Voltage Unbalance Effects on Induction Motor Performance

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Abstract - The reliability of electric drives and driven motors depends on the quality of the power supply voltage especially in the critical industrial process.
In this work, a theoretical study of the effects of voltage unbalances, sags and swells on induction motor (IM) is performed by using the conventional method based on the theory of symmetrical components. For this study, MATLAB software program is developed for calculating currents, torque, power losses, temperature rises and derating factor. Besides, experiments have been carried out for obtaining currents, torque and power losses. An agreement that is found between the theoretical predictions and experimental data allows us to take into consideration the predicted derating factor.

Key-words : -Voltage unbalance, symmetrical components, sags, efficiency, power losses and derating factor.

1 Introduction

Power quality is an issue to which electrical engineers have to pay special attention. It can be defined as a study of sources, effects and control of disturbances in the electric power supply.
Power quality disturbances are divided into three types such as frequency disturbances, waveform disturbances (non-sinusoidal waveform) and voltage disturbances (unacceptable RMS value).
The voltage disturbances include sags, swells and voltage unbalances. They cause failure and malfunction of many equipment such as electronic Adjustable Speed Drives (ASD's) and process control. Sag is a decrease of 10% up to 90% in RMS voltage or current at the power frequency during half cycle up to one minute. However, swell is an increase of 10% up to 90% in RMS voltage or current at the power frequency during half cycle up to one minute. The most common cause of sags and swells is a sudden change in the current flow through the source impedance that is due to faults or overloads. The effects of sags are more noticeable than those of swells however, the effect of the later can be often more destructive [1,2].
The three phase induction motors are designed to work under three phase balanced voltage condition, but a small amount of voltage unbalance that is caused by the introduction of a negative sequence voltage may increase the current very substantially. Its effect on the motor can be severe and the motor may be over-heated and hence burn.
According to the National Electrical Manufacturers Association (NEMA), the voltage unbalance is defined as follows [3]:

$$V_{unbal} = \frac{\Delta V_{\max}}{V_{avg}} \times 100\% \qquad (1)$$

Where $\Delta V_{\max}$ is the maximum deviation from the average of the three phase voltages, and V_{avg} is the average of the three phase voltages.
However, the International Electro-technique Comity (IEC) definition of the voltage unbalance is based on the theory of symmetrical components, where the voltage unbalance factor is given as [4]:

$$V_{uf} = \frac{V_2}{V_1} \qquad (2)$$

Where V_1 is the positive sequence voltage and V_2 is the negative sequence voltage.
When the motor continuous to operate under unbalanced voltage conditions, its efficiency will be reduced. Because both an increase in current and an increase in resistance due to over-heating cause a reduction in efficiency. As the resulting losses increase, the heat increases rapidly that may lead to a condition of uncontrollable heat rise called "thermal runaway". This results in a rapid deterioration of the winding insulation that will end up with failure of the winding.

2 Induction Motor Modeling Under Voltage Unbalance Condition

Modeling of IM operating under voltage unbalance condition has been performed using the symmetrical components method. The negative sequence currents, however set up a reverse field, so that if the rotor slip is ‘s’ with respect to the positive sequence field, it will be (2-s) relative to the negative sequence field. Where, the motor behaves as the addition of two separate motors; one running at slip 's' with voltage V_1 and the other running at slip (2-s) with voltage V_2.

To facilitate the analysis, some assumptions have been made as [5]:

- all circuit elements values are constants, and the frequency dependency on the circuit parameters is neglected.
- The mechanical losses including friction and windage are neglected.
- The machine windings are connected in delta or ungrounded Wye, which means the zero sequence currents are absent.

The sequence impedances of the equivalent circuit as shown in Fig.1 can be written as

$$Z_{si} = R_{si} + jX_{si} \quad (3a)$$

$$Z_{ri} = R_{ri} + jX_{ri} \quad (3b)$$

Where i=0 for zero sequence, i= 1 for positive sequence and i=2 for the negative sequence [6].

Different analysis steps may be followed in order to transform known quantities into symmetrical components and then back to phase quantities using the sequence networks.

Step 1: Transformation of the line voltages into sequence line voltages [7].

$$[V_L]_{abc} = [A]\cdot[V_L]_{seq} \quad (4)$$

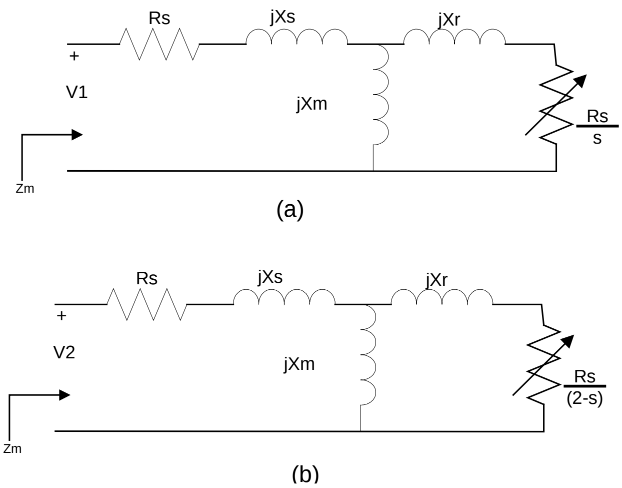

Fig.1 Sequence equivalent circuit (a) positive, (b) Negative.

where, $A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$ and "a" is Fortescue operator.

Step 2 : Computation of the phase voltages.

$$[V_\phi]_{seq} = [T]\cdot[V_L]_{seq} \quad (5a)$$

And,

$$[V_\phi]_{abc} = [W]\cdot[V_l]_{abc} \quad (5b)$$

where, $[W] = [A]\cdot[T]\cdot[A]^{-1}$, (5c)

$T = \begin{bmatrix} 1 & 0 & 0 \\ 0 & t & 0 \\ 0 & 0 & t^* \end{bmatrix}$, and $t = \frac{1}{\sqrt{3}} \angle -30^0$.

Step 3 : Determination of the sequence line currents that flow in the machine :

$$I_{a0} = 0 \quad (6a)$$

$$I_{a1} = \frac{V_{an1}}{Z_{m1}} \quad (6b)$$

$$I_{a2} = \frac{V_{an2}}{Z_{m2}} \quad (6c)$$

Step 4 : Transformation of the sequence currents to phase currents.

$$[I]_{abc} = [A]\cdot[I]_{seq} \quad (7)$$

Step 5 : Computation of the input phase complex powers and the total three phase power :

$$[S]_{abc} = [V_\phi]_{abc} \cdot [I]^*_{abc} \quad (8)$$

$$S_{tot} = S_a + S_b + S_c \quad (9)$$

Step 6 : Using the sequence stator and rotor impedances, the positive and negative sequence ABCD parameters of T sequence equivalent circuit are given by :

$$\begin{aligned} Am_i &= 1 + Ym_i \cdot Z_{si} \\ Bm_i &= Z_{si} + Z_{ri} + Ymi \cdot Z_{si} \cdot Z_{ri} \\ Cm_i &= Ym_i \\ Dm_i &= 1 + Ym_i \cdot Z_{ri} \end{aligned} \quad (11)$$

Note that

$Am_i \cdot Dmi \cdot Bmi \cdot Cmi = 1$

The rotor sequence phase voltages (V_{ri}) and currents (I_{ri}) are given by :

$$\begin{bmatrix} V_{ri} \\ I_{ri} \end{bmatrix} = \begin{bmatrix} Ami & -Bmi \\ -Cmi & Dmi \end{bmatrix} \begin{bmatrix} V_{si} \\ I_{si} \end{bmatrix} \quad (12)$$

The rotor phase voltages (V_r) and currents (I_r) are given by :

$$[Vr]_{abc} = A \cdot V_{ri} \quad (13)$$

$$[Ir]_{abc} = A \cdot I_{ri} \quad (14)$$

The output power is given by :

$$P_{out} = V_{ra} \cdot (I_{ra})^* + V_{rb} \cdot (I_{rb})^* + V_{rc} \cdot (I_{rc})^* \quad (15)$$

The copper rotor losses :

$$[P_r]_{abc} = R_r \cdot \left[|I_r|^2\right]_{abc} \quad (16)$$

$$P_{rtot} = P_{ra} + P_{rb} + P_{rc} \quad (17)$$

The stator copper losses :

$$[P_s]_{abc} = R_s \cdot \left[|I_s|^2 \right]_{abc} \quad (18)$$

$$P_{tot} = P_{sa} + P_{sb} + P_{sc} \quad (19)$$

The total input power :

$$P_{in} = real\left[V_{sa} \cdot (I_{sa})^* + V_{sb} \cdot (I_{sb})^* + V_{sc} \cdot (I_{sc})^* \right] \quad (20)$$

The derating factor is determined as the ratio of the calculated output power to the rated power.

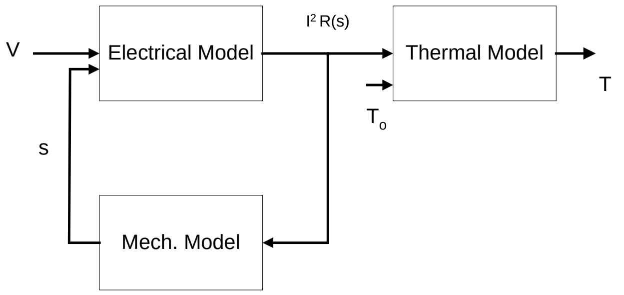

Fig.2 Induction motor models block diagram.

The motor temperature rise can be predicted through the use of the models shown in figure 2. The electrical model is used to calculate motor losses which will be fed into the thermal model. The thermal model is the equation of heat rise due to current flowing in a conductor characterized by the thermal capacitance, the thermal resistance and the slip. Thus, the temperature rise depends on the power loss averaged over the time period caused by motor current flowing in the windings.

Table 1 Induction motor (50Hz , 4 pole) ratings.

P (kW)	V (V)	Xs (Ω)	Xr (Ω)	Xm (Ω)	Rs (Ω)	Rr (Ω)
0.175	220	42	308	350	44.4	33.33
2	220	0.984	0.441	4.5	0.175	0.188
37.3	460	0.251	0.251	10.9	0.087	0.228

3 Simulation Results and Discussion

To study the effects of voltage unbalance on induction motor with different power levels and parameters as given in table 1, two different methods of unbalancing the supply voltages are applied. In both cases the average of the voltage magnitude is held constant. The first method, named case A, can be attained by holding the magnitude V_{bc} constant and increasing the magnitude of V_{ab} at the same rate that the magnitude of V_{ca} is reduced.

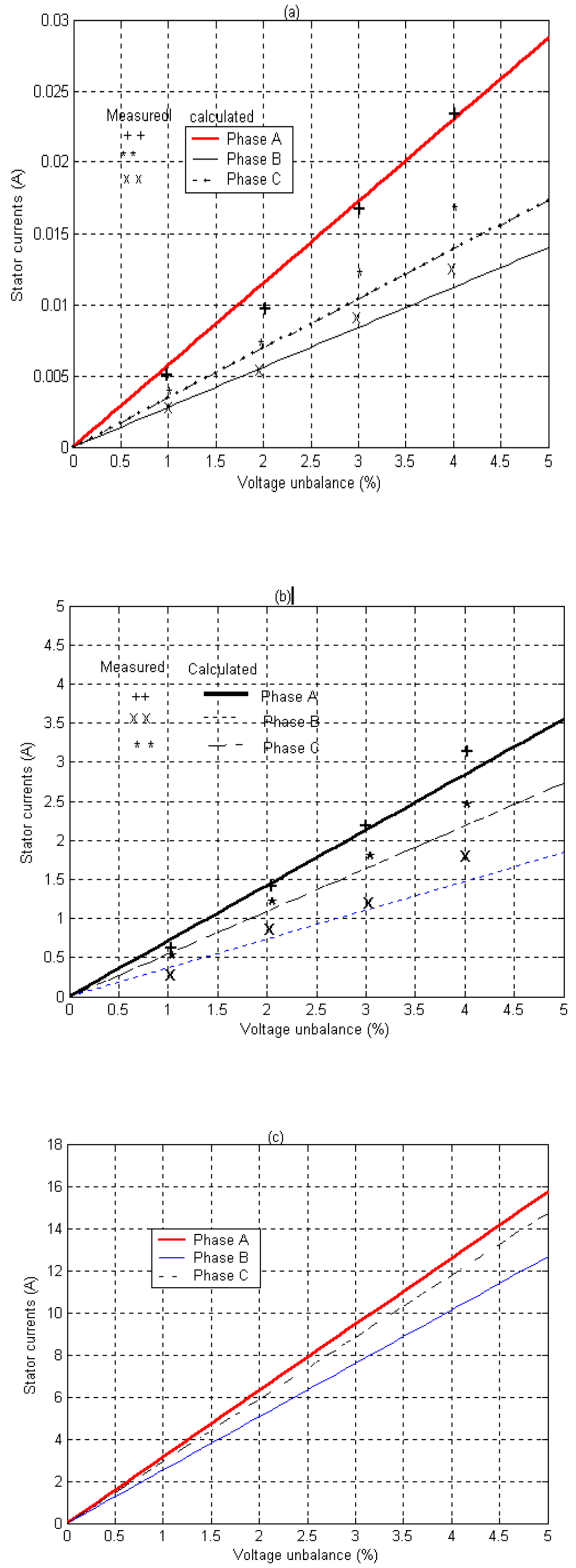

Fig.3 Stator currents as function of voltage unbalance of case A for power levels (a) 175W, (b) 2kW and (c) 37.3 kW.

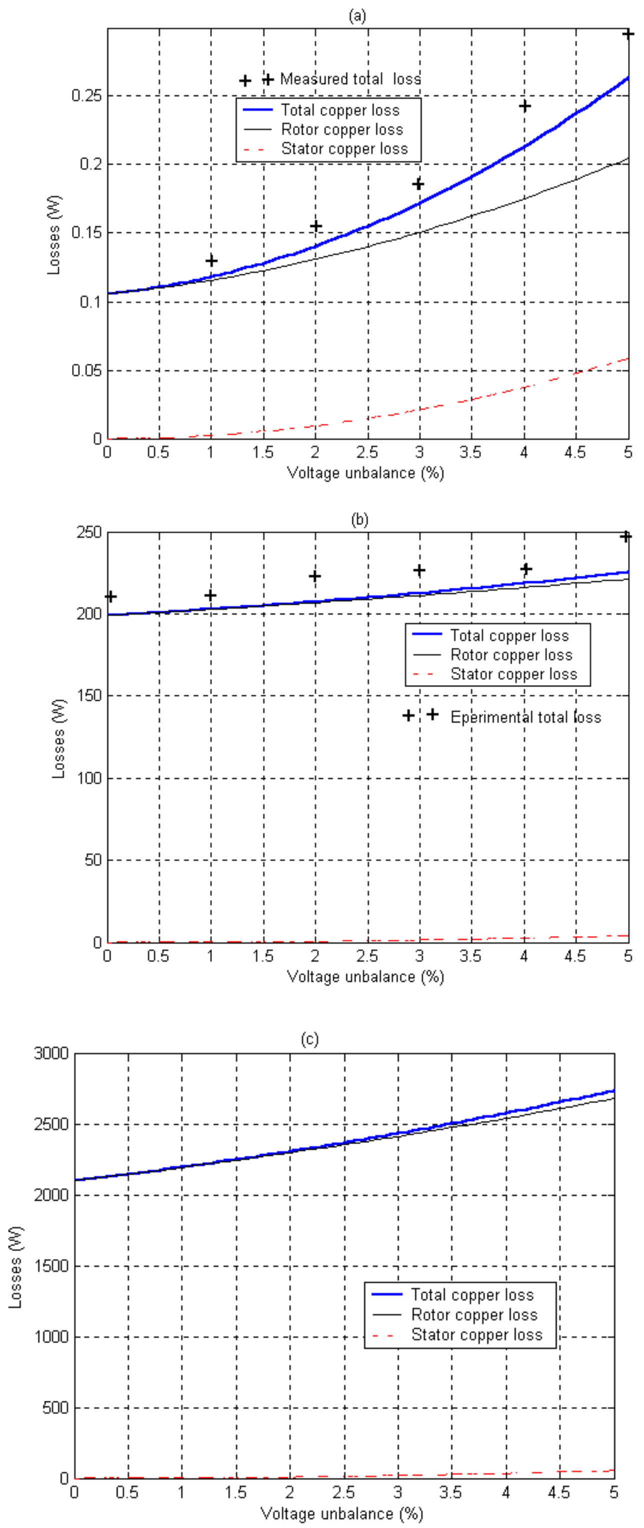

Fig.4 Copper losses of case A for power levels (a) 175W, (b) 2 kW and (c) 37.3 kW.

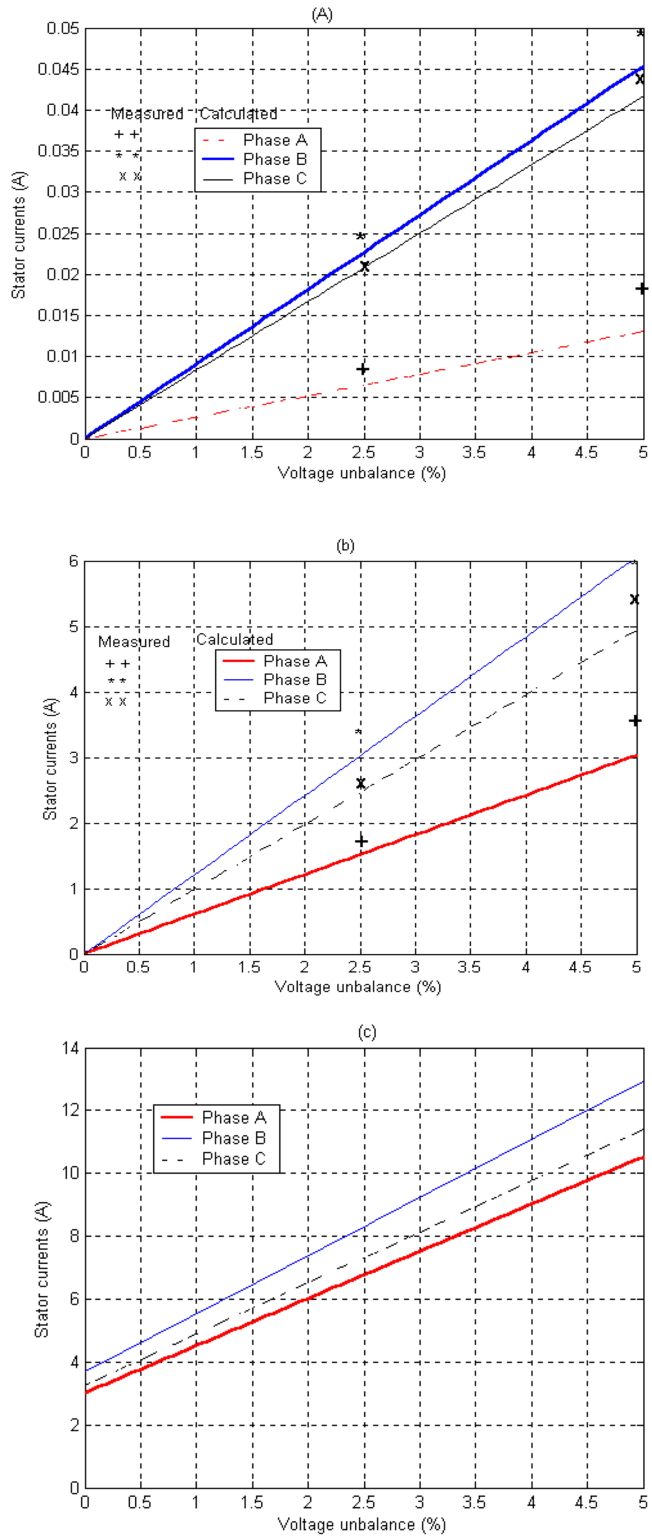

Fig.5 Stator currents as function of voltage unbalance of case B for power levels (a) 175W, (b) 2kW and (c) 37.3 kW.

The second method as case B, can be performed by increasing both V_{ab} and V_{ca}, while the magnitude of V_{bc} is reduced.

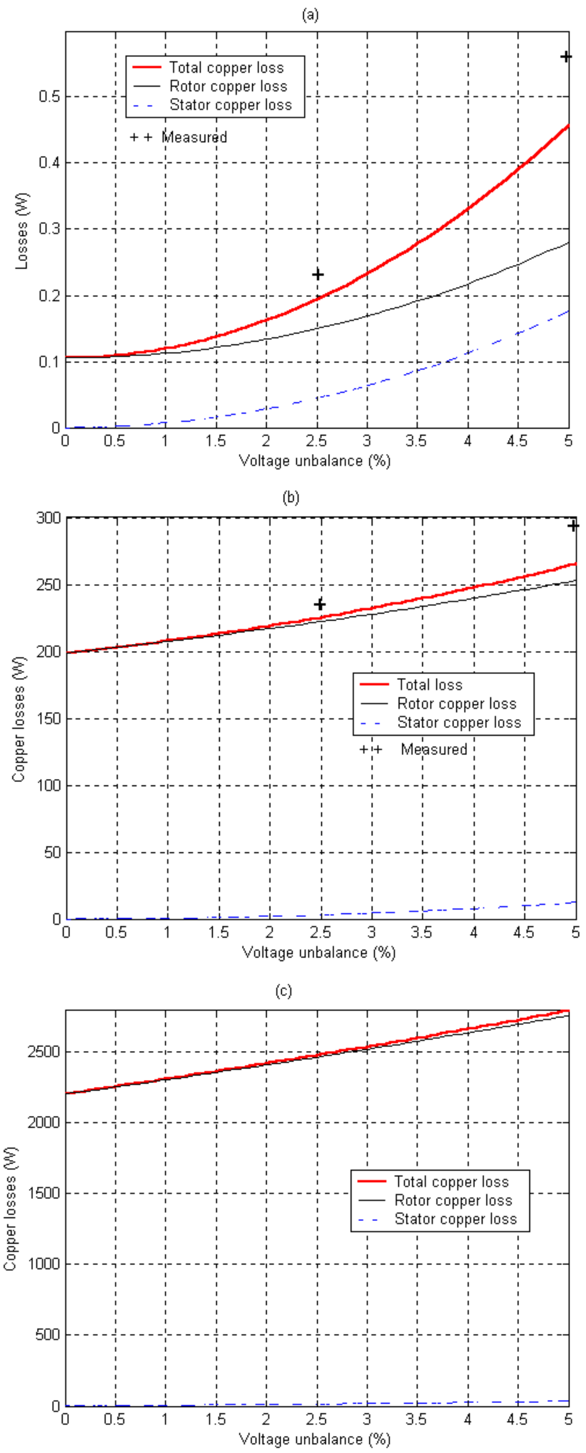

Fig.6 Additional copper losses of case A for power levels (a) 175W, (b) 2 kW and (c) 37.3 kW.

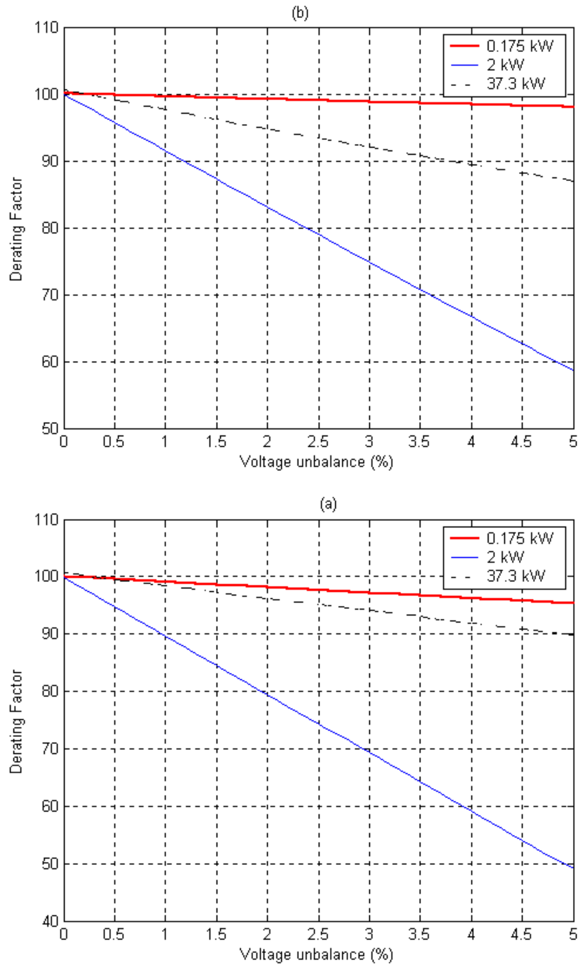

Fig.7 Derating factor (a) for case B, and (b) for case A.

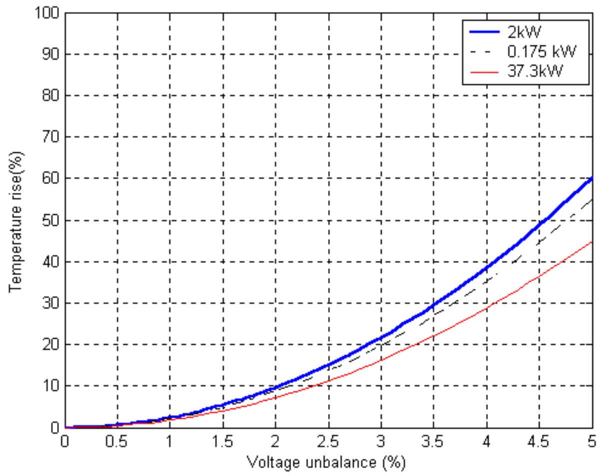

Fig.8 temperature rise of different induction motor power levels for case B.

Figures 4, 6 and 7 shows that the worst case by taking losses and derating factor is the case B.

Moreover, two power levels of induction motor 175 W and 2 kW (Lab.Volt Ref. EMS 8239 and EMS 8555-1 respectively) that are available in our laboratory have been used in this experiment. As shown in figures 3 (a) and (b), 4 (a) and (b), 5 (a) and (b), and 6 (a) and (b), the obtained experimental results agree the calculated ones that allows us to take in consideration the remaining calculated parameters such as derating factor. In the case B which is the worst case, more critical temperature rise is produced as shown in figure 8.

4 Conclusion

The voltages at the distribution level can become unbalanced due to unequal system impedances and unbalanced loads.

Even a low level of voltage unbalance can have serious impacts on the induction motor. Where the amount of current unbalance is present in several time the amount of voltage unbalance, this current leads to very high stator and rotor copper losses. These high additional losses cause an important increase in motor heating while leads to make faster thermal aging and hence insulation failure. It can be noticed that the needed derating degree is comparatively more important for very low power induction motors. However, in general for high power level induction motors of the order of 50 hp the degree of derating is lower.

The induction motor are designed to tolerate a low level of unbalance and they have to be derated to prevent the motor against overheating in case of substantial voltage unbalance, and hence it will not be able to reach the load requirements (speed and torque). NEMA standards recommended a maximum voltage unbalance of 1% without derating [8]. If the unbalanced protection is not provided, the motor should be derated to 40 up 60% of its rated power [9].

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