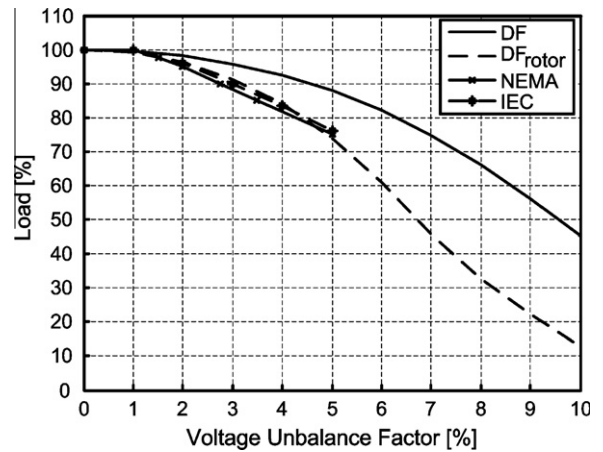


Fig. 11. IM with closed-slots rotor type.

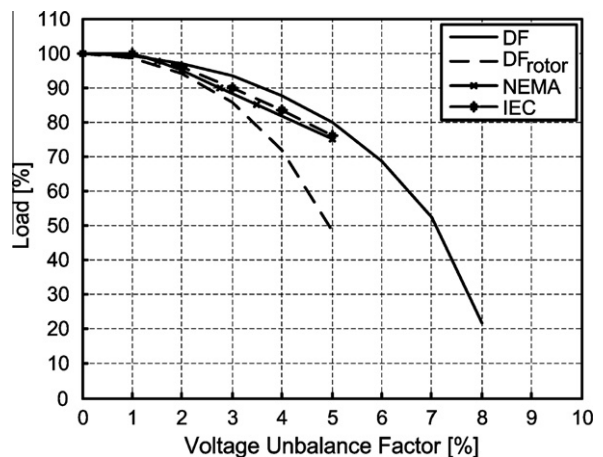


Fig. 12. IM with open-slots rotor type.

Table 5
Technical data and parameters of IM.

Frequency	50	(Hz)
Rated speed	1470	(RPM)
Power	5.5	(kW)
Voltage	380	(V)
Rated current	11.4	(A)
Power factor	0.85	–
V_1	220	(V)
r_s	0.8	(Ω)
r_r	0.4	(Ω)
x_s	0.9625	(Ω)
x_r	0.9625	(Ω)
x_m	39.27	(Ω)
P_f	100	(W)

are similar to those proposed by the standards. Those derating factors are not enough to keep the ohmic losses in the rotor at the rated level.

An analysis of Figs. 11 and 12 shows that the IM with open-slots rotor is more vulnerable to voltage unbalance than the IM with closed-slots rotor.

In the IM with open-slots rotor the increase of losses are greater than in the one with closed-slots rotor, then a bigger derating factor must be applied to keep the losses at rated level. This difference in losses is due to the negative-sequence leakage reactance behavior. In closed-slots rotors the leakage reactance increases with slip. However, in open-slots rotors the leakage reactance does not change with the slip. The larger reactance in closed-slots rotors causes lower currents and losses than in the cases with open-slots rotors. Thus, closed-slots rotors are more resilient to voltage unbalance.

7. Conclusions

In this paper, we use an equivalent IM circuit to obtain the behavior of the IM under unbalanced voltage conditions. We proposed a method to determine the derating factors for any voltage unbalanced condition and IM.

In this paper we show that the increase in negative-sequence reactance of the rotor with closed slots when the load decreases produces smaller negative-sequence currents. Then, for a given voltage unbalance, motors with closed rotor slots show a lesser increase of rotor losses, than motors with open rotor slots.

In the IM with open-slots squirrel-cage rotor there is no significant change on the negative-sequence reactance with the load, thus requiring a smaller derating factor than in the case of closed-slots rotor type.

In the IM with rotor winding it is recommended to use the derating factors obtained from keeping the ohmic losses in the rotor of the IM on the rated level. This recommendation is made because this type of IM has insulation in the rotor, which deteriorates with increasing on the temperature.

Acknowledgments

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Appendix A

Technical data and parameters of IM used for the calculation in the analytical model of the IM are shown in Table 5.

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