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In Electronics Systems Engineering

Study of the Effects of Unbalanced Sinusoidal Voltage Supply on Induction Motor Steady State Performance

By

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ملخص

هذا العمل يهتم بدراسة نظرية مفصلة لتأثير توتر التغذية غير المتوازن، على محركات حثية مختلفة القدرة في الحالة المستقرة مزودة مباشرة من منبع جيبي ثلاثي الأطوار، و هي تميز الحالة التي لا تزال سائدة في بلادنا حيث أن محولات إلكترونيك القدرة رغم استعمالها المتزايد، لا تزال تشغل حيزا صغيرا من السوق.

مقدار عدم التوازن في التوتر يحسب بناء على التعريفين الأكثر شهرة، تعريفا NEMA وIEC. تم دراسة تأثيرات التوتر غير المتوازن على متغيرات المحركات الحثية في الحالة المستقرة و هي: العزم، تيارات العضو الساكن و العضو الدوار و كذا الفقد النحاسي الزائد.

كذلك تم تعيين العلاقة الرابطة بين قيمة معينة للتوتر غير المتوازن و التأثيرات الضارة على المحرك، حيث أن التأثير الأساسي، هو الفقد الزائد بنسبة أساسية مؤديا إلى ارتفاع كبير للحرارة التي تستلزم التخفيض للقدرة المنتجة للمحرك بنسبة مئوية محددة. على ضوء النتائج المتحصل عليها ، وجد أن التخفيض للقدرة المنتجة المطلوب متعلق كذلك بالقدرة المقننة للمحرك.

كما أنه تم دراسة حالة التغذية بفقدان طور، ضياع طور من الأطوار الثلاثة للمنبع، و هي حالة قصوى للتوتر غير المتوازن، حيث تبين هذه الدراسة أن لهذه الحالة تأثيرات شديدة على المحرك فيما يخص الضغط الحراري المرتفع، ارتفاع الفقد النحاسي و كذا درجة حرارة اللفات إلى مستوى من حالة شاذة متطلبا فصل المحرك فوريا لحمايته من تعطيل دائم.

Abstract

The present work concerns a detailed theoretical investigation of the effects of unbalanced supply voltages on the steady state operation of induction motors for different power levels fed directly from a three-phase sinusoidal supply system, which represent a still dominating situation in our country as power electrical converters though in increasing use are still a minor part of the market.

The voltage unbalance is calculated on the basis of the two mostly known definitions, the NEMA and IEC definitions. The effects of voltage unbalance on the induction motors steady state parameters: torque, stator and rotor currents and additional power copper losses are computed and studied.

Correlation between a well defined voltage unbalance and resulting detrimental effects on the machine have been established. The principal effect is additional losses in substantial proportion leading to large temperature increase entailing the derating of the machine in a given quantified percentage. Also according to the study, the needed derating is found to depend on the machine nominal rated power.

Also, Single phasing, the loss of one supply phase, is an extreme case of voltage unbalance has also been studied. The study shows that single phasing can have very severe effects on the machine in terms of excessive thermal stress, large losses and winding temperatures rising to abnormally high levels requiring therefore immediate machine disconnection, to protect it from permanent damage.

Résumé

Le présent travail concerne une étude théorique détaillée sur les effets des tensions d'alimentation non équilibrées sur le fonctionnement en régime permanent des moteurs asynchrones pour différents niveaux de puissance, alimentés directement à partir d’un système sinusoïdal triphasé; ce qui représente une situation prépondérante dans notre pays, les convertisseurs électroniques de puissance installés étant encore en nombre limité.

Le déséquilibre de tension est calculé sur la base des deux définitions les plus connues, définition NEMA et définition IEC. Les effets du déséquilibre de tension sur les paramètres des moteurs asynchrone en régime permanent: le couple, les courants statorique et rotorique ainsi que les pertes additionnelles de cuivre sont calculés et étudiés.

La corrélation entre un déséquilibre de valeur donnée et les effets néfastes qui en découlent sur la machine a été établie. L'effet principal se manifeste par des pertes additionnelles dans des proportions substantielles causant une grande élévation de température nécessitant par conséquent le déclassement de la machine d'un pourcentage donné. Selon l'étude, le déclassement nécessaire dépend aussi de la puissance assignée nominale de la machine.

Par ailleurs, l’alimentation en monophasé, suite à une perte d'une phase d'alimentation triphasée, représentant un cas extrême de déséquilibre de tension a été étudiée. L'étude montre que la perte d’une phase peut avoir des effets très graves sur la machine en termes de contrainte thermique excessive, occasionnant des pertes et des températures d’enroulement très élevées exigeant donc le débranchement immédiat de la machine, afin de la protéger contre tout endommagement permanent.

ACKNOWLEDGEMENTS

In submitting this thesis project, there are a number of people who I would like to thank for their help in one way or another to complete my thesis. Many thanks must go to my advisor Pr. L. REFOUFI for his continuous support, encouragement and guidance during this research period towards accomplishing this work.

I would like to thank every one in the department of Electrical and Electronics Engineering. I am thankful also to the post-graduate teachers, Pr. K. Hariche, Dr. Y. Kribes, Dr. M. Noureddine and Mr. A. Dahimene for enriching my knowledge and the tolerance they had shown. Also, special thanks go to Dr. H. BENTARZI.

Thanks also to the jury members for the interest they gave to this work in accepting its evaluation. Pr. Dj. BENAZZOUZ as the president of jury, Dr. D. OUAHDI and Dr. C. LARBES as examiners.

Thanks also to the other members of EPE / ELECTRO-INDUSTRIES /SPA, particularly Mr. A. AKLI, Mrs. T. AKLI and Miss L. AMEUR for the knowledge shared during this time and for many useful technical discussions. Most of all I would like to thank all my family; especially my parents who have always supported encouraged me.

Table of content

1 Chapter one

INTRODUCTION

Power quality of the supply affects every consumer, from the homeowner to large industry and mining. Customer awareness of poor power quality of supply is increasing due to the more sensitive nature of modern equipment on one hand and the ever increasing deployment of non- linear loads on the other.

Inevitably there is always a finite amount of supply voltage unbalance due to objective reasons like unsymmetrical transformer windings or transmission line impedance, unbalanced three phase loads, and large single phase loads often cause an unbalanced voltage at the point of utilisation [1]. Regardless of the cause, large negative sequence currents can occur, even if the phase voltage unbalance is small, due to relatively small negative sequence impedance [1]. The currents at normal operating speed with unbalanced voltages will be greatly unbalanced in the order of approximately 6 to 10 times the voltage unbalance [2].

If the percent unbalanced voltage in the order of 1% the additional losses are considered not important enough to warrant a derating of the motor [3], [4], [5]. However, it is not unusual that voltage unbalance can reach much larger proportion and therefore be the cause of much more important additional losses entailing a necessary derating of the motor. This introduces a complex problem in selecting the proper overload protective devices, particularly since devices selected for one set of unbalanced conditions may be inadequate for a different set of unbalanced voltages. Increasing the size of the overload protective device is not the solution in as much as protection against heating from overload and from single phase operation is lost [2].

A more upstream approach would be to set a limit on voltage unbalance that will be imposed by the electric utilities (SONELGAZ in our case).

The complex voltage unbalance will give results that are more accurate since the CVUF contains two parameters the magnitude and the angle, it is used to fully describe the voltage unbalance phenomenon [6].

Calculation of projected additional losses due to voltage unbalance according to two definitions, NEMA and IEC, are carried out in a simple way. This is an attractive feature, when used with the fundamentally simple theory of symmetrical components will lead to results represents credible effort with simple means under MATLAB environment studies.

The degree of the effect of voltage unbalance on the induction motor performances depends on the power level and the design of induction motors. Therefore, in our work different power level induction motors have been studied and analysed under different operating conditions.

First, the thesis starts with an introduction to our work, than chapter two describes the steady state analysis of induction motors of different power levels under sinusoidal balanced supply condition. Using the exact equivalent circuit of the induction motors, the stator currents, torques, power factors and efficiencies speed characteristics have been given for each motor.

The following chapter illustrates the different definitions of the voltage unbalance factor. Equivalence between the two definitions of voltage unbalances the NEMA definition and the IEC definition is established in terms of a percentage value.

The effects of the voltage unbalance on the induction motors using these two definitions have been analysed and given in a details in chapter four. This study is based on the symmetrical components theory; the positive and negative sequence equivalent circuits have been used to determine the effects of voltage unbalance on the induction motor performances with the emphasis on the derating and the temperature rise using different cases of the terminal voltages.

Chapter five deals with the effects of single phasing, is defined as the extreme case of voltage unbalance on the four different power level motors, which have been used in the previous chapter. Then important conclusions regarding the research will be made. Lastly, several suggestions on possible future research work will be given.

CHAPTER 2

STEADY STATE PERFORMANCE OF INDUCTION MOTORS UNDER SINUSOIDAL BALANCED SUPPLY CONDICTION

2

2.1 Introduction

Induction ac motor is the simplest and most rugged electric motor and consists of two basic electrical assemblies: the wound stator and the rotor assembly. There are two types of rotor windings: squirrel-cage rotor and form-wound rotor. The induction ac motor derives its name from currents flowing in the secondary member (rotor) that are induced by alternating currents flowing in the primary member (stator). The combined electromagnetic effects of the stator and rotor currents produce the force to create rotation.

The most common type of motors is the squirrel-cage polyphase induction motor because is the simplest to manufacture and the easiest to maintain [7]. It consists of conducting bars embedded in slots in the rotor iron and short-circuited at each end by conducting end rings. The rotor bars are usually made of copper, aluminium, magnesium or alloy placed in slots. Viewed from the end, the rotor assembly resembles a squirrel cage; hence the name squirrel-cage motor is used to refer to induction motors.

Standard squirrel-cage rotors have no insulation since bars carry large currents at low voltages. The squirrel-cage motor is a constant speed motor with either a normal or high starting torque depending on the design. These characteristics fulfil the requirements of the majority of industrial applications, making the squirrel-cage motor ideal for such applications including lathes, presses, blowers, pumps, etc

2.2 The operation principle

The operation of the squirrel-cage motor is simple. When the stator winding of a three phase induction motor is connected to a three-phase power source, it produces a rotating magnetic field. This rotating magnetic field is constant in magnitude and revolves around the rotor. The speed at which the magnetic field rotates is the synchronous speed of the motor and is determined by the number of poles in the stator and the frequency of the power supply as:

$$N_s = \frac{f}{p} \ rev/s = \frac{60\ f}{p} \ rpm \tag{2.1}$$

Where: N_s = synchronous speed

f = frequency

P = number of pole pairs

Synchronous speed is the absolute upper limit of motor speed. At synchronous speed, there is no difference between rotor speed and rotating field speed which is never attained, so no voltage is induced in the rotor bars, hence no torque is developed. Therefore, when running, the rotor must rotate slower than the magnetic field. The rotor speed is just slow enough to cause the proper amount of rotor current to flow, so that the resulting torque is sufficient to overcome windage and friction losses, and drive the load. This speed difference between the rotor and magnetic field, called slip, is normally referred to as a percentage of synchronous speed:

$$S = \frac{(N_s - N_a)}{N_s}.100 \tag{2.2}$$

Where: s = slip

N_s = synchronous speed,

N_a = actual speed

Squirrel-cage motors are made with the slip ranging from less than 5% to around 20% according to the machine design. Motors with slip of 5% or higher are used for hard-to-start applications. A motor with a slip of 5% or less is called a normal slip motor. A normal slip motor is often referred to as a constant speed motor because the speed changes very little with variations in load.

2.3 The per phase equivalent circuit of the induction motor

The per phase equivalent circuit of an induction motor is developed with the underlying assumption that the three phase induction motor is fed by a balanced three phase sinusoidal supply. Figure 2.1 shows the equivalent circuit of an induction motor representing the true electrical conditions, the rotor quantities being at slip frequency. Dividing the rotor circuit parameters by slip s we obtain the circuit shown in figure 2.2 [8], making how parameter referring to the stator circuit possible.

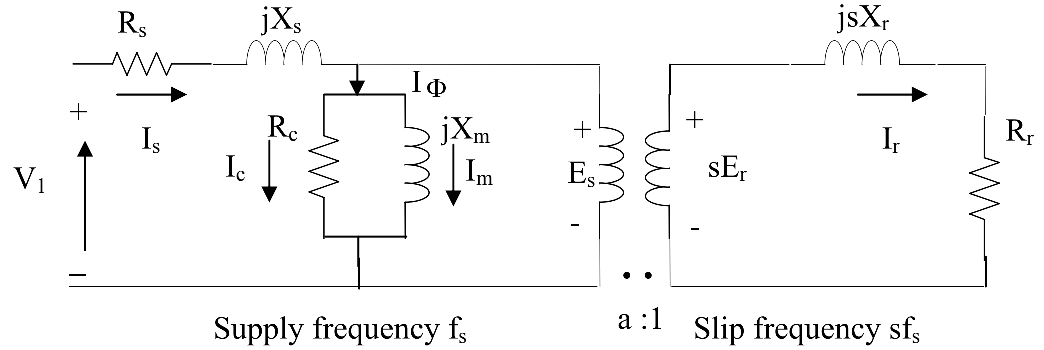


Fig 2.1 Per-phase equivalent circuit of the induction motor

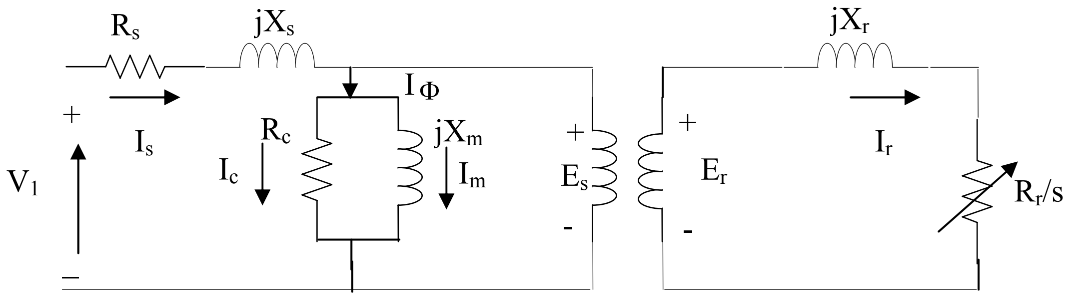


Fig 2.2 Exact equivalent circuit of the induction motor; (Steinmetz model)

Where

V_1 is applied voltage on a per-phase basis,

E_s is a per-phase induced EMF in the stator winding,

E_r is a per-phase induced EMF in the rotor winding,

R_s is a per-phase stator winding resistance,

X_s is a per-phase stator winding reactance,

R_r is a per-phase rotor winding resistance,

X_r is a perphase rotor winding leakage reactance ,

X_m is a per-phase magnetization reactance,

R_c is a per-phase equivalent core-loss resistance,

R_r/s represents a fictitious variable resistance as a function of slip.

I_s is a per-phase current supplied by the source,

I_r is a per-phase rotor winding current,

$I_\Phi = I_c + I_m$ is a per-phase excitation current,

I_c is a per-phase core loss current,

I_m is a per-phase magnetization current.

Defining the ratio of transformation [8], [9]:

$$a = \frac{N_s K_{w1}}{N_r K_{w2}} \tag{2.3}$$

Where K_{w1} is the winding factor of the stator winding, K_{w2} the winding factor of the rotor winding, N_s turns per phase of the stator winding, and N_r turns per phase of the rotor winding.

With the ratio of transformation the equivalent circuit in the figure 2.2 can be transformed to the circuit shown in figure 2.3, where R'_r, X'_r are the referred rotor resistance and reactance to the stator respectively.

$$R'_r = a^2 R_r$$
$$X'_r = a^2 X_b \qquad (2.4)$$
$$I'_r = \frac{I_r}{a}$$

X_b is a per-phase rotor winding leakage reactance at $s = 1$ (i.e. the rotor is at rest),

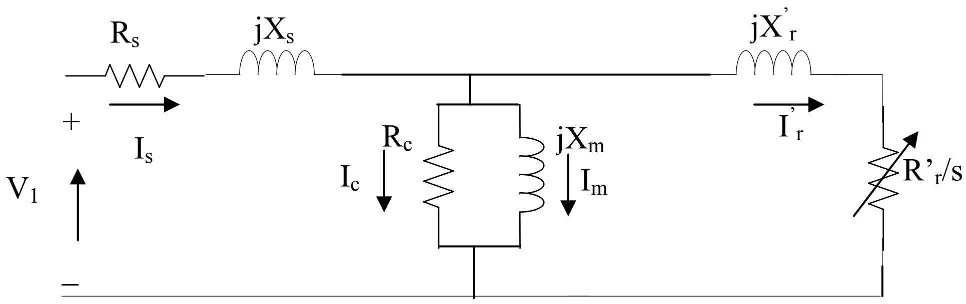


Fig 2.3 The exact equivalent circuit of the induction motor with rotor quantities referred to stator

Decomposing the fictitious variable resistance R'_r/s into fixed and variable components. R'_r represents the copper loss and $R'_r(1-s)/s$ the developed mechanical power.

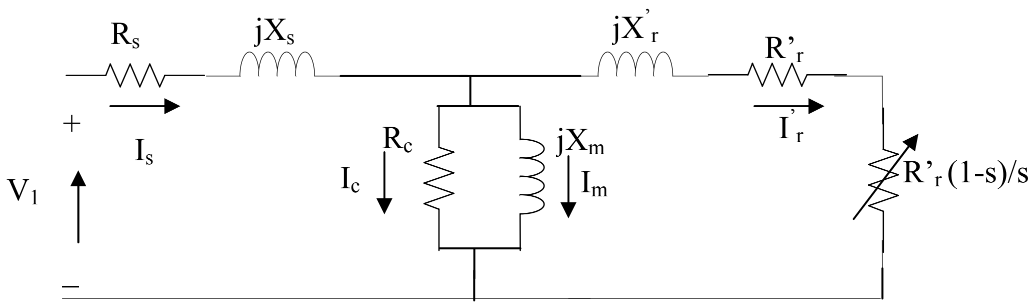


Fig2.4 The exact equivalent circuit of the induction motor

In the circuit, $R'_r I'^2_r$ represents the rotor copper loss referred to the primary and $I'^2_r R'_r (1-s)/s$ the mechanical power developed.

If we assume that $R_c \rangle\rangle X_m$ then the exact equivalent circuit of figure (2.3) will take the form shown in figure (2.5).

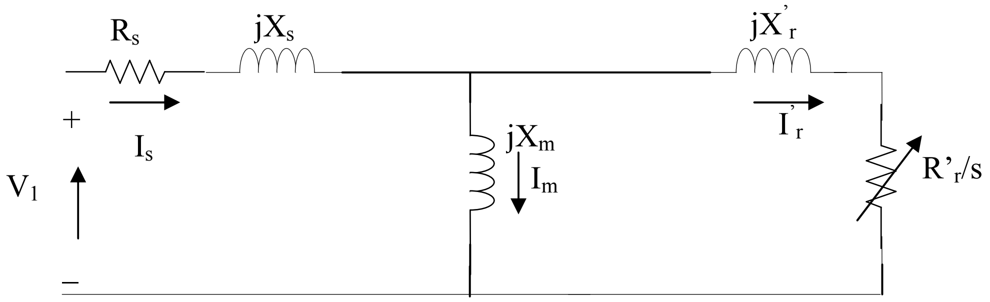


Fig2.5 The exact equivalent circuit of the induction motor

An approximation is possible by putting the; X_m branch straight across the input voltage terminal.

2.4 Performance calculations

Calculation of the steady state induction motor performances consists of calculating:

-The electromagnetic torque developed by the motor from starting to full load speed operation (as a function of speed).

- Power factor of the motor (as a function of speed).

-Efficiency of the motor as a function of speed.

-From starting to full load speed operation; the starting current needs to be known with sufficient accuracy.

Referring to figure (2.5), the circuit input impedance is

$$Z_{in} = R_s + jX_s + \frac{jX_m (R'_r/s + jX'_r)}{R'_r/s + j(X_m + X'_r)} \tag{2.5}$$

$$Z_{in} = \frac{\alpha R'_r + SX_{rr}\beta + j(\beta R'_r - \alpha S X_{rr})}{R'^2_r + s^2 X_{rr}^2} \tag{2.6}$$

Where $X_{rr} = X_m + X'_r$ (2.7)

$$X_{ss} = X_m + X_s \tag{2.8}$$

$$\alpha = R'_r R_s + s(X_m^2 - X_{ss} X_{rr}) \tag{2.9}$$

$$\beta = R'_r X_{ss} + sR_s X_{rr} \tag{2.10}$$

Then, the stator current is given by

$$I_s = \frac{V_1}{Z_{in}} \tag{2.11}$$

$$I_s = \frac{V_1\left(R'_r + jsX'_r\right)}{\alpha + j\beta} \tag{2.12}$$

The rotor current referred to stator circuit is given by:

$$I'_r = \frac{V_1 \ .jsX_m}{\alpha + j\beta} \tag{2.13}$$

The power dissipated is

$$P_\Omega = 3\left|I_s\right|^2 R_s + 3\left|I'_r\right|^2 R'_r \tag{2.14}$$

Stator and Rotor Copper losses being respectively

$$P_{SCL} = 3\left|I_s\right|^2 \ R_s \ , \ \ P_{RCL} = 3\left|I'_r\right|^2 R'_r = sP_{ag} \tag{2.15}$$

Where the air gap power is given by

$$P_{ag} = 3\left|I'_r\right|^2\left(\frac{R'_r}{s}\right) \tag{2.16}$$

Hence the power developed by the motor is given by

$$P_d = P_{ag} - s \ P_{ag} = (1-s)P_{ag} \tag{2.17}$$

From the general formula of power, we can extract the torque developed:

$$P_d = T_{em}\omega_m \tag{2.18}$$

Where T_{em} is the electromagnetic torque developed by the motor is:

$$T_{em} = 3\frac{R'_r\left|I'r\right|^2}{\omega_m}\left(\frac{1-s}{s}\right) \tag{2.19}$$

And

$$\omega_m = \omega_s(1-s) \tag{2.20}$$

Hence

$$T_{em} = 3\frac{R'_r\left|I'r\right|^2}{\omega_s s} = \frac{P_d}{\omega_m} = \frac{P_{ag}}{\omega_s} \tag{2.21}$$

Under sinusoidal operation the total power is

$$P_{in} = 3\left(\frac{V_{l-l}}{\sqrt{3}}\right) I_s \cos\varphi\,, \tag{2.22a}$$

Or

$$P_{in} = 3V_1 I_s \cos\varphi = \sqrt{3}V_{l-l} I_s \cos\varphi\,. \tag{2.22b}$$

Where the power factor is given by

$$\mathrm{Pf} = \frac{P_{in}}{V_1 I_s} = \frac{V_1 I_s \cos\varphi}{V_1 I_s} = \cos\varphi\,. \tag{2.23}$$

The motor efficiency is the ratio of its mechanical output power to its electrical input power.

$$\eta = \frac{Pout}{Pin} = \frac{Pin - \sum losses}{Pin} = \frac{Pout}{Pout + \sum losses}\,, \tag{2.24}$$

$$\sum losses = P_{SCL} + P_{RCL} + P_{Fe} + P_{FW} + P_{STRAY}$$

Where

P_{SCL} are the stator copper losses in watts.

P_{RCL} are rotor copper losses in watts.

P_{Fe} are the core losses in watts.

P_{FW} are the friction and windage losses in watts.

P_{stray} are the stray load losses in watts.

Given the total copper losses, stator and rotor acceptable, other (non copper) losses can be estimated with reasonable accuracy for the present purpose by using an empirical rule [9], the core losses are made equal to the rotor copper loss, the mechanical losses, friction and windage losses can be estimated to be equal to 10%-15% of the total losses. The stray load losses are estimated to be equal to 5%-10% of the total power loss [10].

2.5 Theveninized circuit

The thevenin theorem is useful in making calculations easier without loosing accuracy. The thevenin equivalent circuit of that of the figure 2.5 is shown in figure 2.6.

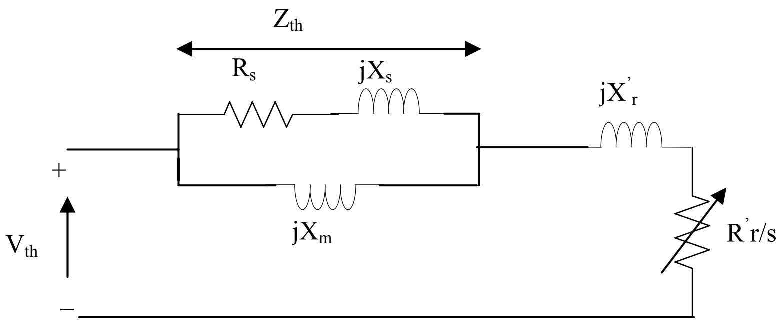


Fig 2.6 Thevenin Equivalent Circuit of Induction Motor

Where,

$$V_{th} = V_1 \frac{jX_m}{j(X_s + X_m)} = V_1 \frac{X_m}{X_s + X_m}, \tag{2.25}$$

And,

$$Z_{th} = \frac{jX_m(R_s + jX_s)}{R_s + j(X_s + X_m)} = \frac{R_s X_m}{X_s + X_m} + j\frac{X_m X_s}{X_s + X_m}, \tag{2.26}$$

$$Z_{th} = jX_1 + R_1 .$$

The stator current at starting is obtained by putting $s = 1$

$$I_{st} = \frac{V_{th}}{R_1 + R'_r + j(X_1 + X'_r)} \tag{2.27}$$

The electromagnetique torque T_{em} is given by

$$T_{em} = 3\frac{R'_r |I'r|^2}{\omega_m}\left(\frac{1-s}{s}\right) \tag{2.28a}$$

By substituting (2.13) in (2.28a) we find

$$T_{em} = \frac{3R'_r V_{th}^2}{s\omega_s((R_1 + R'_r / s)^2 + (X_1 + X_r)^2)} \tag{2.28b}$$

The starting torque is given by equation (2.28b) with s=1

$$T_{st} = \frac{3R'_r V_{th}^2}{\omega_s((R_1 + R'_r)^2 + (X_1 + X_r)^2)} \tag{2.29}$$

We can derive the maximum torque at the maximum slip by differentiating the torque equation with respect to s and setting the result equation to zero. $\frac{dT_{em}}{ds} = 0$

The slip at which torque is maximum is given by

$$s_m = \frac{R'_r}{\sqrt{(R_1^{\ 2} + X_e^{\ 2})}} \tag{2.30}$$

Where, $X_e = X_1 + X_r$

Replacing the expression of s_m in the torque equation, the maximum torque is obtained as:

$$T_{\max} = \frac{3V_{th}^{\ 2}}{2\omega_s}\left[\frac{1}{R_1 + \sqrt{R_1^{\ 2} + (X_1 + X_r)^2}}\right] \tag{2.31}$$

Equation (2.31) indicates that T_{max} is independent of the rotor resistance. This feature has been used to vary the speed of the wound rotor induction motor.

2.6 Standard designs of induction motors

Polyphase squirrel-cage ac motors are basically constant-speed machines, but some degree of flexibility in operating characteristics results from modifying the rotor slot design. These variations in ac motors produce changes in torque, current, and full-load speed. Evolution and standardization have resulted in four fundamental types of ac motors.

The NEMA standards mainly specify four design types for AC induction motors, Design A, B, C and D, [11] depending on the relationship between torque and speed, their basic features are given in table 2.1. NEMA Design A is a variation of Design B having higher locked rotor current. Design E is similar to Design B, but has a higher efficiency, high starting currents and lower full-load running currents [11], [12]. Their typical torque-speed curves are shown in Figure 2.6 [13].

NEMA Design	**Starting current**	**Locked rotor**	**Break-down torque**	**% Slip**	**Applications**
A, B	Medium	Medium Torque	High	Max. 5%	low inertia, high acceleration (fans, blowers, centrifugal pumps and machine tools)
C	Medium	High torque	Medium	Max. 5%	High starting torques, compressors crushers, boring mills, conveyor equipment, textile machinery, wood working equipment.
D	Medium	Extra high torque	low	5% or more	Bulldozers, shearing machines, punch presses, stamping machines, hoists.

Table 2.1 NEMA torque designs for polyphase motors

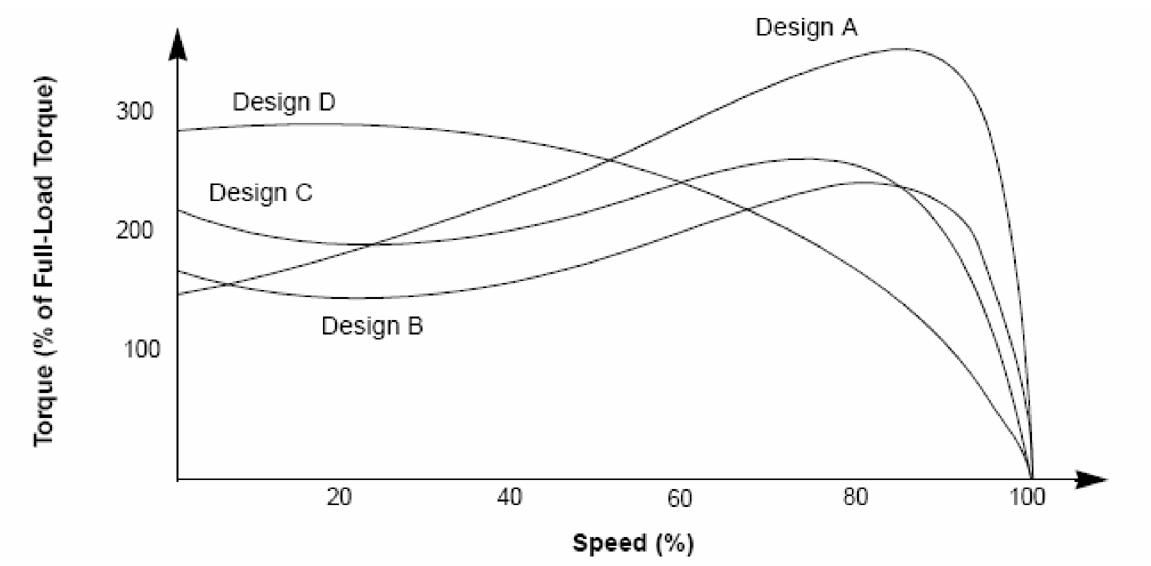


Fig 2.6 Torque speed curves of different NEMA standard motors [13]

2.7 Computation of the induction motor performance

Using the per phase analysis described in the previous section the torque, stator current, power factor, and efficiency versus speed under sinusoidal balanced supply operation for a 3 hp, 50 hp, 500 hp and 2250 hp squirrel cage induction motors which are found in appendix A.

2.7.1 A 3 hp induction motor characteristics

In figure (2.7), the torque, stator current speed characteristics are shown for the 3 hp induction motor.

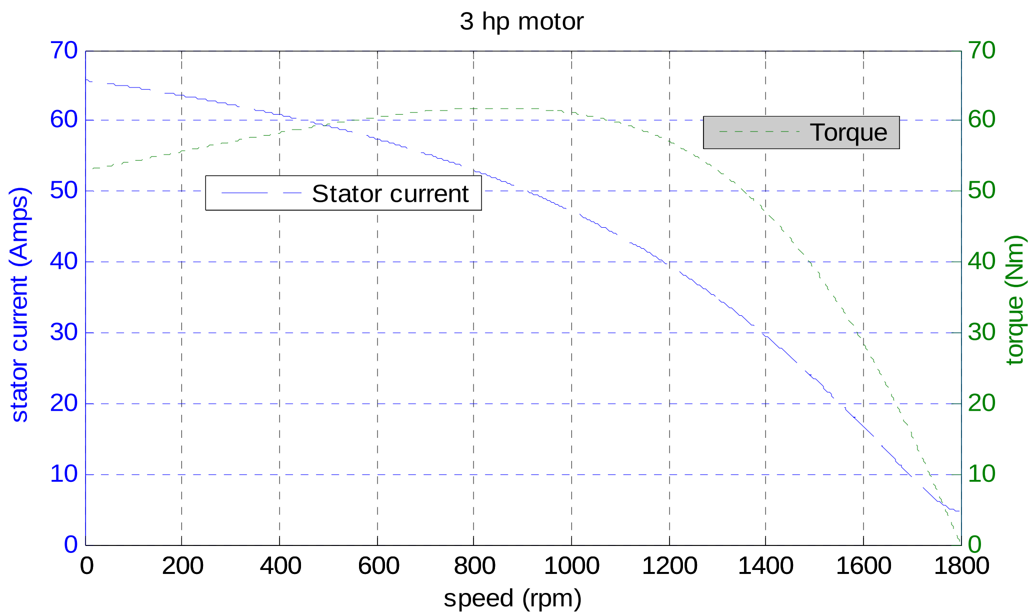


Fig 2.7 3 hp motor torque and stator current speed characteristics

The power factor and efficiency speed characteristics are shown for the 3 hp induction m otor in figure 2.8.

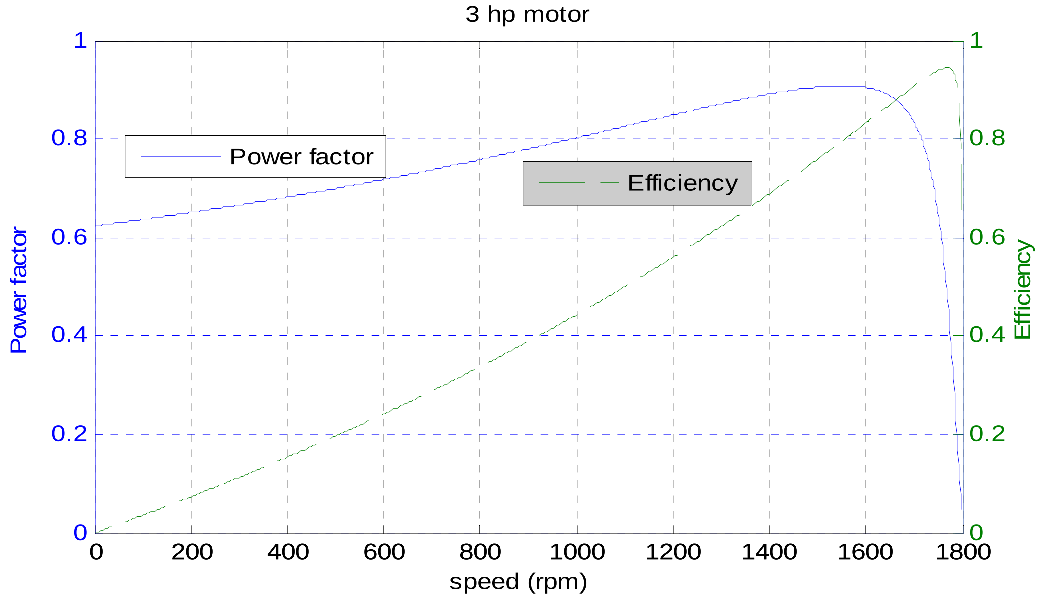


Fig 2.8 3 hp motor power factor and efficiency speed characteristics

2.7.2 A 50 hp induction motor characteristics

In figure (2.9), the torque, stator current speed characteristics are shown for the 50 hp induction motor.

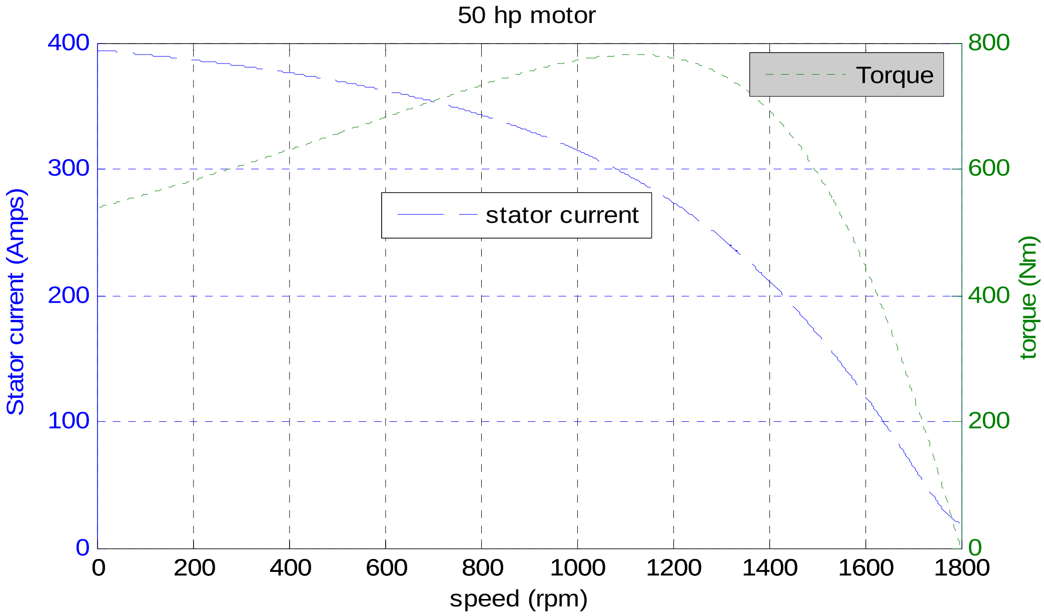


Fig 2.9 50 hp motor Torque and stator current speed characteristics

The power factor and efficiency speed characteristics are shown for the 50 hp induction motor in figure 2.10.

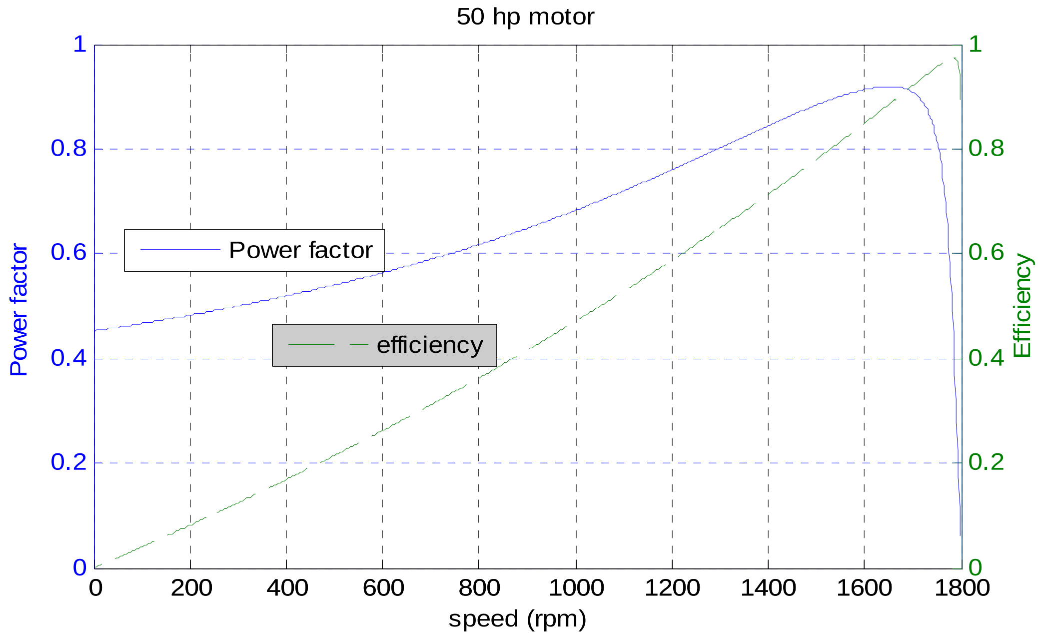


Fig 2.10 50 hp motor power factor and efficiency speed characteristics

2.7.3 A 500 hp induction motor characteristics

In figure (2.11), the torque, stator current speed characteristics are shown for the 500 hp induction motor.

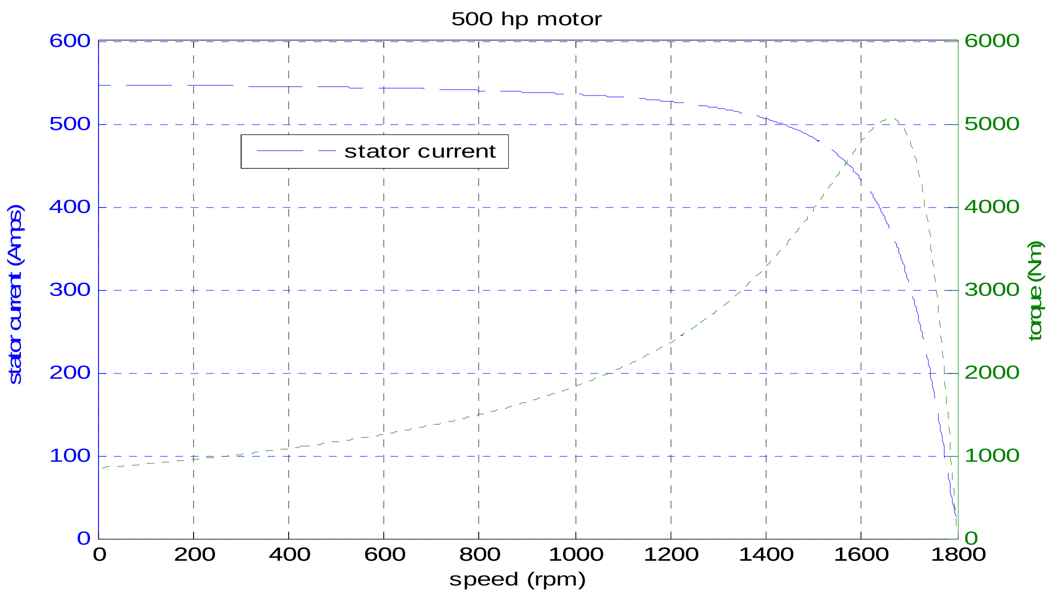


Fig 2.11 500 hp motor torque and stator current speed characteristics

The power factor and efficiency speed characteristics are shown for the 500 hp induction motor in figure 2.12.

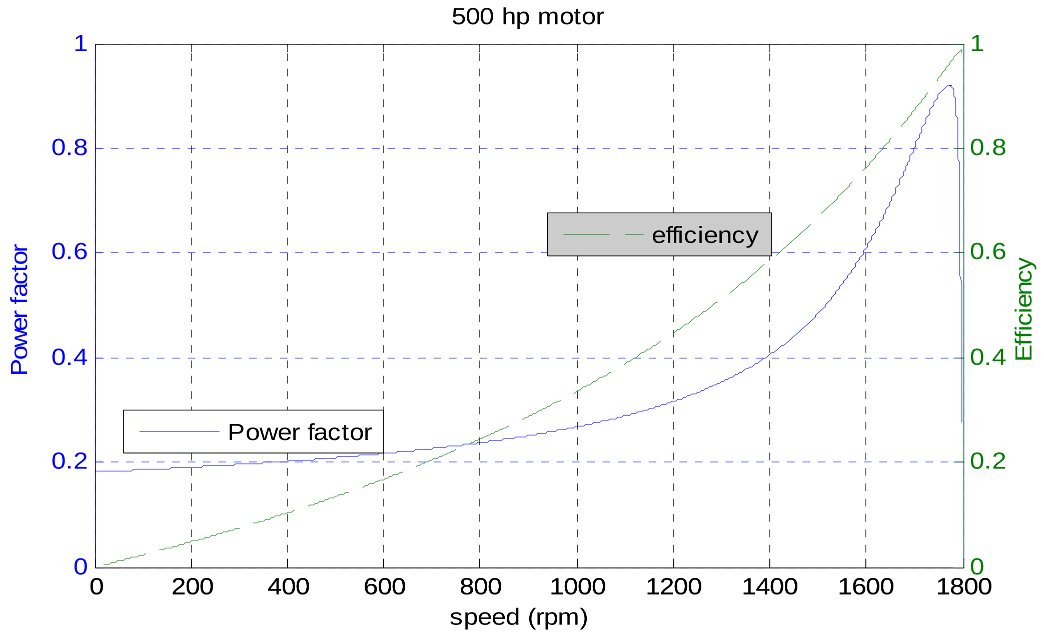


Fig 2.12 500 hp motor power factor and efficiency speed characteristics

2.7.4 A 2250 hp induction motorcharacteristics

The figure (2.13) shows the torque, stator current speed characteristics for the 2250 hp induction motor.

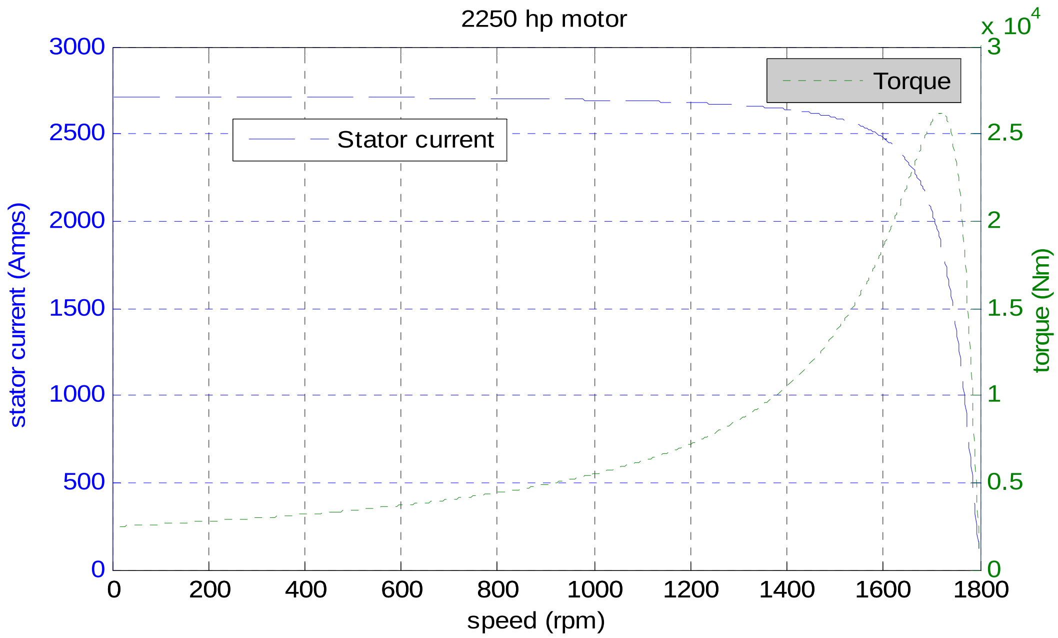


Fig 2.13 2250 hp motor torque and stator current speed characteristics

The power factor and efficiency speed characteristics are shown for the 2250 hp induction motor in figure 2.14.

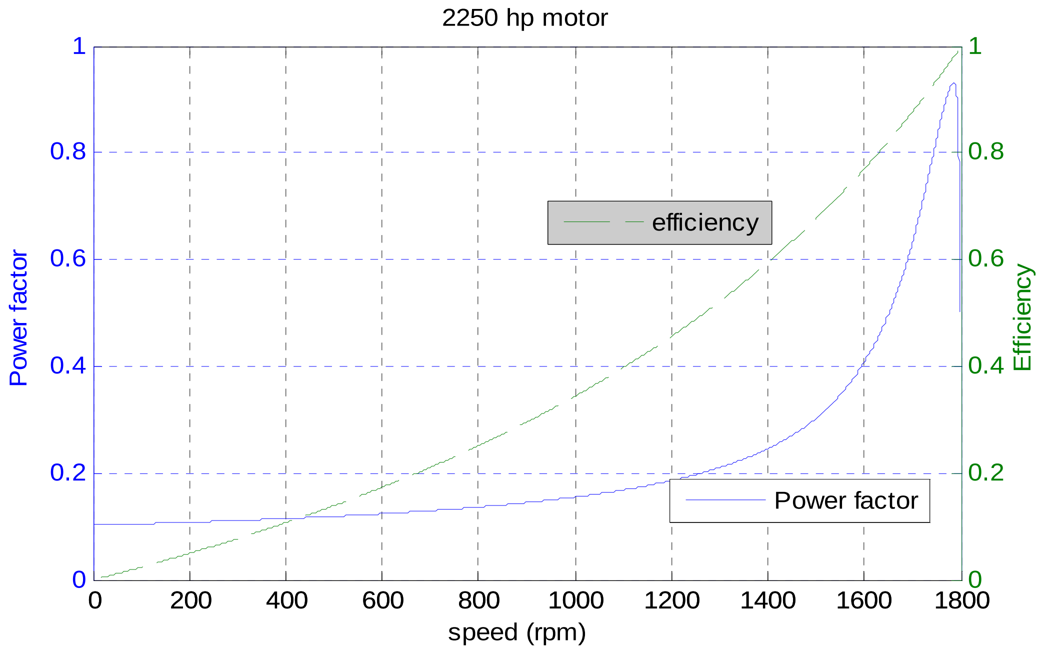


Fig 2.14 2250 hp motor power factor and efficiency speed characteristics

2.8 Conclusion

In this chapter, the steady state analysis of induction motors performances under sinusoidal balanced supply condition of different power level motors has been carried out; torque, input current, power factor and efficiency speed characteristics have been calculated and plotted.

The starting current of a motor will drop very slowly as the motor accelerates and will only begin to fall significantly when the motor has reached at least 75% full speed.

The starting torque of an induction motor will drop a little to the minimum torque as the motor accelerates, then rises to a maximum torque at almost full speed and then drop to zero at synchronous speed.

The actual curves for induction motors can vary considerably depending on the terminal voltage and the motor rotor designs, but the general trend is for a high current until the motor reaches the rated speed.

The power factor of the motors at starting is small, rising to a maximum as the motors accelerate, and then falling again as the motors approach full speed.

The efficiency of the motors at starting is typically zero with no losses, and then increases to a maximum as the motors accelerate then decreases when the motors reach the full speed.

Assuming no saturation the power factor and efficiency are acceptable near full load operation about 75% full loads; they increase as the motor power level increase.

According to the results obtained, the design of each machine can be identified. The 3 hp motor is of the design D, the 50 hp motor is of the design A whereas the 500 hp and 2250 hp motors are of the design B.

3

CHAPTER 3

THREE PHASE UNBALANCED SUPPLY VOLTAGE DEFINITIONS AND SOME PRELIMINARY CALCULATIONS

3.1 Introduction

In a three-phase system, voltage unbalance takes place when the magnitudes of phase or line voltages are different and the phase angles differ from the balanced conditions, or both. There are three definitions of unbalanced voltage factor; these definitions have important implications when studying the effects of voltage unbalance on the performance of three-phase induction machines. What can be regarded as an extreme case of unbalanced operation of a three phase induction motor is that resulting from a one phased supply which is called single phasing. It will be considered in a later chapter.

3.2 Causes and effects of unbalanced voltages

A voltage unbalance occurs when the voltages of a three phase supply are not equal. It can result from unbalanced three phase loads due to unevenly distributed single-phase loads as shown in figure 3.1, malfunctions of automatic power factor correction equipment and voltage regulators in the distribution lines, from unbalanced transformer or capacitor banks (caused by blown fuses) or single phasing conditions, or from unequal lengths of three phase cables [14].

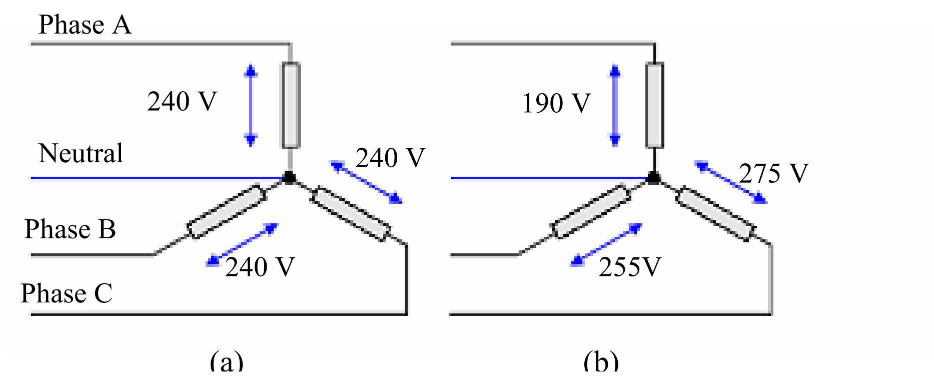


Fig 3. 1 (a) balanced, (b) unbalanced load

The primary concern of voltage unbalance is the heating effect of motors. Voltage unbalance results in additional negative-sequence current circulating in motor rotors. This current can cause the rotor of a motor to quickly overheat. A relatively small voltage unbalance will cause a considerably larger current unbalance. In the phase with the highest current the percentage of the temperature rise will be approximately two times the square of the percentage of voltage unbalance [15]. To illustrate the severity of this condition an approximate 3.5% voltage unbalance will cause an approximate 25% increase in temperature rise [16].

3.3 Definitions of Voltage Unbalance

There are three definitions of voltage unbalance in the nowadays. These definitions are stated and analyzed below.

3.3.1 NEMA (National Equipment Manufacturer's Association) Definition [17], [18]

The NEMA definition of voltage unbalance, also known as the Line Voltage Unbalance Rate (LVUR), is given by

$$\%\mathrm{LVUR}=\frac{\max \textit{voltage deviation from the average line voltage}}{\textit{average line voltage}}\times 100 \tag{3.1}$$

The NEMA definition assumes that the average voltage is always equal to the rated value, it works only with magnitudes, and phase angles are not included.

3.3.2 IEEE Definition [17]

The IEEE definition of voltage unbalance, also known as the Phase Voltage Unbalance Rate (PVUR), is given by

$$\%\mathrm{PVUR}=\frac{\max \textit{voltage deviation from the average phase voltage}}{\textit{average phase voltage}}\times 100 \tag{3.2}$$

The IEEE definition is the same as the NEMA one, the only difference being that the IEEE uses phase voltages rather than line-to-line voltages. Here again, phase angle information is discarded since only magnitudes are considered.

3.3.3 IEC Definition [18], [19]

The IEC definition of voltage unbalance also known as the true definition of voltage unbalance is defined as the ratio of the negative sequence voltage component to the positive sequence voltage component. The percentage voltage unbalance factor (% VUF), or the so called true definition, is given by

$$\%\mathrm{VUF}=\frac{\textit{negative sequence voltage component}}{\textit{positive sequence voltage component}}\times 100=\frac{V_n}{V_p}\times 100 \tag{3.3}$$

The positive sequence voltage component V_p and negative sequence voltage component V_n are obtained by resolving three-phase unbalanced line voltages V_{ab} , V_{bc} , and V_{ca} (or phase voltages) into two symmetrical components V_p and V_n (of the line or phase voltages). The two balanced components are given by:

$$V_p = \frac{V_{ab} + aV_{bc} + a^2 V_{ca}}{3} \tag{3.4}$$

$$V_n = \frac{V_{ab} + a^2 V_{bc} + aV_{ca}}{3} \tag{3.5}$$

Where $a = 1\angle 120^\circ$;

$a^2 = 1\angle 240^\circ$;

The positive and negative sequence voltages can be used when analyzing induction motor behaviour under unbalanced conditions.

An extension of the VUF is the complex voltage unbalance factor (CVUF) that is defined by the ratio of the negative sequence voltage phasor to the positive sequence voltage phasor [20]. The CVUF is a complex quantity having the magnitude and the angle in the form of:

$$CVUF = \frac{V_n}{V_p} = k_v .e^{j\theta_v} \tag{3.6}$$

Where k_v refers to magnitude and θ_v to the angle of the CVUF.

The IEC definition involves both magnitude and angles (complex algebra) when calculating the positive and negative sequence voltage components, the empirical formula given by equation (3.7) avoids the use of the complex algebra but gives a good approximation of the true definition [17].

$$\%\ voltage\ unbalance = \frac{82.\sqrt{V^2_{abe} + V^2_{bce} + V^2_{cae}}}{average\ line\ voltage} \tag{3.7}$$

Where

V_{abe} is the difference between the line voltage V_{ab} and the average line voltage.

V_{bce} is the difference between the line voltage V_{bc} and the average line voltage.

V_{cae} is the difference between the line voltage V_{ca} and the average line voltage.

3.4 Voltage unbalance calculations according to the three definitions

The following example shows how to use the three definitions of voltage unbalance given above. Suppose three unbalanced line-to-line voltages are applied to an induction machine.

$$V_{ab} = 576\angle 0^\circ$$

$$V_{bc} = 480\angle 221.4^\circ$$

$$V_{ca} = 384\angle 124.2^\circ$$

The average value of the magnitudes will be

$$(576 + 480 + 384)/3 = 480 \text{ V}$$

Hence, the maximum deviation from average value is

$$(576 - 480) = 96 \text{ V}$$

Therefore, the percent voltage unbalance according to NEMA definition will be

$$100\,(96/480) = 20\%$$

The positive sequence voltage is

$$V_p = 473.1\angle -5.04^\circ$$

The negative sequence voltage is

$$V_n = 112.6\angle 21.74^\circ$$

According to the above three unbalanced voltages, the percent voltage unbalance according to IEC definition will be

$$100\,(112.6/473.1) = 23.8\%$$

Applying the approximate formula to the above example results in

$$V_{abe} = (576 - 480) = 96$$

$$V_{bce} = (480 - 480) = 0$$

$$V_{cae} = (480 - 384) = 96$$

Therefore percent voltage unbalance will be: $82\,(135.8/480) = 23.2\%$

This value is close to the IEC voltage unbalance of 23.8%. The induction machine will respond to the true value of voltage unbalance, but NEMA definition of voltage unbalance will be assuming 20% unbalance for the same set of voltages.

3.5 Simulation results

In order to understand the implications of using these definitions of voltage unbalance, an analysis was conducted. Since the IEEE and NEMA definitions are similar and the derating curve is based on NEMA, it was decided to compare the NEMA definition with the approximation of the IEC definition of voltage unbalance.

Suppose V_{ab}, V_{bc}, V_{ca} are three unbalanced voltages with

$$\begin{cases} V_{ab} = V_{ab}\angle 0^o \\ V_{bc} = V_{bc}\angle \theta_b \\ V_{ca} = V_{ca}\angle \theta_c \end{cases} \tag{3.8}$$

For a given voltage unbalance based on NEMA definition, for example 10% voltage unbalance and assuming an average voltage of 460 V and choosing the voltage with the largest deviation from the average to be V_{ab}

Then $$V_{ab} - 460 = 0.1 \times (average\ \ voltage)$$

Then

$$V_{ab} = 506\ \ Volts \tag{3.9}$$

$$The\ \ average\ \ voltage = \frac{V_{ab} + V_{bc} + V_{ca}}{3} = 460\ \ \text{V}$$

And

$$V_{bc} + V_{ca} = 874\,\text{V} \tag{3.10}$$

Then

$$V_{ca} = 874 - V_{bc}$$

We can write

$$\left|V_{bc} - 460\ V\right| < 46\ V$$

$$\left|V_{ca} - 460\ V\right| < 46\ V$$

$$414\ V > V_{ba} < 460\ V$$

And

$$414\ V < V_{ca} < 460\ V$$

The vector sum of the line voltages is

$$\overline{V_{ab}} + \overline{V_{bc}} + \overline{V_{ca}} = 0$$

Or $$V_{ab}\angle 0° + V_{bc}\angle\theta_b + V_{ca}\angle\theta_c = 0$$

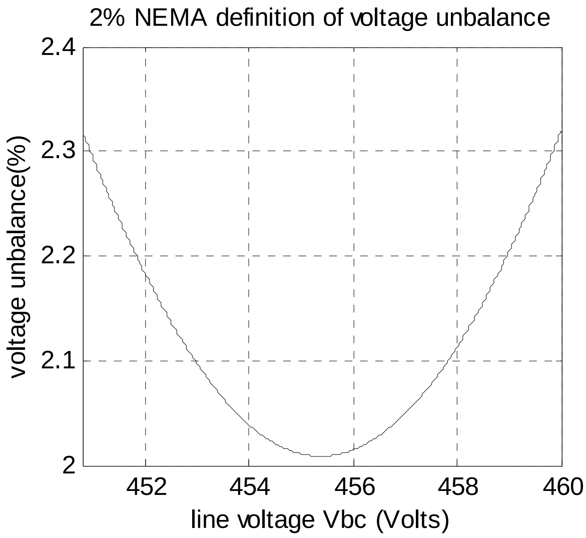
Further $$506 + V_{bc}\cos(\theta_b) + jV_{bc}\sin(\theta_b) + (874 - V_{bc})\cos(\theta_c) + j(874 - V_{bc})\sin(\theta_c) = 0 \qquad (3.11)$$

So for a given V_{bc}, angle θ_b and angle θ_c can be obtained from equation 3.11 by separating it into two parts, real and imaginary, and solving the two equations.

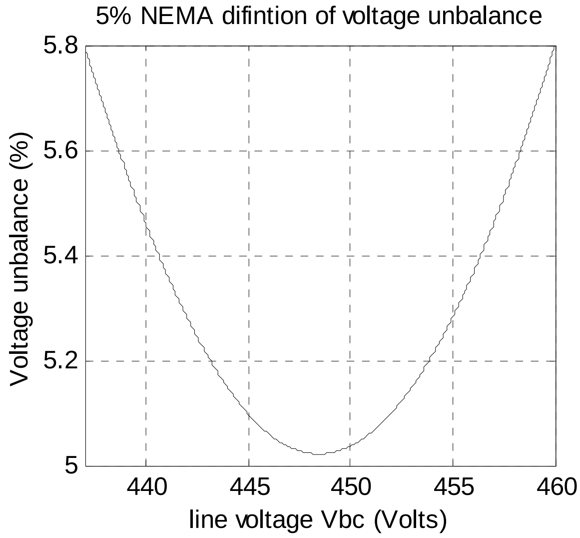
From the above calculations, the approximation formula of the IEC definition of voltage unbalance will be given by

$$\%\ voltage\ unbalance = \frac{82\sqrt{(506-460)^2 + (V_{bc}-460)^2 + ((874-V_{bc})-460)^2}}{460} \qquad (3.12)$$

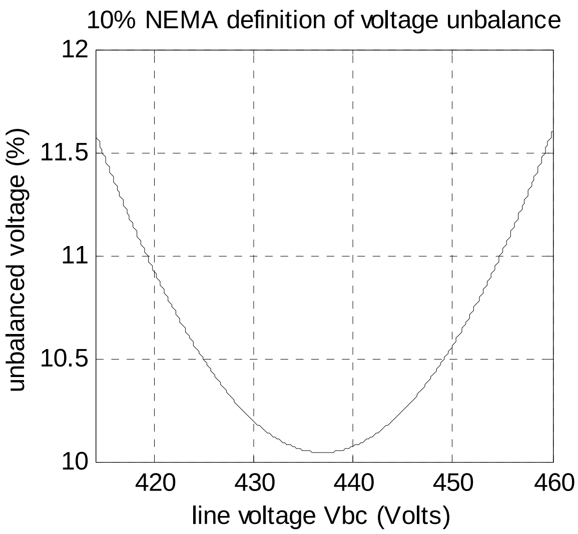
From this analysis, it is found that for a given value of percent unbalance, based on the NEMA definition, there is range of percent unbalance based on the approximation formula of the true definition. This is shown in Figure 3.2 for 2%, 5%, 10%, and 20% NEMA definition of voltage unbalance.



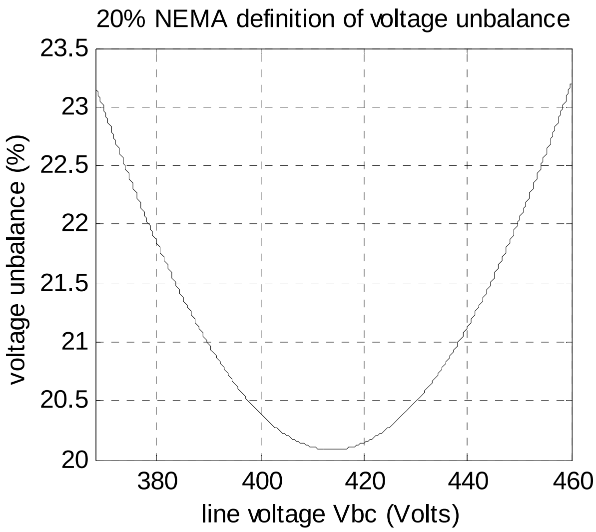
(a)



(b)



(c)



(d)

Fig 3.2 Relationship between the IEC definition of voltage unbalance and NEMA definition for (a) - 2%, (b) - 5%, (c)-10%, and (d)-20% values of NEMA unbalance

Figure 3.2.(a) shows that for a 2% NEMA unbalance the approximation formula true definition range from 2% to 2.32%. For 5% NEMA voltage unbalance shown in Figure 3.2.(b) with the approximation formula, the percent unbalance starts to increase slightly from 5% to 5.8%.

Figures 3.2.(c) and 3.2.(d) show that as the percentage NEMA unbalance increases, the range of the approximation formula is in between the 0.3% to 0.8%.

The difference between the NEMA definition and the approximation formula can differ substantially when the voltage unbalance is extremely high, as shown in Figure 3.2. (d).

Table 3.1 shows the range of the approximation formula of the IEC definition of the percentage unbalance obtained at 2%, 5%, 10%, and 20% NEMA unbalance.

NEMA	**IEC**
%	%
2	2 - 2.3
5	5 - 5.8
10	10 - 11.6
20	20 - 23.2

Table 3.1 Range of voltage unbalance

Below 5% NEMA unbalance, the maximum difference between the NEMA and the true definition is 0.8%. Above that, say 20%, the difference can be as high as 3.8%. The motor will respond to the true value of 23.8%, but NEMA will be assuming a 20% unbalance.

3.6 Conclusion

In this chapter three definitions of voltage unbalance have been described. An analysis was done to show how these definitions are related. It was found that for a given NEMA unbalance, there is a range of unbalance based on the approximation formula of the IEC definition. Below 5% unbalance, the difference between the NEMA definition and the IEC definition is very small 0.8%.

The difference between the NEMA definition of voltage unbalance and the IEC definition can differ substantially when the voltage unbalance is extremely high (say 20%).

4

CHAPTER 4

EFFECTS OF UNBALANCED VOLTAGE SUPPLY ON INDUCTION MOTORS

4.1 Introduction

In many routine power engineering calculations, balanced conditions are assumed. In a balanced three-phase power system, the negative and zero sequence values are zero. This effectively simplifies a three-phase system into a single-phase system for the purposes of various calculations. However, unbalanced conditions with the presence of negative and zero sequence components are a reality in modern power systems [21]. The zero-sequence component is zero; this is often the case since the machines are typically connected Delta or ungrounded Wye [22]. Therefore the operating conditions are determined by the complete analysis of the positive and negative sequence networks.

Voltage unbalance can be considered an abnormality of the power supply system; an unbalanced three-phase voltage causes three-phase motors to draw unbalanced current, which can cause the rotor of a motor to overheat. In fact, the temperature rise caused by unbalanced current is much greater than the rise caused by balanced current.

The negative-sequence impedance of the motor is very small compared with its positive sequence impedance; hence the motor is very sensitive to the negative-sequence voltage. A low level of negative-sequence voltage can produce a significant level of negative sequence current. When line voltages applied to a polyphase induction motor are not exactly the same, unbalanced currents will flow in the stator windings, whose magnitudes depending upon the amount of unbalance. A small amount of voltage unbalance may increase the current to an excessive amount.

Unbalanced currents lead to torque pulsations, increased vibrations and mechanical stresses, increased losses, and hence motor overheating, which results in a shorter winding insulation life [23], [24]. To avoid possible damage to the motor, the motor must be derated. NEMA Standard *MG 1-14.35* recommends derating an induction motor when the voltage unbalance exceeds one percent and recommends not operating a motor when the voltage unbalance exceeds five percent.

The temperature difference relative to the ambient temperature is called the temperature rise. The temperature rise of a machine is not only dependent on the losses but also on the ambient temperature and the coolant temperature. The cooling is generally provided to increase the operating range of the machine without exceeding the temperature limits of the parts such as insulations.

A relatively small unbalance in voltage will cause a considerable increase in temperature rise. In the phase with the highest current, the percentage increase in temperature rise will be approximately two times the square of the percentage voltage unbalance [15], [25]. The increase in losses and consequently, the increase in average heating of the whole winding will be slightly lower than the winding with the highest current [25].

4.2 Induction Motor Modeling under Unbalanced Supply

Three phase unbalanced supply voltage can be modeled using the symmetrical component theory. Each set of positive and negative sequence voltages produce corresponding balanced currents in the induction motor, and the synthesis of the two sets of current vectors represents the actual currents produced in the three stator phases by the original unbalanced voltages.

The behavior of the machine due to the positive sequence voltage is essentially the same as for normal balanced operation [15]. Whereas the negative sequence currents 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. The motor behaves as the addition of two separate motors, one running at slip **s** with a terminal voltage of V_p per phase and the other running with a slip of **(2-s)** and a terminal voltage of V_n [26] . The equivalent circuits of the induction motor for each sequence are shown in figures 4.1 and 4.2.

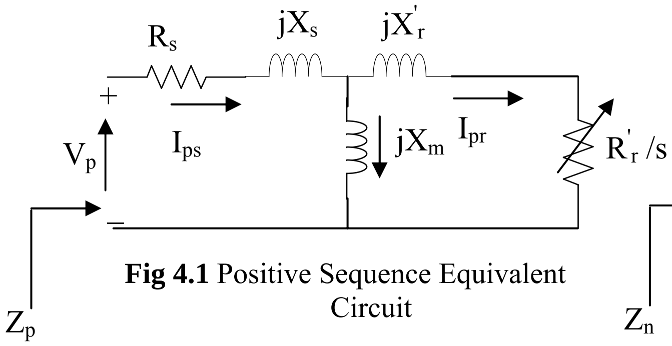


Fig 4.1 Positive Sequence Equivalent Circuit

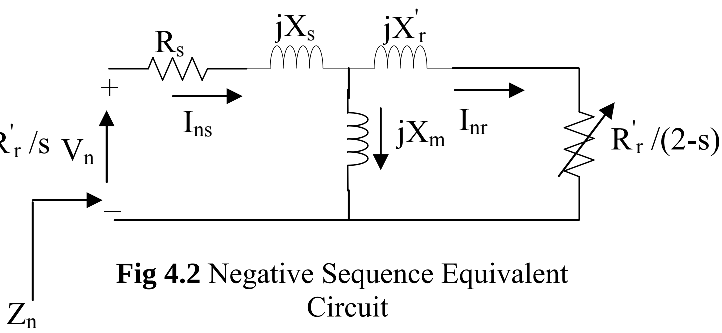


Fig 4.2 Negative Sequence Equivalent Circuit

Where

V_p : is the positive sequence voltage.

V_n : is the negative sequence voltage.

R_s: is the stator resistance.

R'_r: is the rotor resistance referred to stator.

Z_p: is the positive sequence impedance.

X_s: is the stator reactance.

X'_r: is the rotor reactance referred to stator.

X_m: is the magnetizing reactance.

S: is the slip.

Z_n : is the negative sequence impedance.

To make easy our analysis, the following simplifying assumptions are made [24]

(A) All the circuit parameters in figures 4.1 and 4.2 are constant**;**

(B) The mechanical losses, friction and windage losses, are neglected;

(C) For convenience the positive-sequence voltage is constant while the negative-sequence voltage is variable.

The phase voltages of the motor are V_a**,** V_b and V_c. The corresponding zero- positive- and negative-sequence components (V_0**,** Vp and V_n,) of the voltages are given by

$$\begin{bmatrix} V_0 \\ V_p \\ V_n \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} . \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (4.1)$$

Where a is the Fortescue operator given by $a = \exp\left(\frac{j2\pi}{3}\right)$.

The Voltage Unbalance Factor according to IEC definition is given by:

$$VUF = \left|\frac{V_n}{V_p}\right| \times 100\,\% \quad (4.2)$$

The positive-sequence currents of the stator and the rotor are given by:

$$I_{ps} = \frac{V_p (R_r + jsX_2)}{A_p + jB_p} \quad (4.3)$$

$$I_{pr} = \frac{V_p . jsX_m}{A_p + jB_p} \quad (4.4)$$

Where A_p and B_p are given by:

$$A_p = R_r R_s + s(X_m{}^2 - X_1 X_2) \quad (4.5)$$

$$B_p = R_r X_1 + sR_s X_2 \quad (4.6)$$

Where,

$$X_1 = X_m + X_s$$
$$X_2 = X_m + X_r$$

Likewise, the negative-sequence stator and rotor currents are given

$$I_{ns} = \frac{V_n (R_r + j(2-s)X_2)}{A_n + jB_n} \quad (4.7)$$

$$I_{nr} = \frac{V_n . j(2-s)X_m}{A_n + jB_n} \quad (4.8)$$

Where

$$A_n = R_r R_s + (2-s)(X_m{}^2 - X_1 X_2) \quad (4.9)$$

$$B_n = R_r X_1 + (2-s)R_s X_2 \quad (4.10)$$

The three-phase stator line currents are given by:

$$I_a = I_{ps} + I_{ns} \quad (4.11)$$

$$I_b = a^2 I_{ps} + aI_{ns} \quad (4.12)$$

$$I_c = aI_{ps} + a^2 I_{ns} \tag{4.13}$$

Where the three-phase rotor currents are given by:

$$I_{ra} = I_{pr} + I_{nr} \tag{4.14}$$

$$I_{rb} = a^2 I_{pr} + aI_{nr} \tag{4.15}$$

$$I_{rc} = aI_{pr} + a^2 I_{nr} \tag{4.16}$$

4.3 Current Unbalance Factor (CUF)

Because a given small amount of voltage unbalance will generally imply a comparatively larger current unbalance, it is in order to consider the Current Unbalance Factor (CUF).
When the stator voltages are unbalanced, the stator currents will also be unbalanced. The current unbalance factor is defined as [25]:

$$CUF = \left| \frac{I_n}{I_p} \right| \times 100\,\% \tag{4.17}$$

It is desirable to correlate the **VUF** to the **CUF** through the appropriate sequence motor impedances. The positive and negative sequence impedances of the motor can easily be obtained from equations (4.3) and (4.7) as:

$$Z_p = \sqrt{\frac{A_p^{\,2} + B_p^{\,2}}{R_r^{\,2} + (sX_2)^2}} \tag{4.18}$$

$$Z_n = \sqrt{\frac{A_n^{\,2} + B_n^{\,2}}{R_r^{\,2} + [(2-s)X_2]^2}} \tag{4.19}$$

The current unbalance factor CUF**,** can be expressed in terms of the voltage unbalance factor VUF and the motor positive- and negative-sequence impedances as:

$$CUF = \left| I_{ns} / I_{ps} \right| = \frac{V_n / Z_n}{V_p / Z_p} = (Z_p / Z_n) VUF \tag{4.20}$$

Interestingly, one can note that the ratio of the motor positive to negative-sequence impedances (Z_p / Z_n) can indeed be interpreted in a basically simple way as the sensitivity of current unbalance to voltage unbalance.

Under normal operating conditions, the positive-sequence impedance of a motor is much greater than its negative-sequence impedance [27]. This is easily verified by replacing parameters values into equations (4.18) and (4.19).

The ratio of current unbalance factor to voltage unbalance factor in terms of impedances can be expressed as

$$\frac{CUF}{VUF}=\frac{Z_p}{Z_n}=\sqrt{\frac{A_p{}^2+B_p{}^2}{A_n{}^2+B_n{}^2}}\cdot\sqrt{\frac{R_r{}^2+[(2-s)X_2]^2}{R_r{}^2+(sX_2)^2}} \tag{4.21}$$

It is a non linear function of slip only, assuming machine parameters stay constant.

A low level of voltage unbalance can result in a considerable level of motor line current unbalance. The rule of thumb for a standard-efficiency induction motor is that for every one percent of voltage unbalance, the resulting percent of current unbalance will be about five to six times as much.

For high efficiency motors, the current unbalance resulting from a given voltage unbalance can be even higher because of the motor lower resistance, especially with Design-E motors [28]. In other words, the problem of voltage unbalance and its corollary, the current unbalance will gain in importance with the expected large scale use of high efficiency induction motor in the near future in our country.

4.3.1 Illustrative example

An illustrative example is given using the data of a practical induction motor to show how to calculate the motor current unbalance resulting from voltage unbalance with different values of slip. The motor parameters are as follows:

Three-phase, Y connected, 220 V (line-to-line), 7.5 kW**,** 60 Hz, six poles.

The per phase equivalent circuit parameters in ohms per phase referred to the stator are:

R_s=0.294 **Ω**; R_r= 0.144 **Ω**;

X_s = 0.503 **Ω**; X_r = 0.209 **Ω**;

X_m=13.25 **Ω**.

To facilitate the analysis and to emphasize the influence of negative-sequence voltage, the positive-sequence component of the phase voltages has been assumed to be constant [24]. Hence, the negative-sequence voltage can be obtained directly from the voltage unbalance factor. $VUF=\left|\frac{V_n}{V_p}\right|\times 100\,\%$

Figure 4.3 shows the current unbalance factor caused by the voltage unbalance at per unit slip of **0.03**, **0.05** and **0.15**.

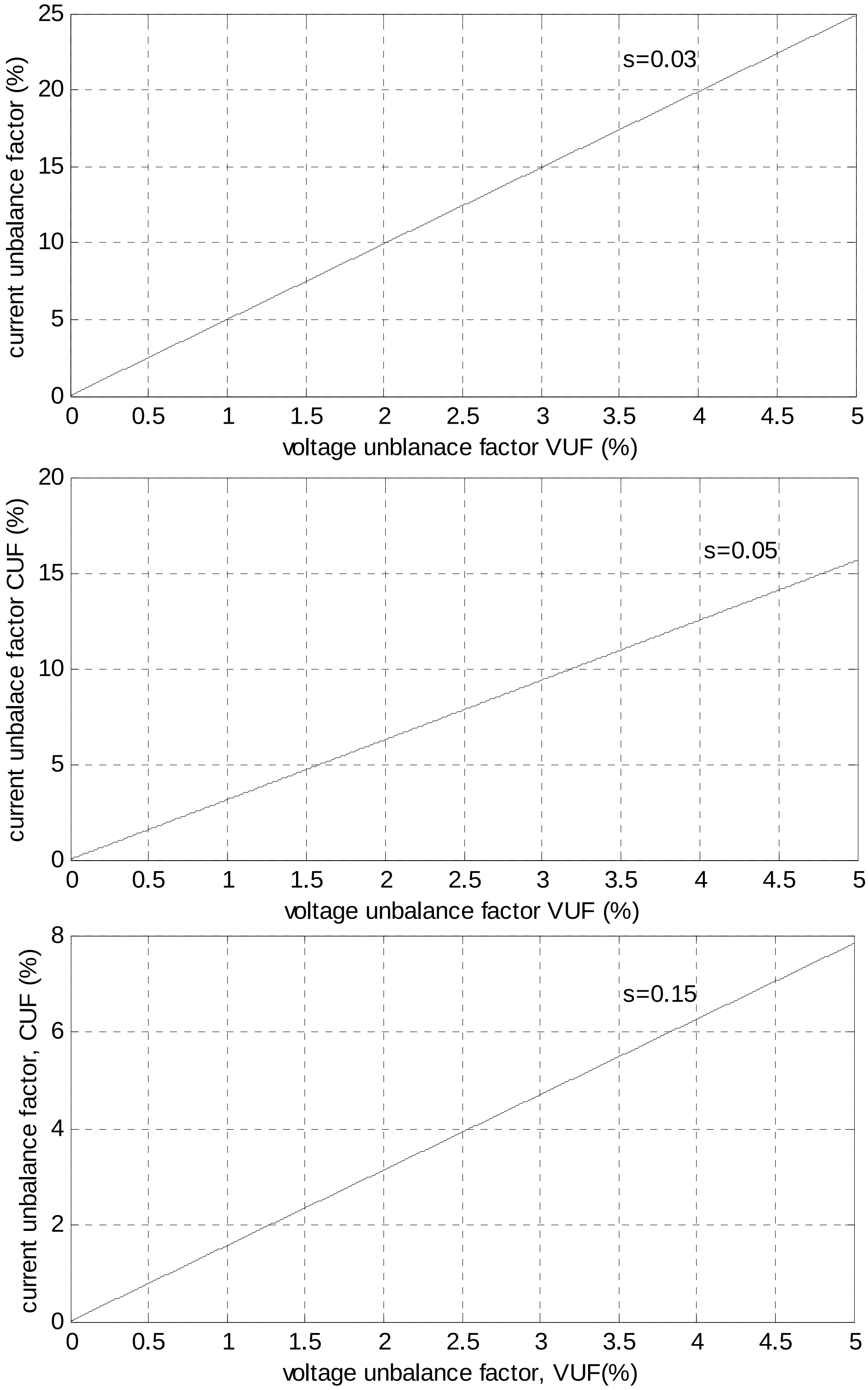


Fig 4. 3 Variation of current unbalance versus voltage unbalance factor at different slips

It is important to note that the current unbalance factor is higher under full load operation; at artificially higher slip, the correlation shows that current unbalance is not magnified. Figure 4.3 indicates that current unbalance effects are higher under most relevant operating conditions.

CUF when correlated to a given VUF is maximum at full load operation which would imply that losses are maximum, requiring attention.

4.4 Output Torque and Efficiency

As mechanical losses have been neglected, the motor output mechanical power includes the part produced by the positive-sequence voltage P_p, and the part by the negative-sequence voltage P_n [29]:

$$P_p = 3I_{pr}^{\ 2}\left(\frac{1-s}{s}\right)R_r \tag{4.22}$$

$$P_n = 3I_{nr}^{\ 2}\left(\frac{s-1}{2-s}\right)R_r \tag{4.23}$$

It is noted that P_n**,** is negative at normal slip because the rotor revolves in the opposite direction of the magnetic field produced by the negative-sequence current. The torques produced by the positive- and negative-sequence currents are respectively given by

$$T_p = \frac{P_p}{\omega_m} = \frac{P_p}{\omega_s(1-s)} = \frac{3I_{pr}^{\ 2}R_r}{s\,\omega_s} \tag{4.24}$$

$$T_n = \frac{P_n}{\omega_m} = \frac{P_n}{\omega_s(1-s)} = -\frac{3I_{nr}^{\ 2}R_r}{(2-s)\omega_s} \tag{4.25}$$

Where,

ω_m is the angular speed of the rotor in rad/sec.

ω_s is the synchronous speed in rad/sec**.**

The motor's net output torque is therefore

$$T = T_p + T_n = \frac{3R_r}{\omega_s}\left(\frac{I_{pr}^{\ 2}}{s} - \frac{I_{nr}^{\ 2}}{2-s}\right) \tag{4.26}$$

The motor input electrical power expressed in terms of the symmetrical components of voltage and current is

$$P_e = \mathrm{Re}\left[3.(V_p I_{ps}^{\ *} + V_n I_{ns}^{\ *})\right] \tag{4.27}$$

Where the asterisk (*) refers to the conjugate value. The motor efficiency is given by:

$$\eta = \frac{P_p + P_n}{P_e} \times 100\% \tag{4.28}$$

The power factor is the sum of the real powers for each phase over the sum of the apparent power for each phase.

$$power\ \ factor = \frac{P_a + P_b + P_c}{S_a + S_b + S_c} \tag{4.29}$$

Where P_a, P_b and P_c are the real powers for each phase,

S_a, S_b and S_c are the apparent power for each phase.

4.5 Effects of Unbalanced Voltage Supply on Induction Motor Characteristics

The steady state performance of the induction motor under unbalanced voltages is computed based on the two definitions of voltage unbalance factor is applied to induction motors of different power levels. The motors parameters appear in appendix [A].

The voltage unbalance according to the NEMA definition is the ratio of the maximum deviation from the average voltage which is assumed to be equal to the rated voltage, where line voltage V_{ab} is equal to the rated voltage, V_{bc} increases and V_{ca} decreases. The IEC definition is the ratio of negative sequence over the positive sequence voltage.

To facilitate the analysis the positive sequence voltage is assumed to be constant and equal to the phase voltage [24], and the negative sequence voltage can be obtained from the following

$$VUF = \left|\frac{V_n}{V_p}\right| \times 100\,\%$$

The line voltages and negative sequence voltage are taken such that the unbalance factor will not exceed **5%** which is the maximum voltage unbalance tolerated according to NEMA Standard MG1 12.45.1987 recommendation.

4.5.1 Effects of unbalanced voltages on motors torque

The presence of negative sequence currents due to unbalanced voltage creates a negative sequence torque which subtracts from the positive sequence torque to yield a net torque under unbalanced supply. On the left of the page plots in fig.4.4 through to 4.7 with a maximum value of voltage unbalance tolerated of 5% show a negligible effect on the steady state torque speed characteristics of the four different motors; even though slight difference from one motor to another . The effect remains negligible over the entire speed range and particularly over the negative slope part of the characteristics.

An abnormally very high voltage unbalance of 20%; for exceeding the maximum limit, show some appreciable decrease of torque for 3 hp and 50 hp motors; especially at starting (about 13% decrease), which therefore may affect starting time and protection schemes.

However the effect on normal full load operation is not substantial enough to require attention especially for the relevant part of the representing full load condition. This is further elaborated in figures 4.4 through to 4.7 on the right of the page.

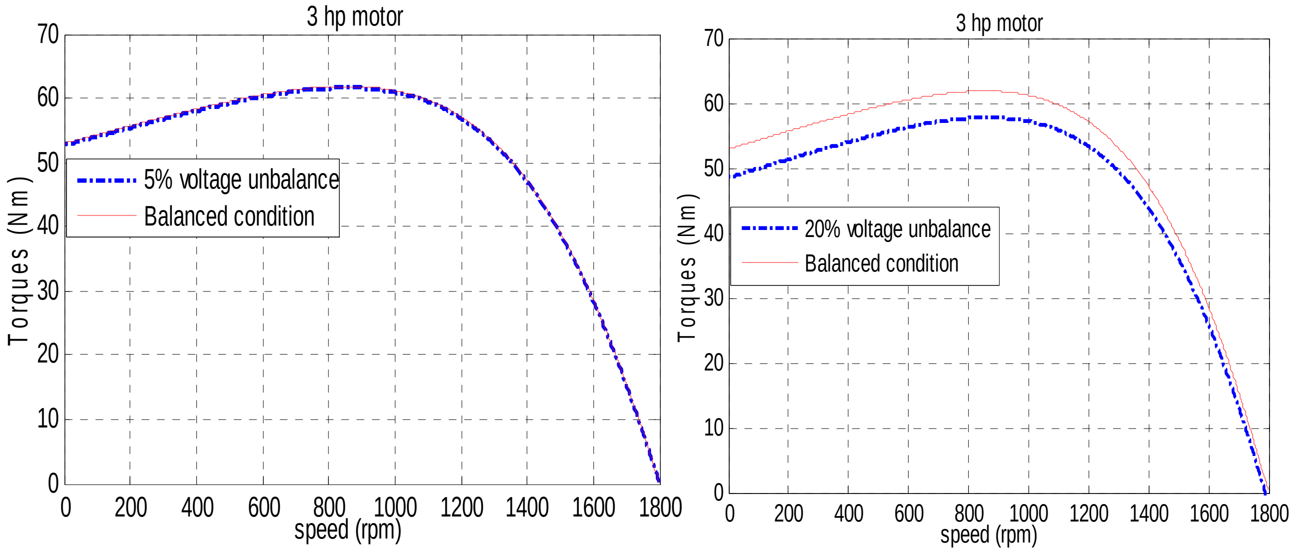


Fig.4.4 3 hp motor torques-speed characteristics for a balanced and unbalanced supply conditions

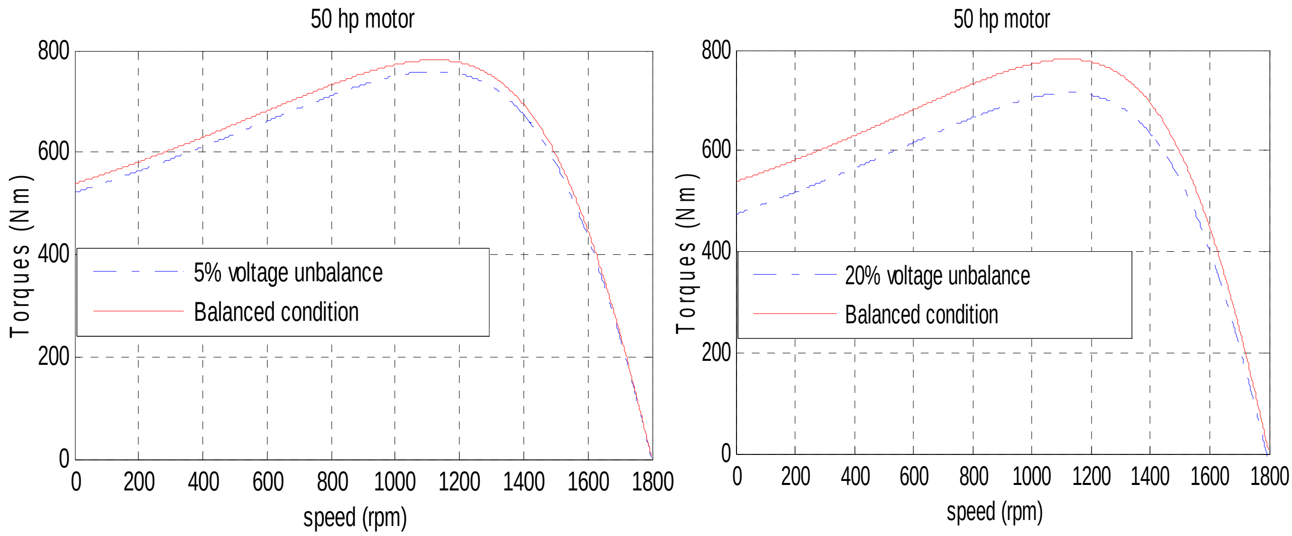


Fig.4.5 50 hp motor torques-speed characteristics for a balanced and unbalanced supply conditions

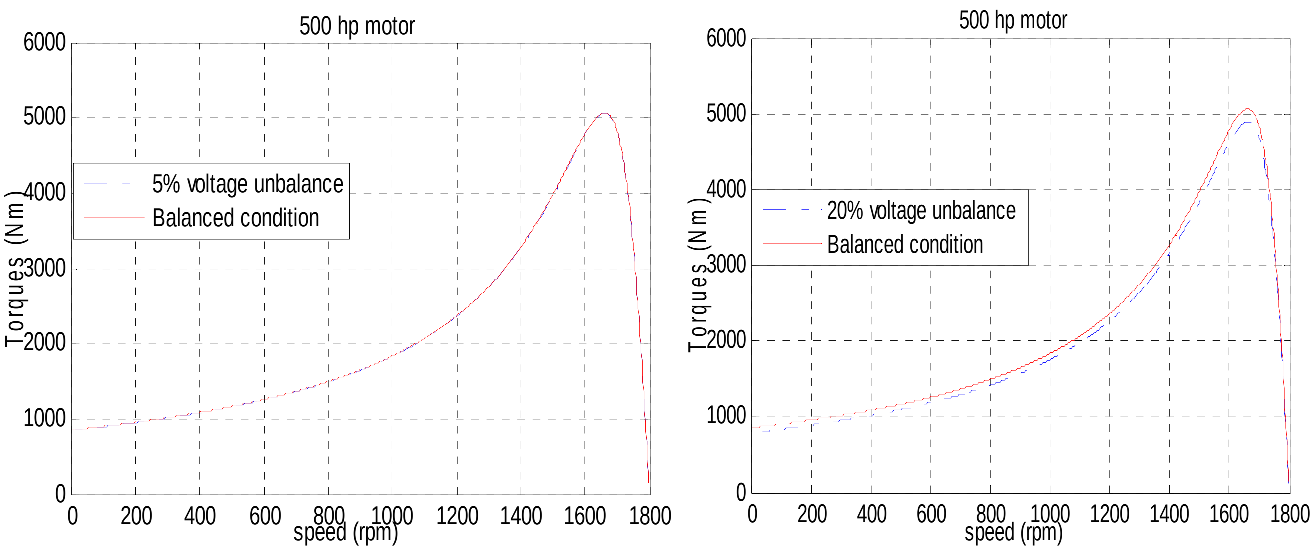


Fig.4.6 500 hp motor torques-speed characteristics for a balanced and unbalanced supply conditions

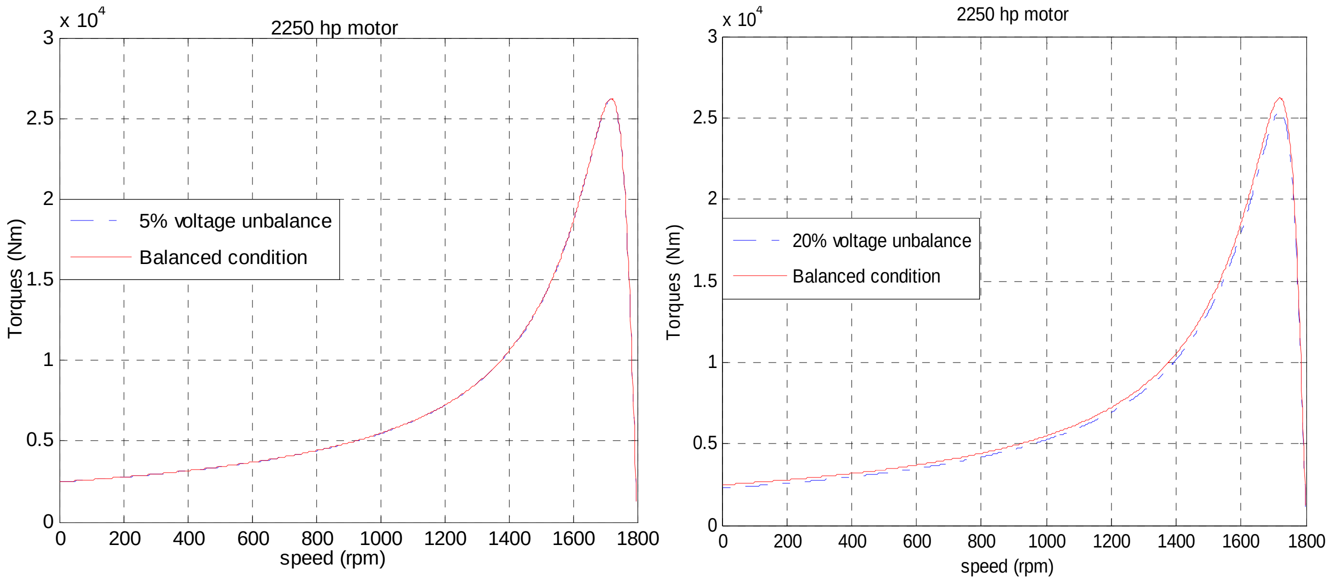


Fig.4.7 2250 hp motor torques-speed characteristics for a balanced and unbalanced supply conditions

The effects on motor torque are negligible over the normal load operation. However the starting and pull out torques are substantially affected. Though comparatively more important, the effect on the starting torque is still negligible not exceeding **0.6%** decrease according to the results shown in figures 4.8 through to 4.11.

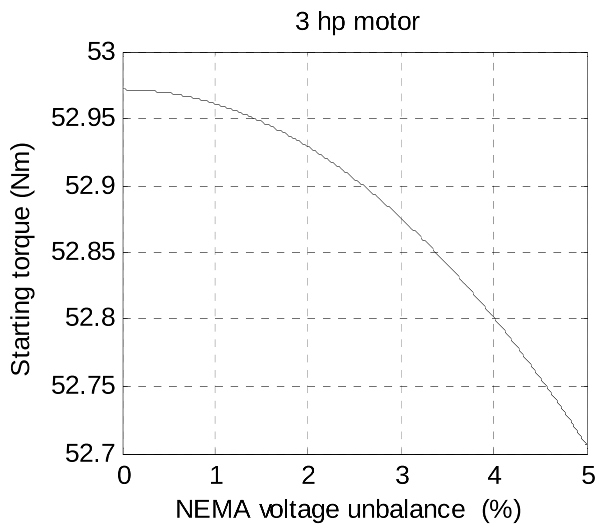


Fig.4.8 Starting torque versus unbalanced voltage for a 3 hp motor

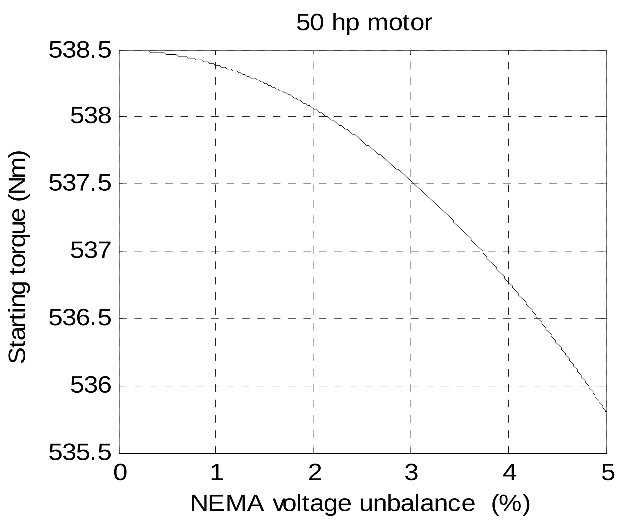


Fig.4.9 Starting torque versus unbalanced voltage for a 50 hp motor

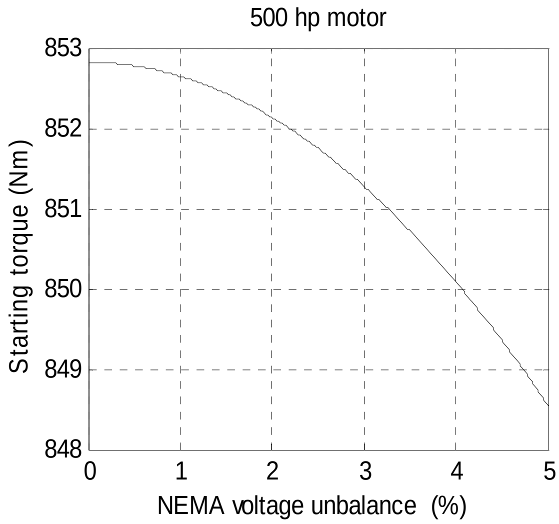


Fig.4.10 Starting torque versus unbalanced voltage for a 500 hp motor

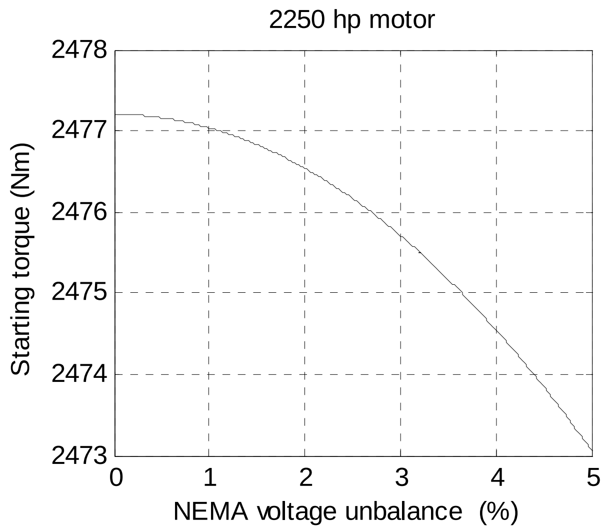


Fig.4.11 Starting torque versus unbalanced voltage for a 2250 hp motor

The influence of unbalanced voltages on the mechanical rated torque of the four three-phase induction motors is shown in figures 4.12 through to 4.15.

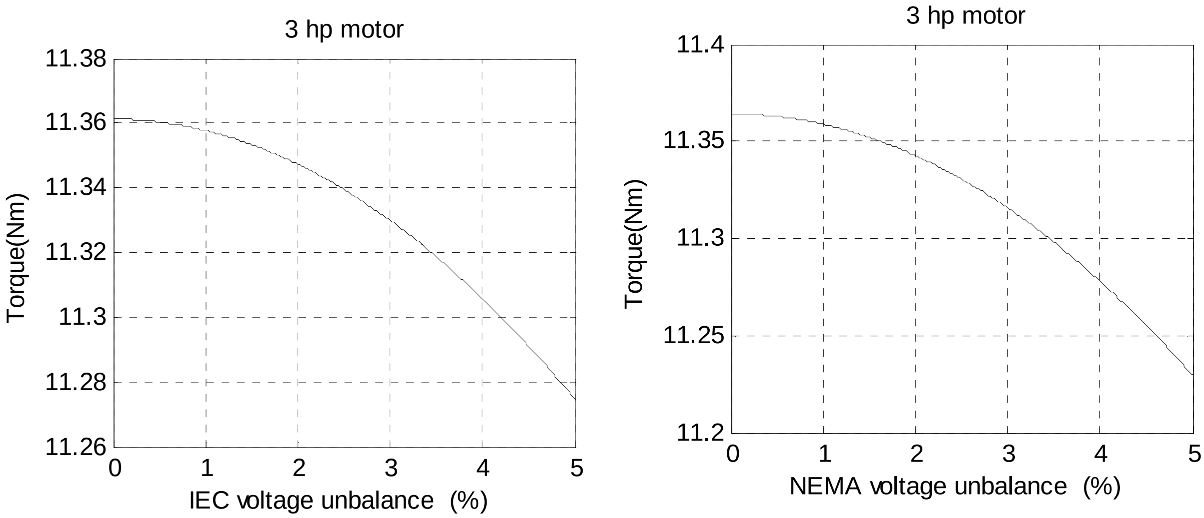


Fig 4. 12 Rated torque variation versus unbalanced voltage for a 3hp motor.

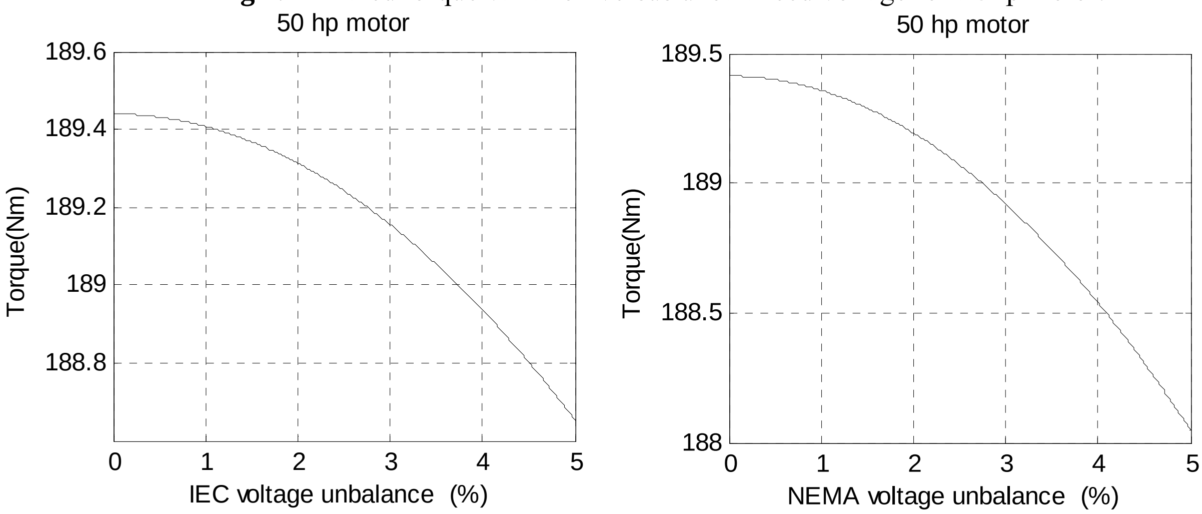


Fig 4.13 Rated torque variation versus unbalanced voltage for a 50hp motor.

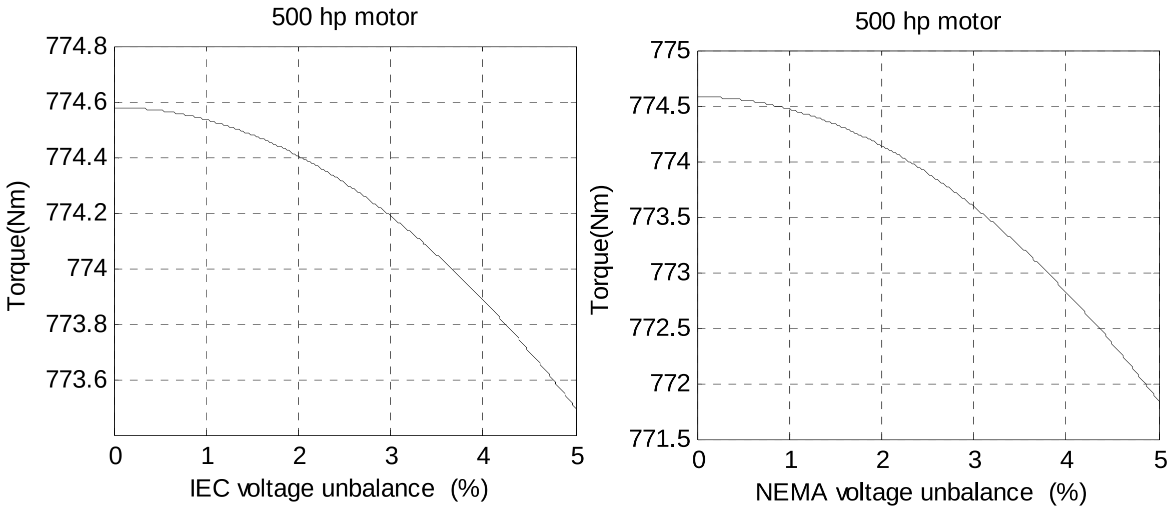


Fig 4.14 Rated torque variation versus unbalanced voltage for a 500 hp motor.

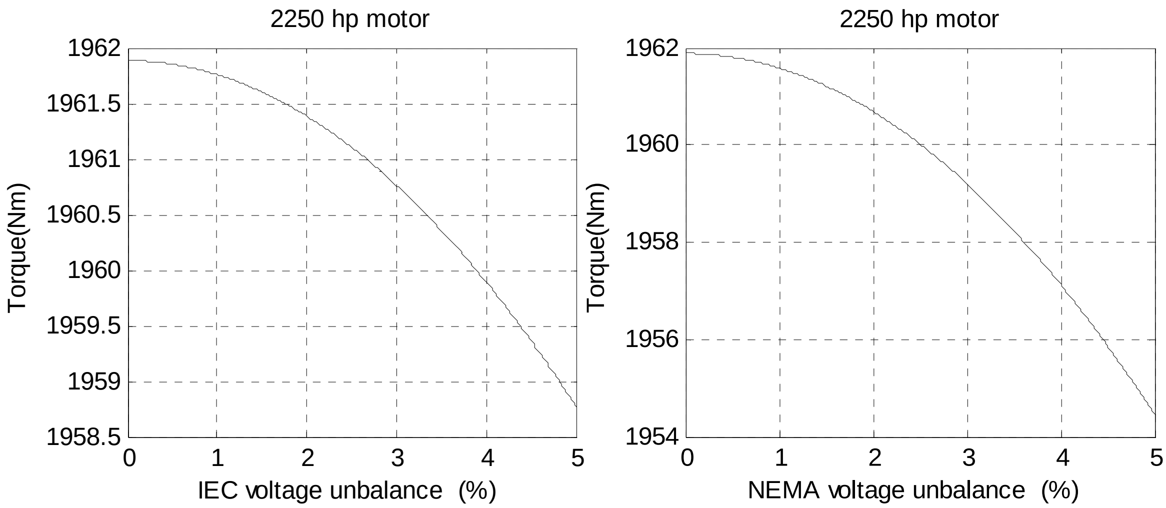


Fig.4.15 Rated torque variation versus unbalanced voltage for a 2250 hp motor.

The power level of each motor is mentioned at the top of each graph. Where the plots which are given using the IEC definition of the voltage unbalance are on the left of the page and those using the NEMA definition are on the right.

4.5.2 Steady state motor current speed characteristics under unbalanced supply operation

Taken on its own, the effect of voltage unbalance on torque development under steady state operation is negligible. However, the picture is truncated, for one must study the effect of voltage unbalance on motor current. The stator currents-speed characteristics of the induction motors under balanced supply voltages and at **5%** voltage unbalance are shown in figures 4.16 through to 4.19. In the light of the figures 4.20 through to 4.24, the maximum stator phase current is the phase current a, hence the unbalanced stator current appearing in the current speed characteristics is the current phase “a”.

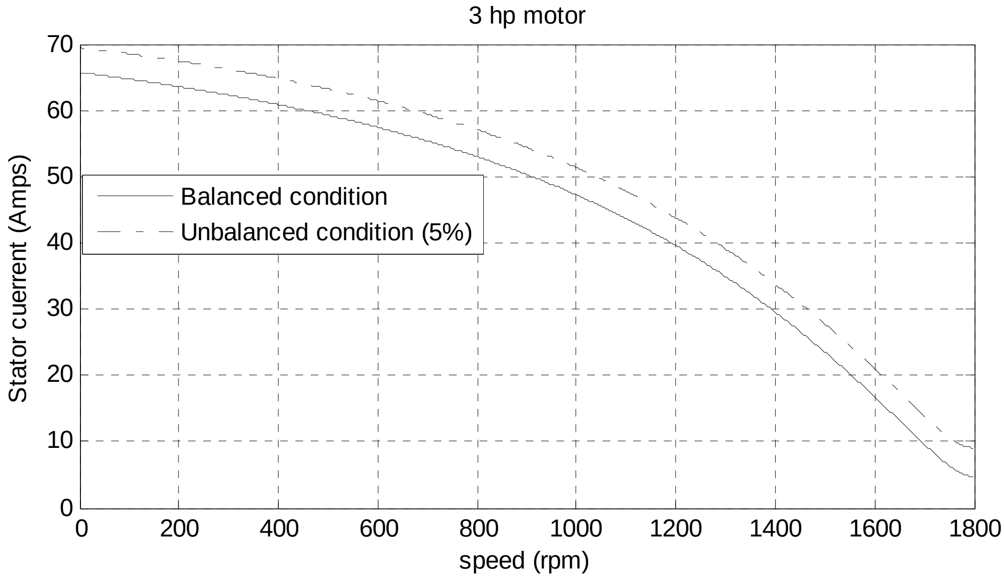


Fig.4.16 Stator currents speed characteristics for a 3 hp motor.

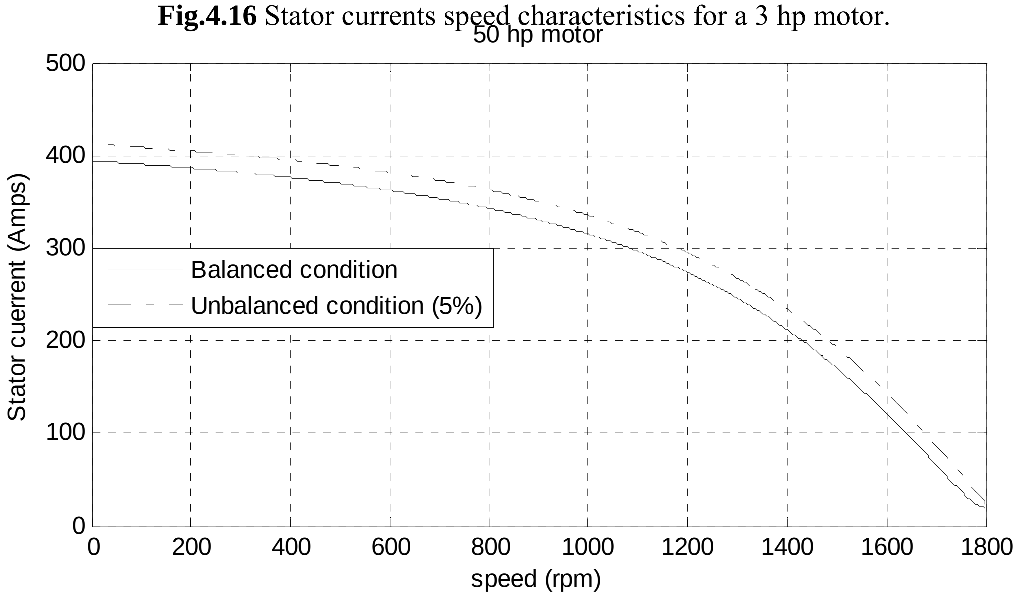


Fig.4.17 Stator currents speed characteristics for a 50 hp motor.

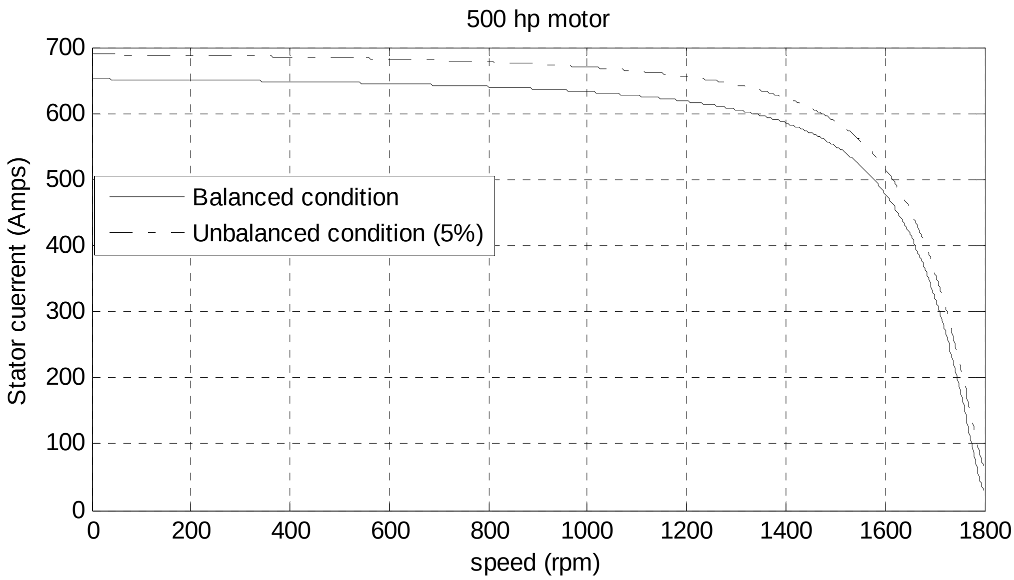


Fig.4.18 Stator currents speed characteristics for a 500hp motor

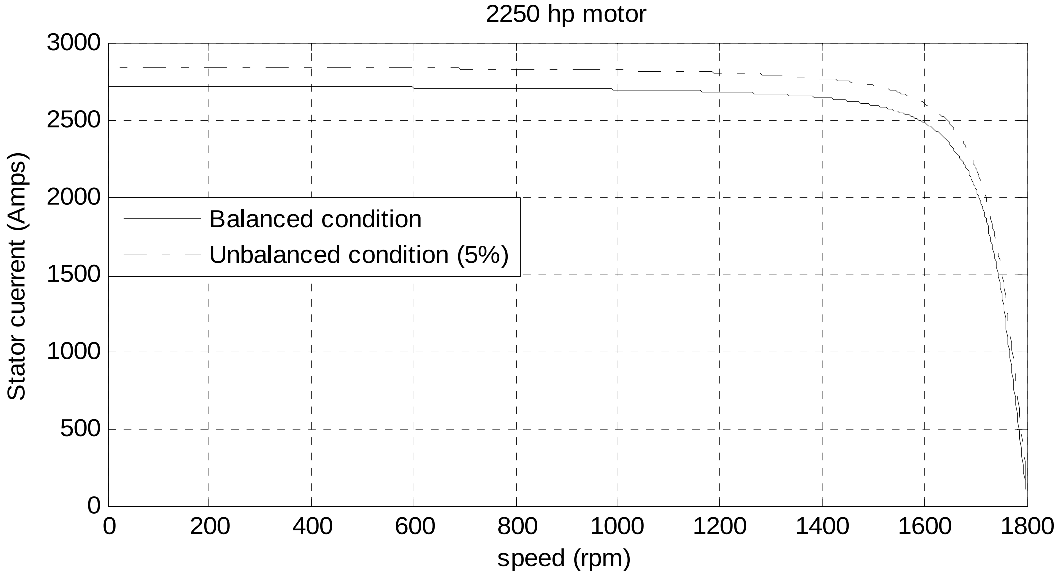


Fig.4.19 Stator currents speed characteristics for a 2250hp motor

The effect of voltage unbalance on the stator and rotor currents according to the two definitions is studied. The stator currents are shown in figures 4.20 through to 4.23, and the rotor currents are shown in figures 4.24 through to 4.27.

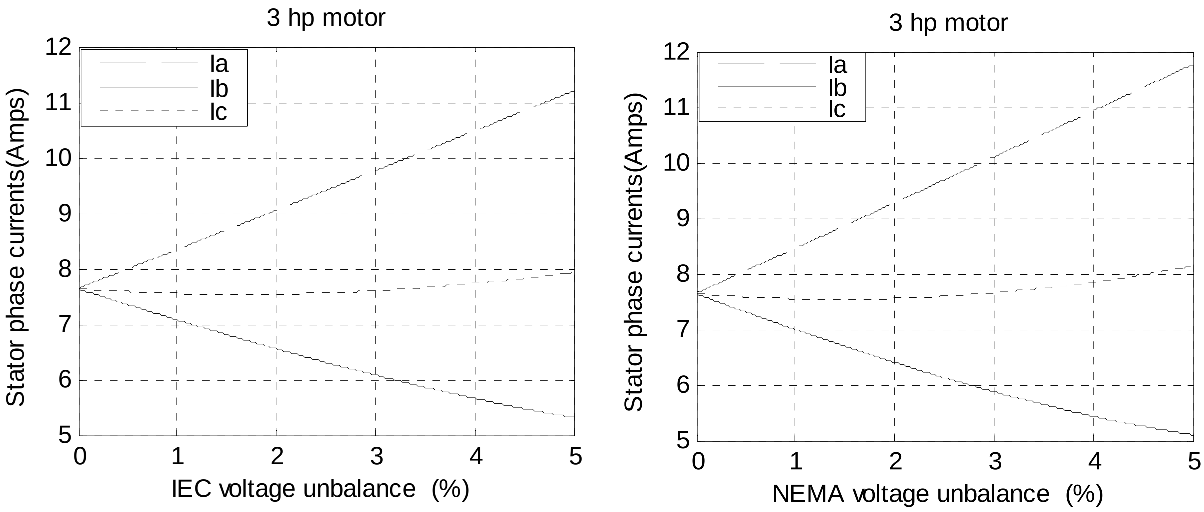


Fig.4.20 Stator phase currents versus unbalanced voltage for a 3 hp motor.

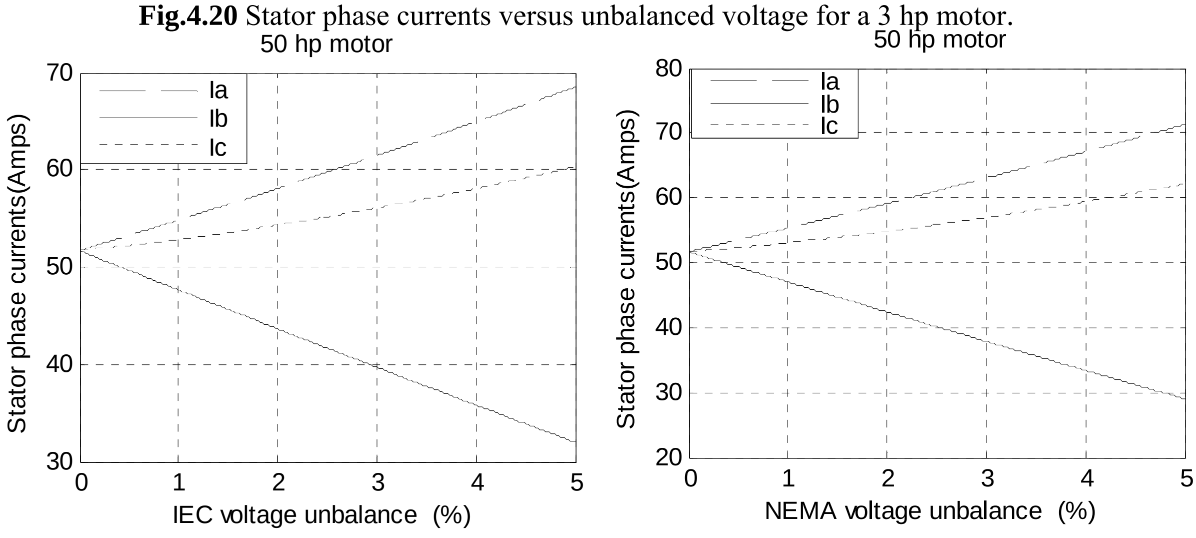


Fig.4.21 Stator phase currents versus unbalanced voltage for a 50hp motor.

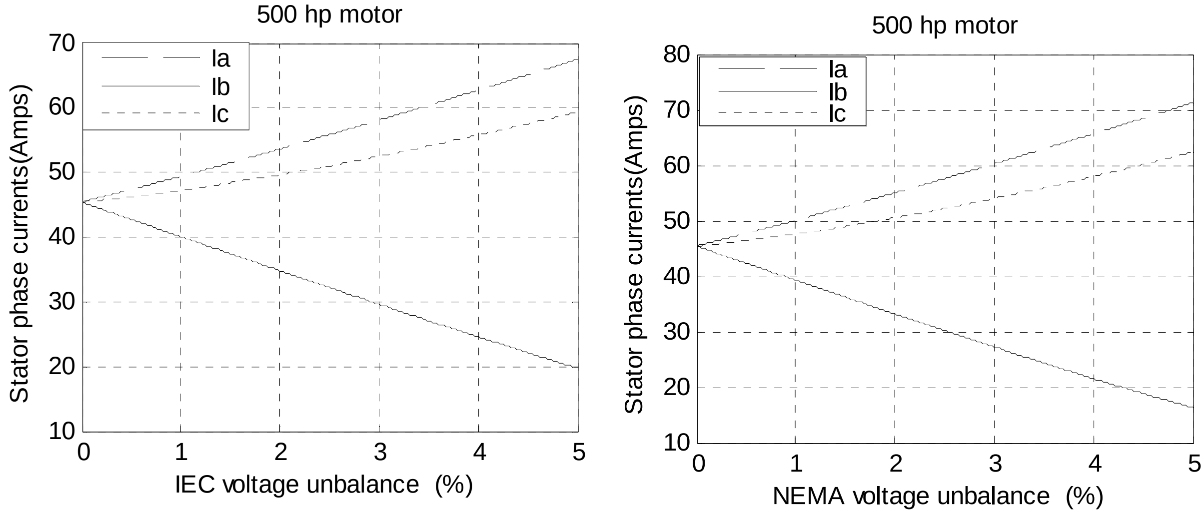


Fig.4.22 Stator phase currents versus unbalanced voltage for a 500hp motor.

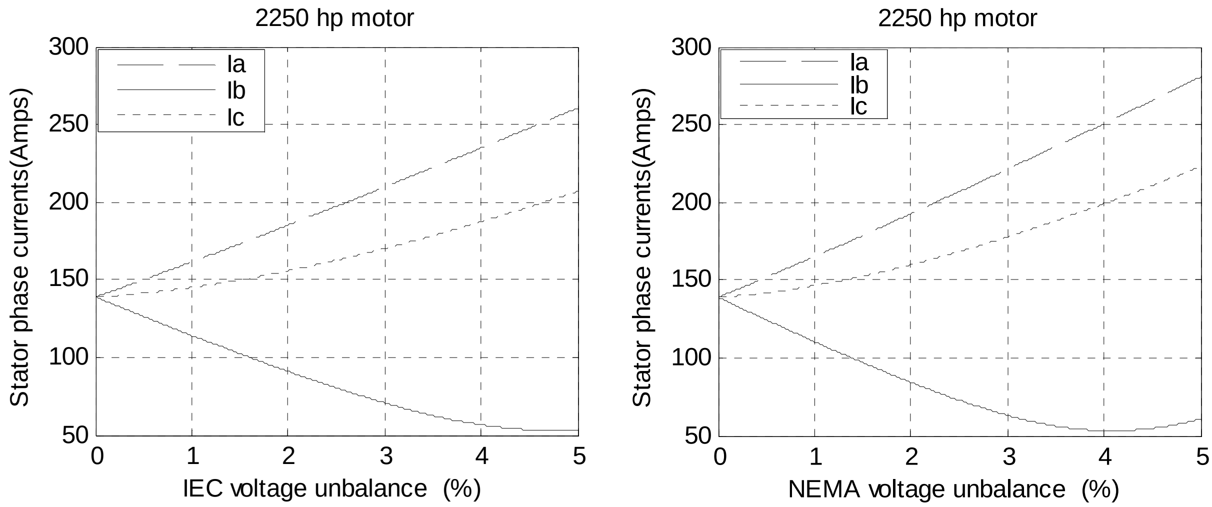


Fig.4.23 Stator phase currents versus unbalanced voltage for a 2250 hp motor.

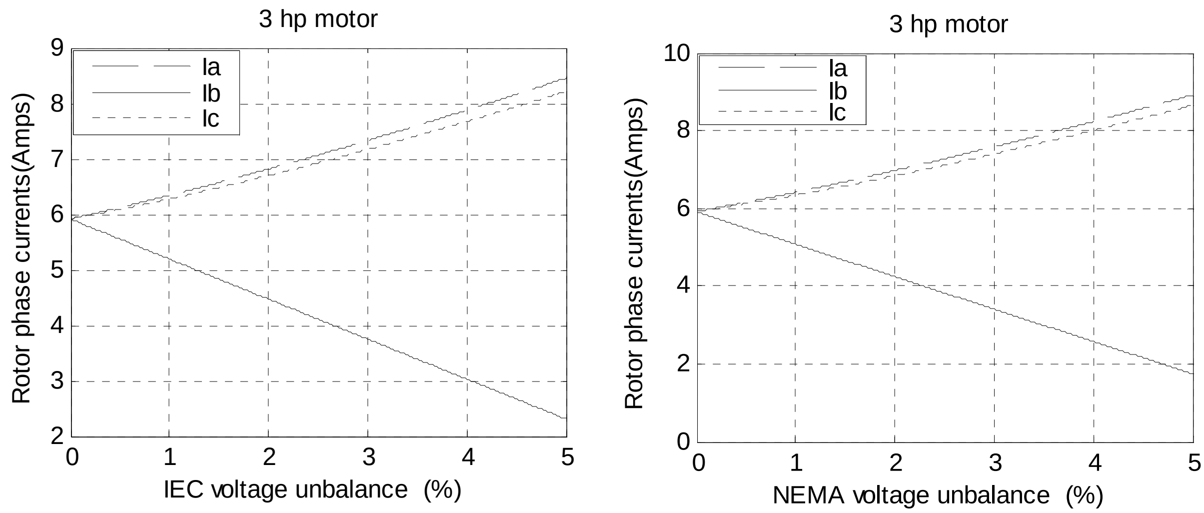


Fig.4.24 Rotor phase currents versus unbalanced voltage for a 3 hp motor.

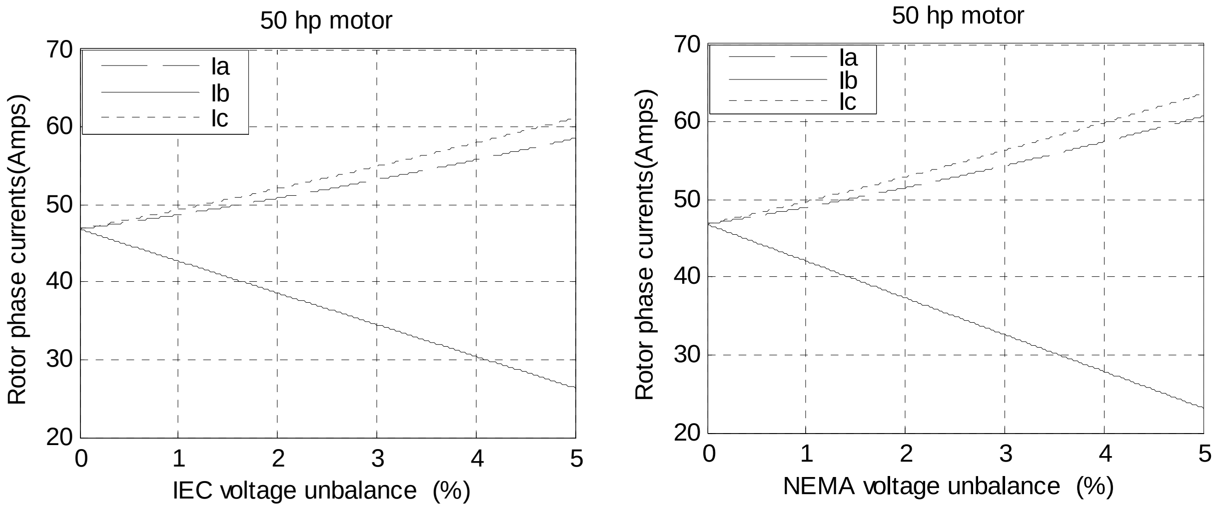


Fig.4.25 Rotor phase currents versus unbalanced voltage for a 50 hp motor.

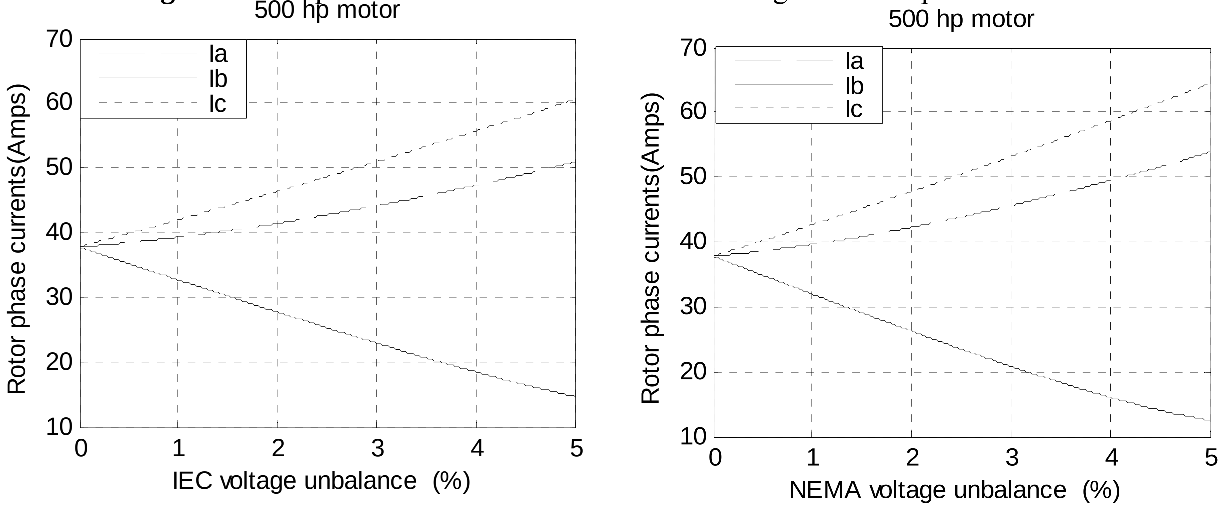


Fig.4.26 Rotor phase currents versus unbalanced voltage for a 500 hp motor.

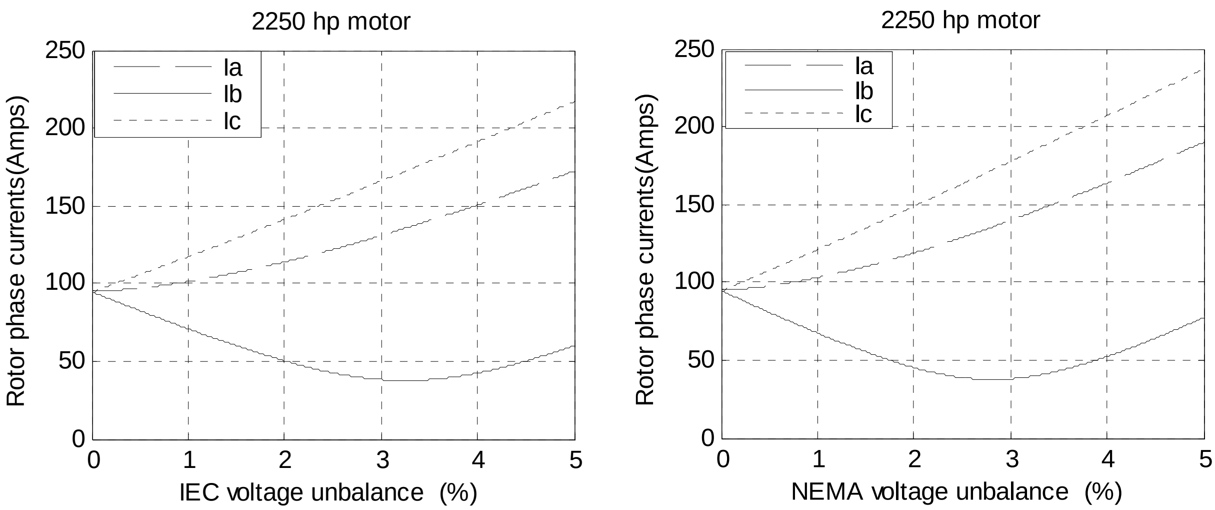


Fig.4.27 Rotor phase currents versus unbalanced voltage for a 2250 hp motor.

It can be noticed from the figures that the three phase currents are not all increasing but one phase (I_b) is decreasing with the maximum phase currents are exceeding the nominal rated currents under balanced condition.

4.5.3 Effect of unbalanced voltage on motors power copper losses

The stator and rotor additional copper losses per phase are shown in figures 4.28 through to 4.31 and figures 4.32 through to 4.35 respectively for the four motors. The total per unit copper losses is shown in figures 4.36 through to 4.39. One per unit copper losses is taken at normal operating condition.

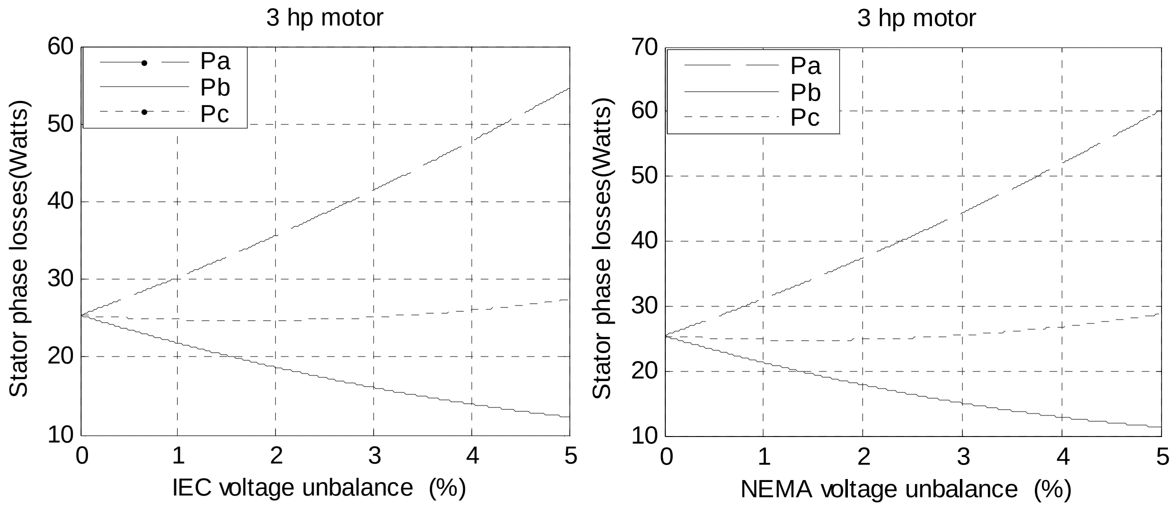


Fig.4.28 Stator phase copper losses versus unbalanced voltage for a 3 hp motor.

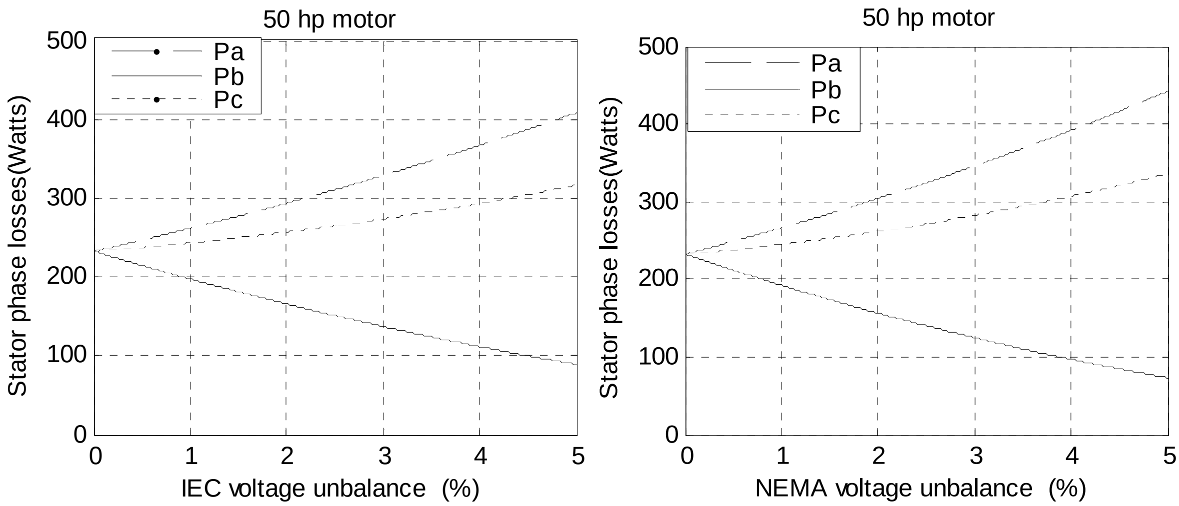


Fig.4.29 Stator phase copper losses versus unbalanced voltage for a 50 hp motor.

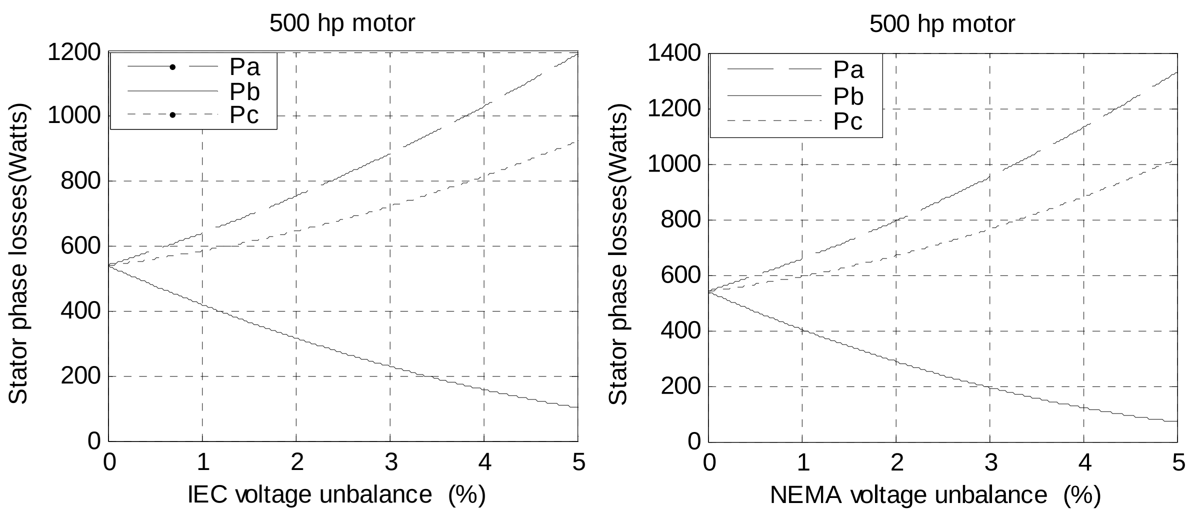


Fig.4.30 Stator phase copper losses versus unbalanced voltage for a 500 hp motor.

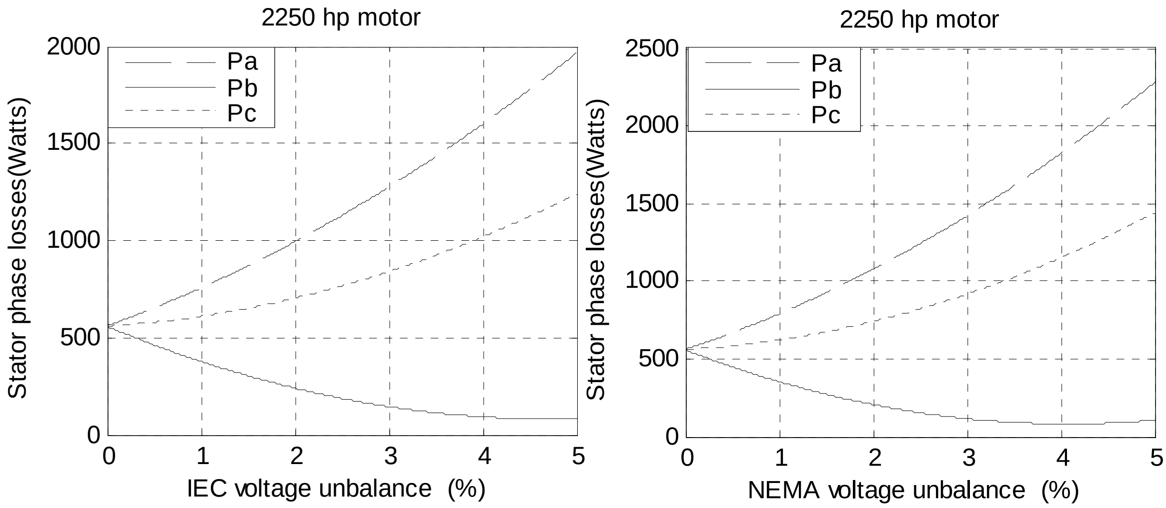


Fig.4.31 Stator phase copper losses versus unbalanced voltage for a 2250 hp motor.

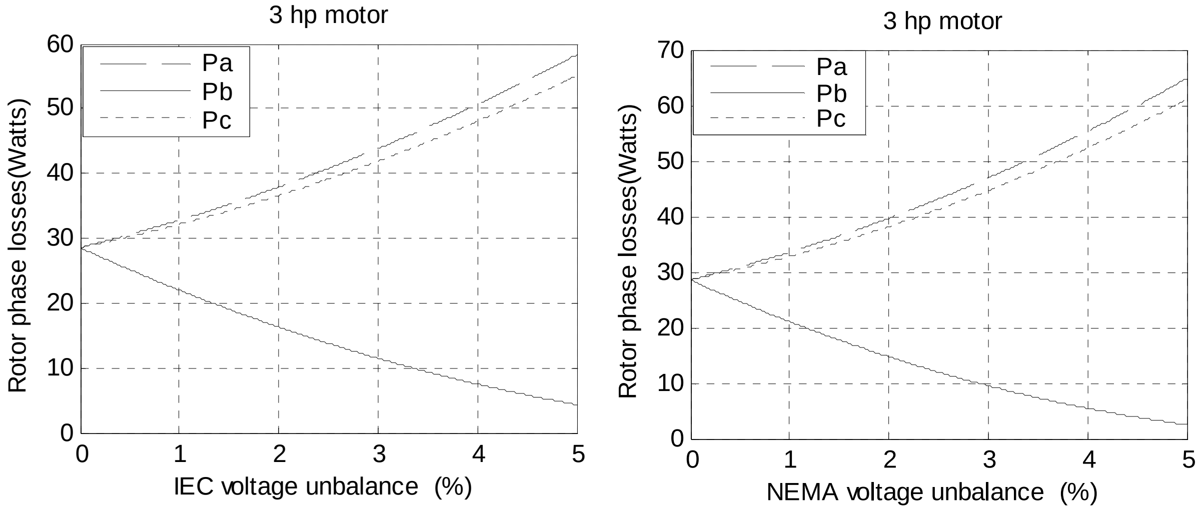


Fig.4.32 Rotor phase copper losses versus unbalanced voltage for a 3 hp motor.

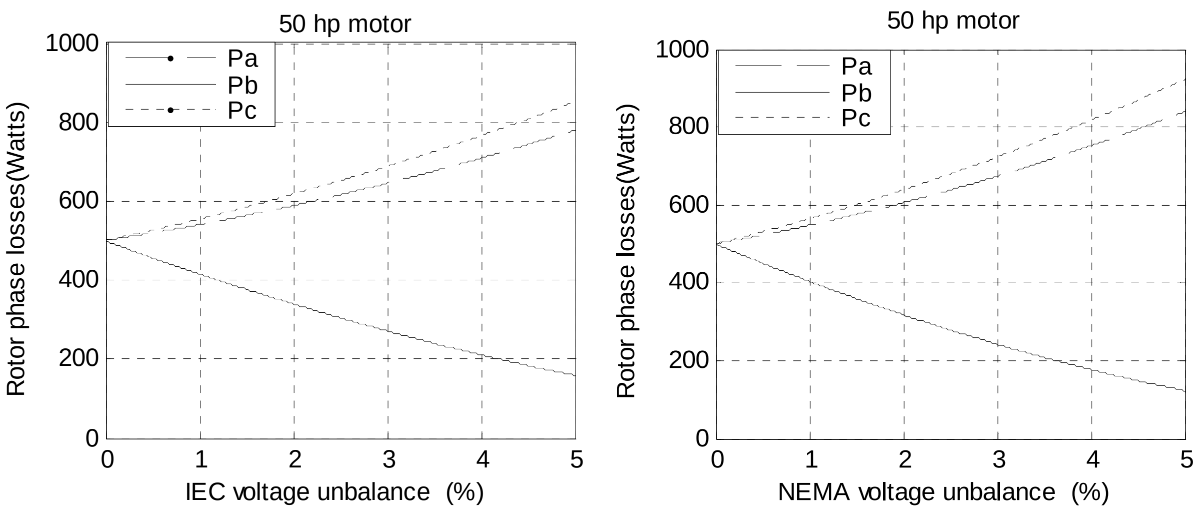


Fig.4.33 Rotor phase copper losses versus unbalanced voltage for a 50 hp motor.

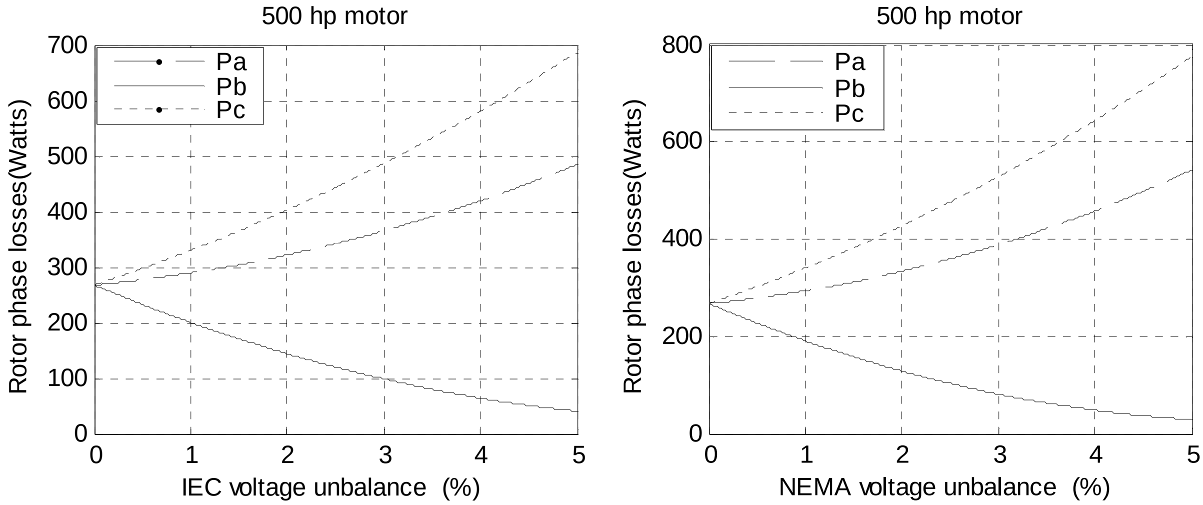


Fig.4.34 Rotor phase copper losses versus unbalanced voltage for a 500 hp motor.

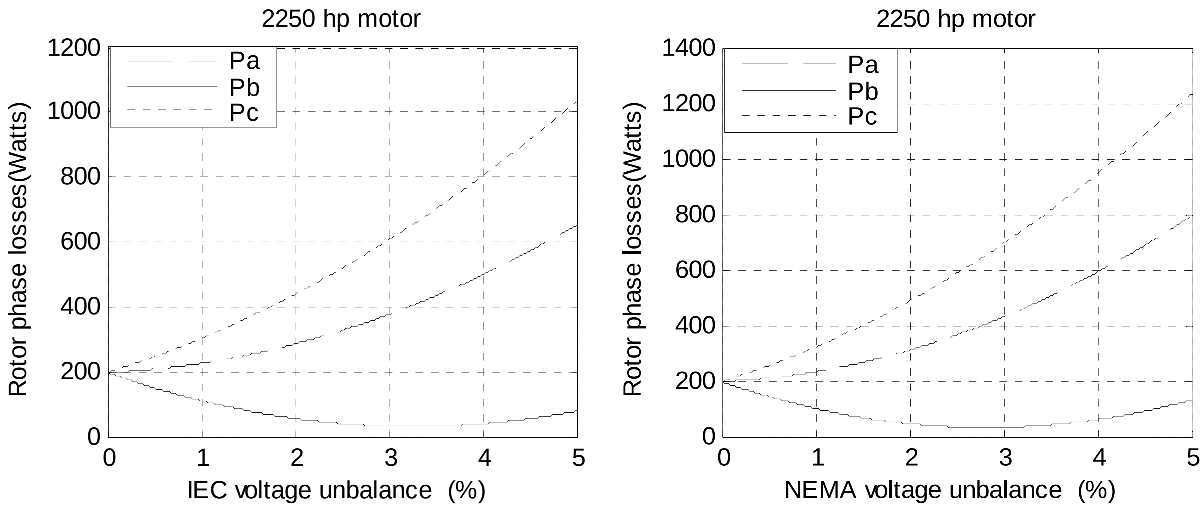


Fig.4.35 Rotor phase copper losses versus unbalanced voltage for a 2250 hp motor.

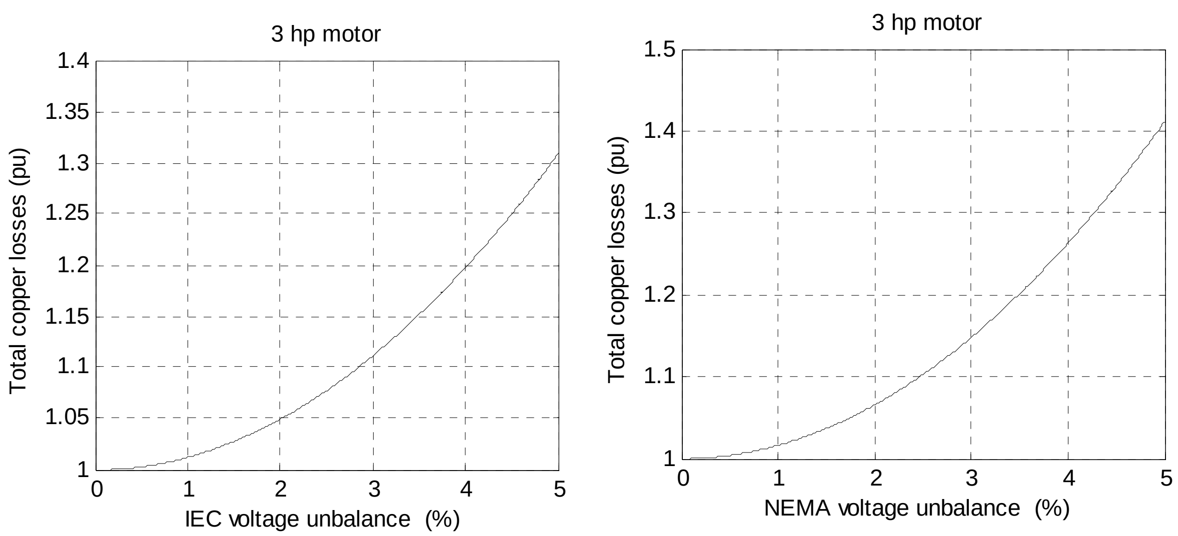


Fig 4.36 Total copper loss in per unit versus unbalanced voltage for a 3 hp motor.

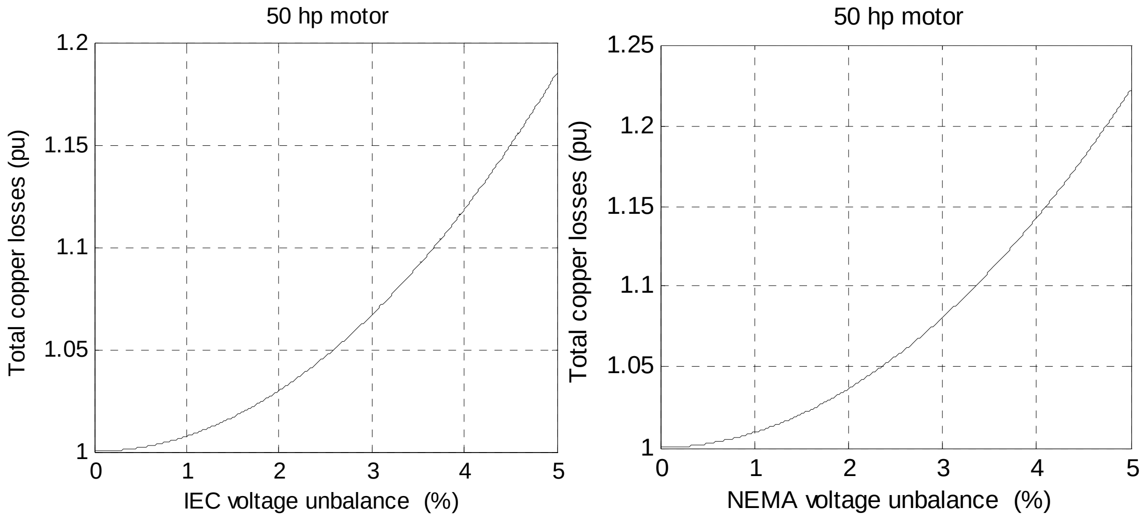


Fig 4.37 Total copper loss in per unit versus unbalanced voltage for a 50 hp motor.

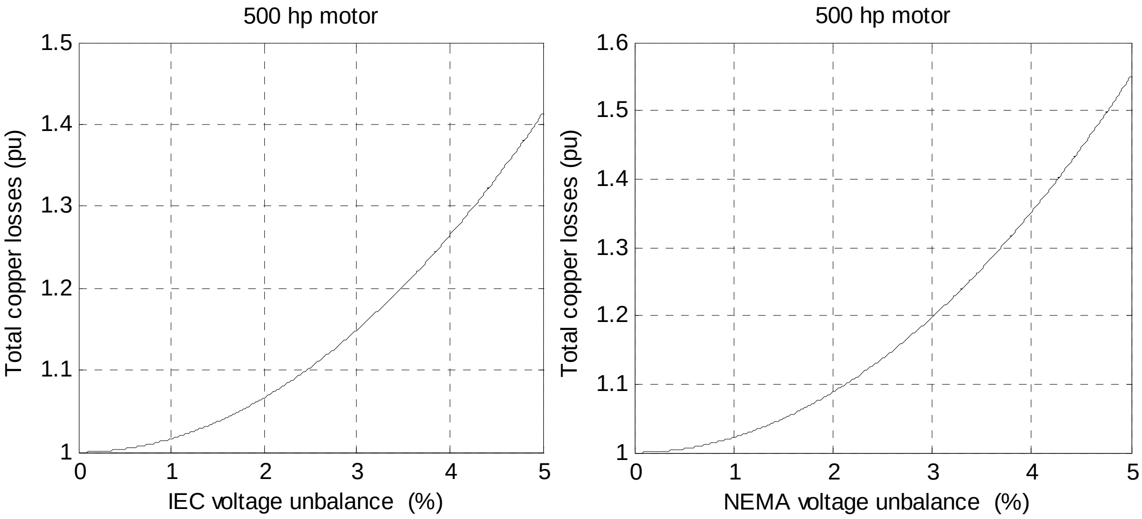


Fig 4.38 Total copper loss in per unit versus unbalanced voltage for a 500 hp motor.

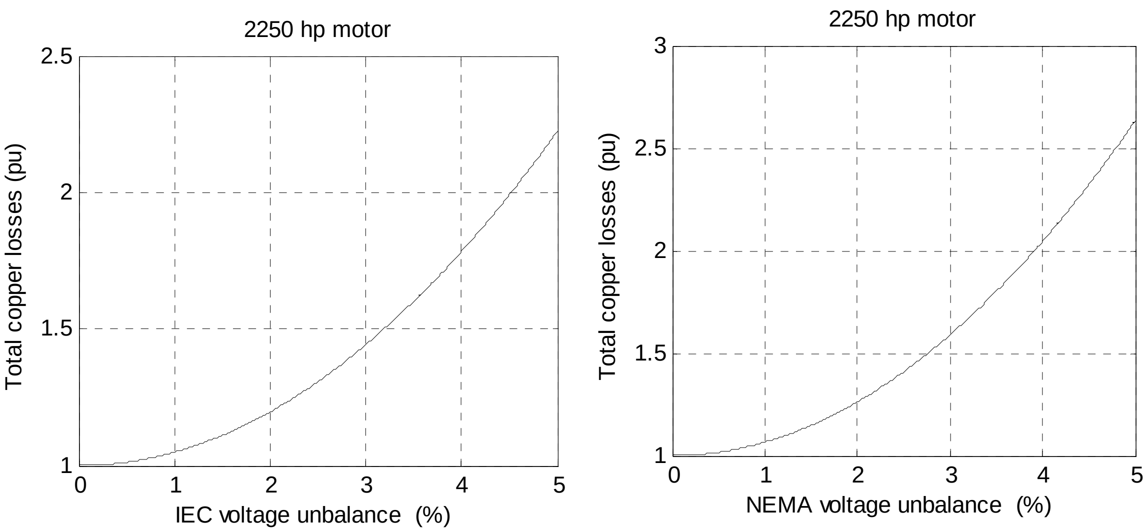


Fig 4.39 Total copper loss in per unit versus unbalanced voltage for a 2250 hp motor.

4.5.4 Effect of unbalanced voltage on motors efficiencies

The motors efficiencies decrease with the voltage unbalance according to figures 4.40 through to 4.43.

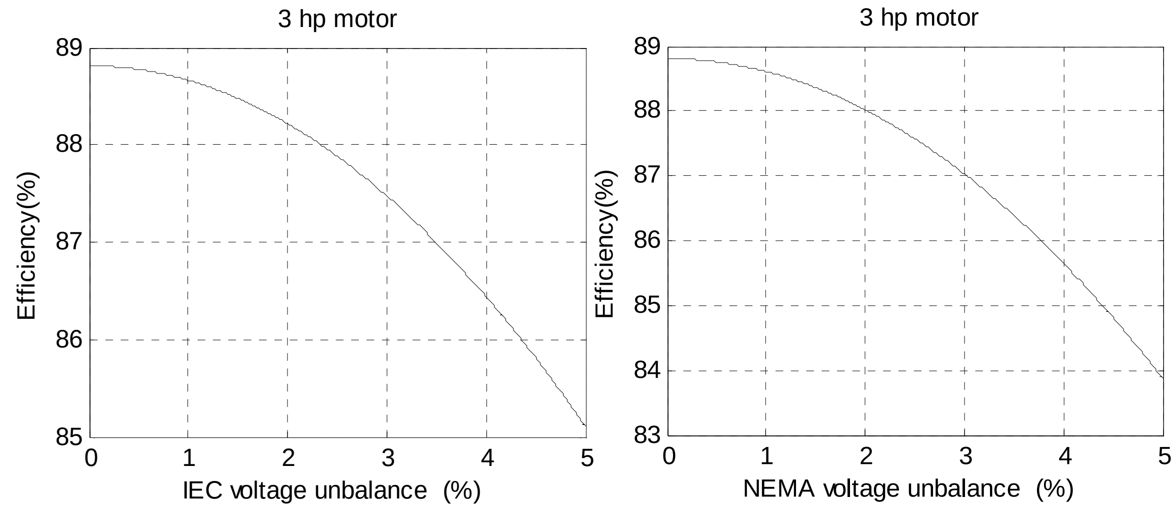


Fig 4.40 Efficiency versus unbalanced voltage for a 3 hp motor.

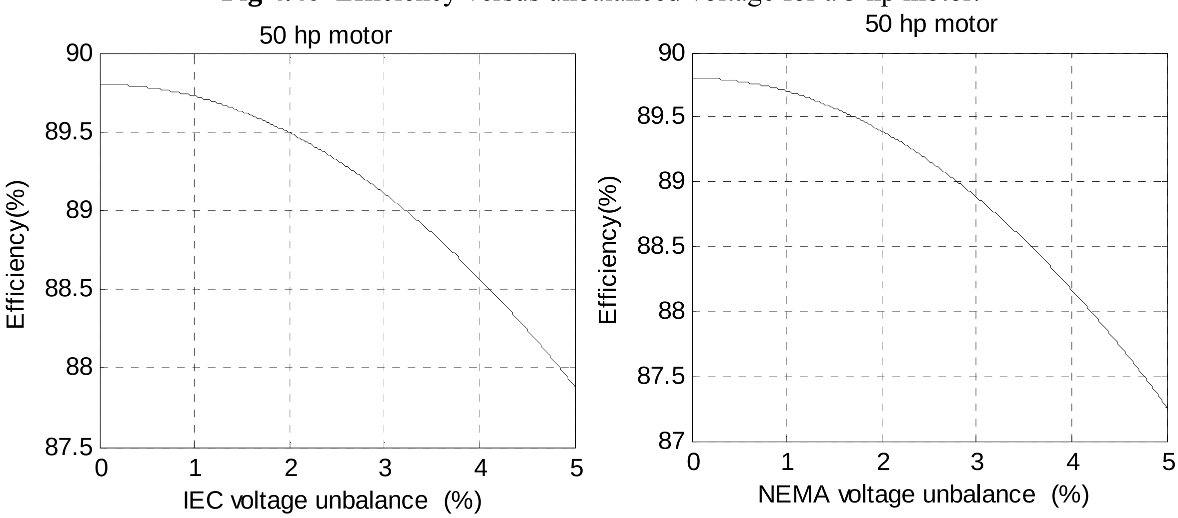


Fig 4.41 Efficiency versus unbalanced voltage for a 50 hp motor.

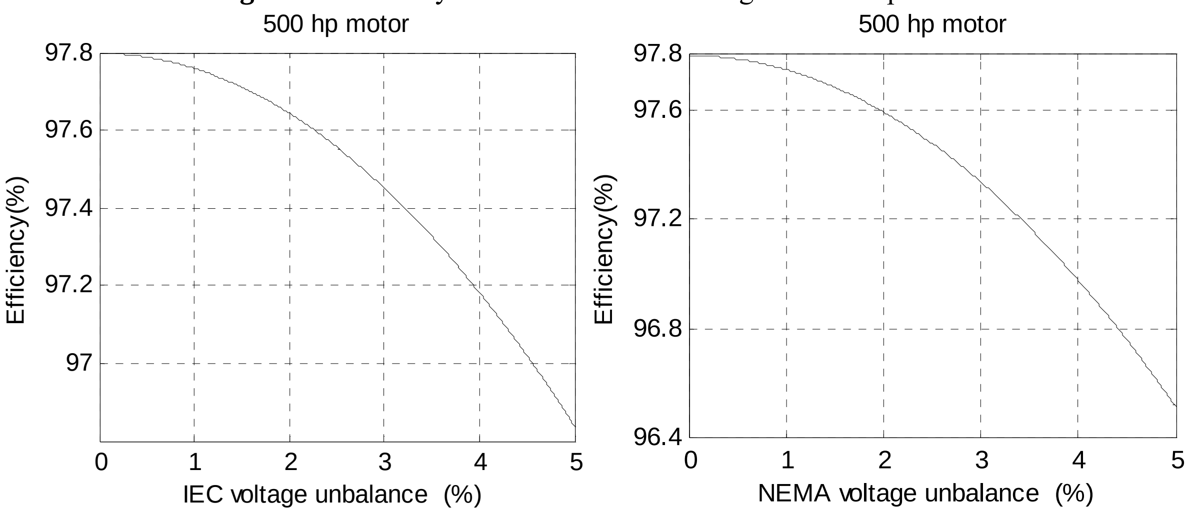


Fig 4.42 Efficiency versus unbalanced voltage for a 500 hp motor.

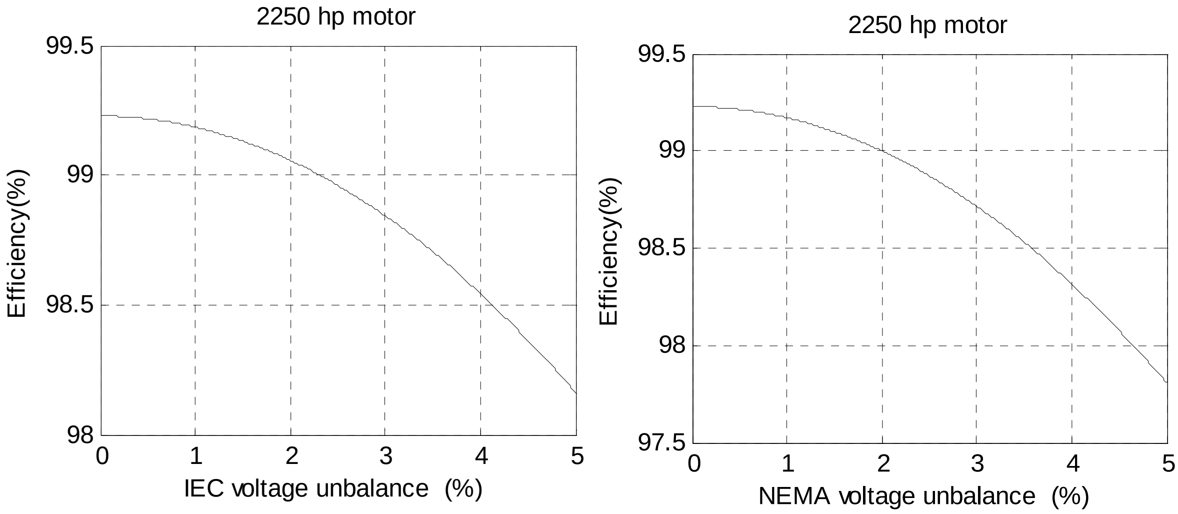


Fig 4.43 Efficiency versus unbalanced voltage for a 2250 hp motor.

4.5.5 Effect of unbalanced voltage on motors derating

Voltage unbalance results in additional losses causing the increase in motor temperature. The most effective way to solve this problem of motors overheating is to eliminate the unbalance. If the voltage unbalance cannot be eliminated, the motor must be derated to ensure long life.

NEMA Standard *MG 1-14.35* recommends derating an induction motor when the voltage unbalance exceeds 1% and recommends not operating a motor at all when the voltage unbalance exceeds 5% [30].

For standard motors, NEMA provides guidance for derating. For voltage unbalances between one and five percent, NEMA *MG-1-1993* suggests derating motors is according to the graph shown in Figure 4.44.

NEMA provides a way on how to derate the motor in the presence of unbalanced voltages to prevent the extra heating, which indicates that when voltages are unbalanced, the percent increase in temperature rise equals about twice the square of the percent voltage unbalance [29]. This is given by:

$$1+\frac{percent\ increase\ in\ winding\ temperature}{100}=\left(\frac{percent\ load}{100}\right)^{(-1.7)} \tag{4.29}$$

$$1+2\frac{(percentunbalance)^2}{100}=\left(\frac{percent\ load}{100}\right)^{(-1.7)} \tag{4.30}$$

There are several ways to develop a derating curve. One is based on the ratio of the mechanical power output divided by the motor's rated power; this is defined as the derating factor. The derating curve is given in figure 4.44

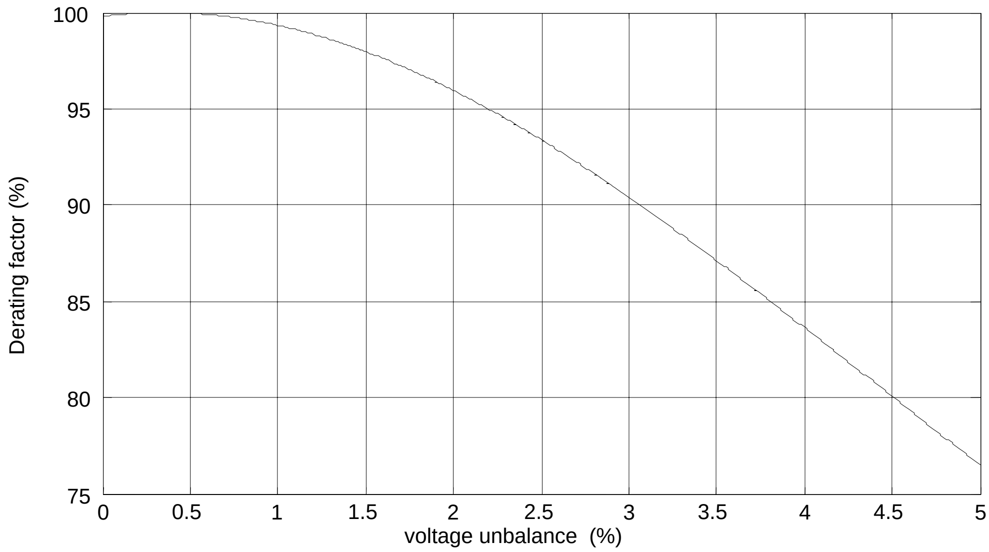


Fig 4.44 NEMA derating curve of an induction motor.

NEMA states that polyphase motors shall successfully operate under running condition at rated load when the voltage unbalance at the motor terminals does not exceed1 % [30],[31].

In the light of figures 4.45 through to 4.48 that the attainable power developed by the motors reduces with the increase of the voltage unbalance.

4.5.5.1 Case 1 voltage unbalance

This is the case used in the previous analysis, the unbalanced voltages are chosen such that: the line voltage 'V_{ab}' is equal to the rated voltage, the line voltage 'V_{bc}' is reduced by the same deviation as the line voltage 'V_{ca}' is increased with the average line voltages is equal to the rated line voltage.

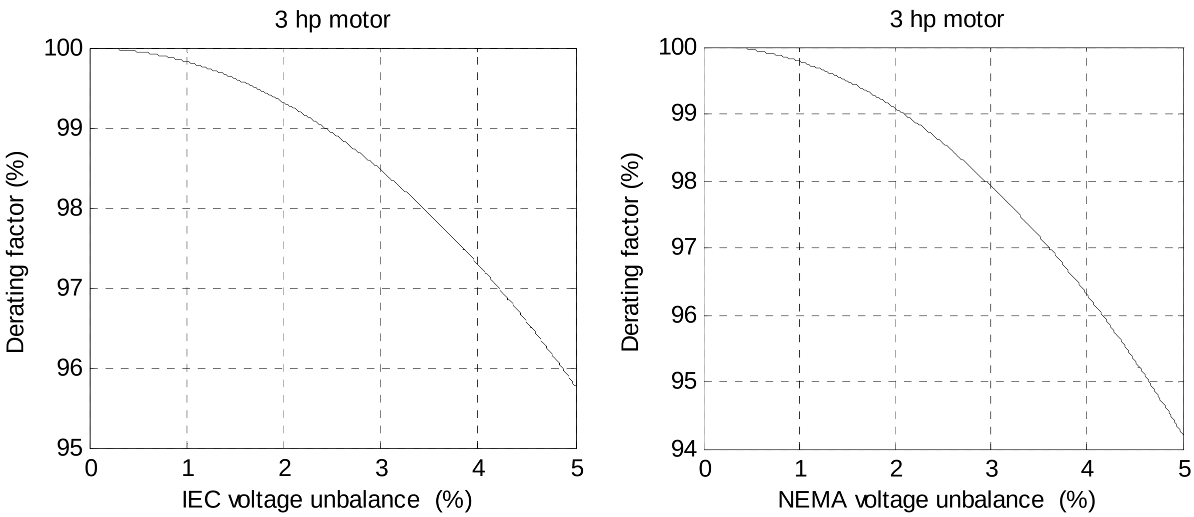


Fig 4. 45 Derating curves for a 3 hp motor.

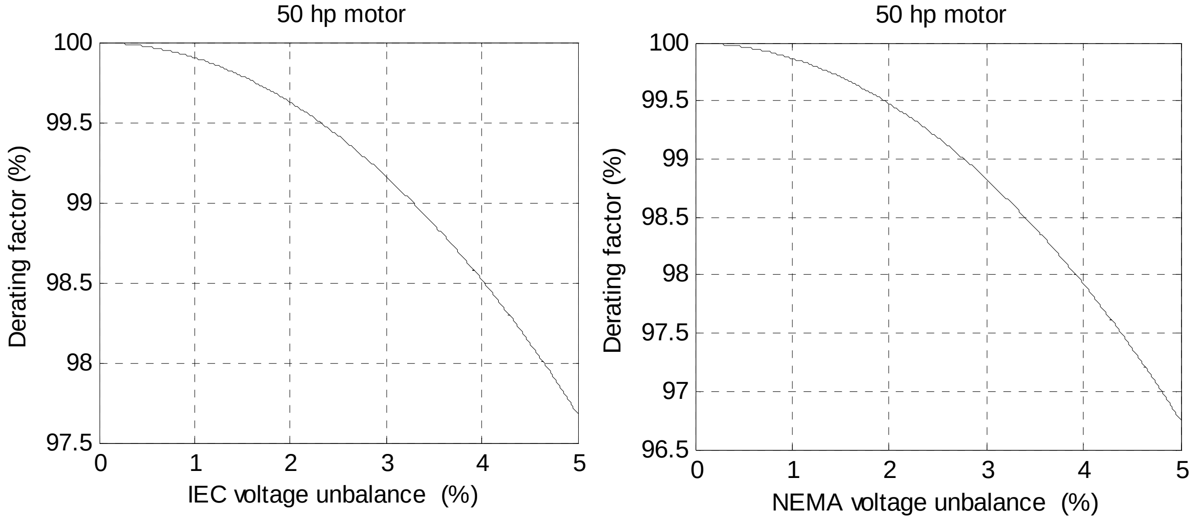


Fig 4. 46 Derating curves for a 50 hp motor.

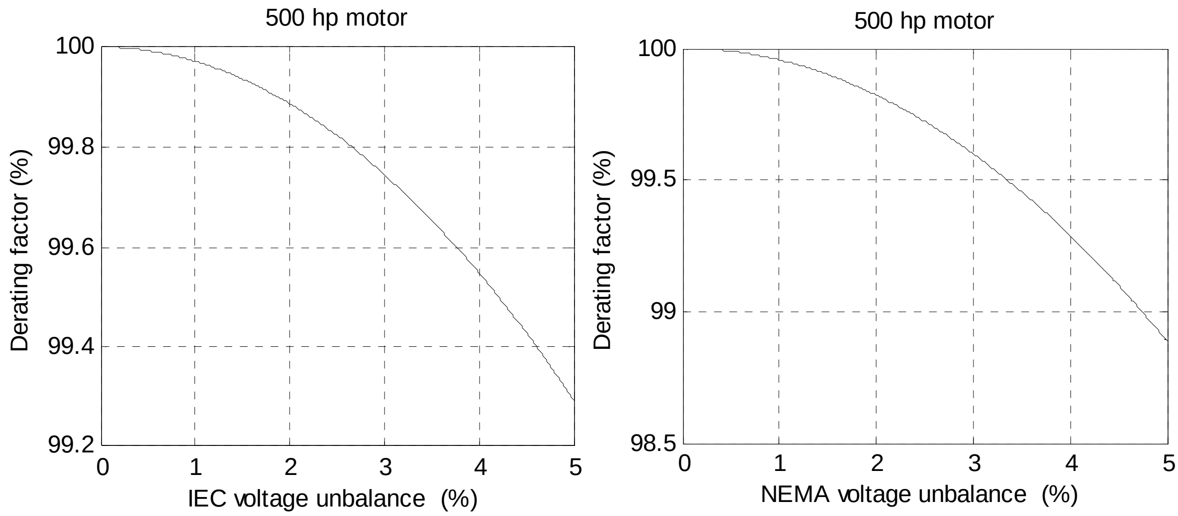


Fig 4. 47 Derating curves for a500 hp motor.

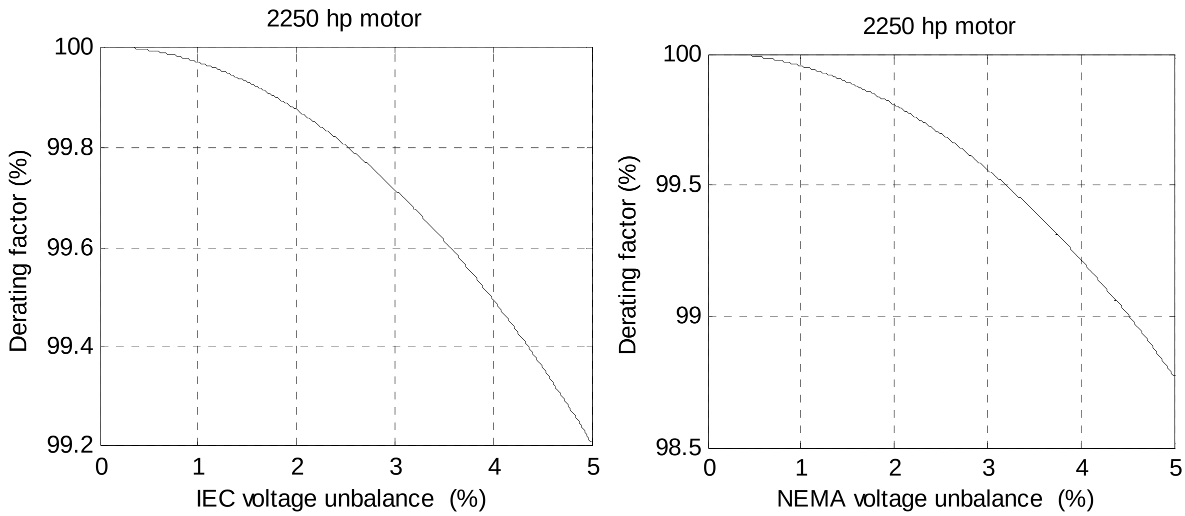


Fig 4. 48 Derating curves for a 2250 hp motor.

4.5.5.2 Case 2 voltage unbalance

In this case the unbalanced voltages are chosen such that: the line voltages V_{ab} and V_{bc} are increased by the same deviation but the line voltage V_{ca} is decreased with the average line voltages is equal to the rated line voltage.

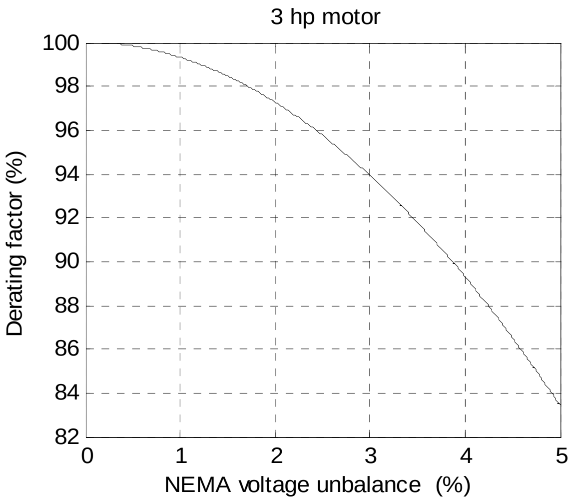


Fig.4.49 Derating curve for a 3 hp motor (case 2)

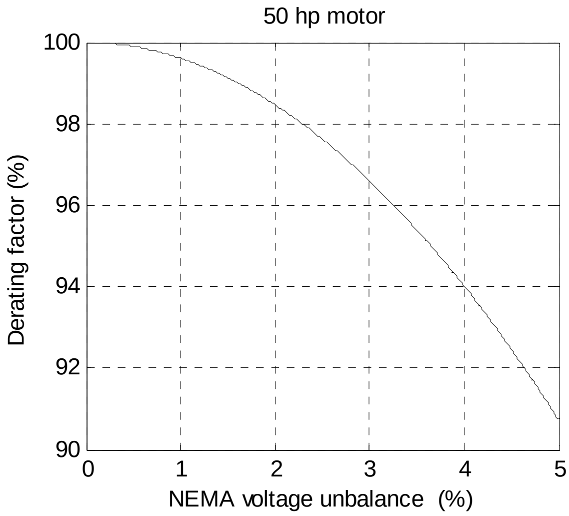


Fig.4.50 Derating curve for a 50 hp motor (case 2)

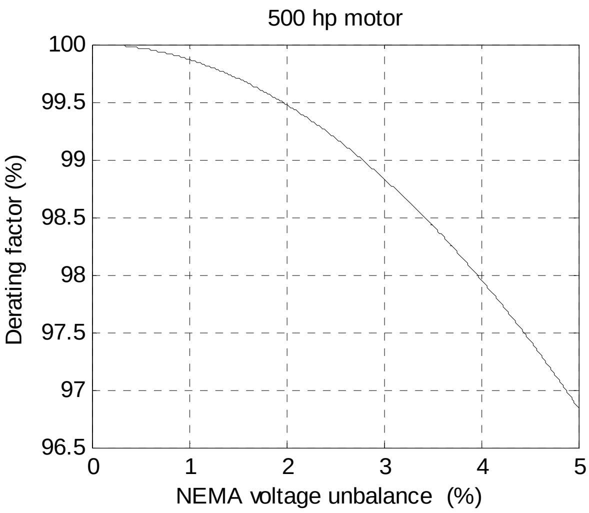


Fig.4.51 Derating curve for a 500 hp motor (case 2)

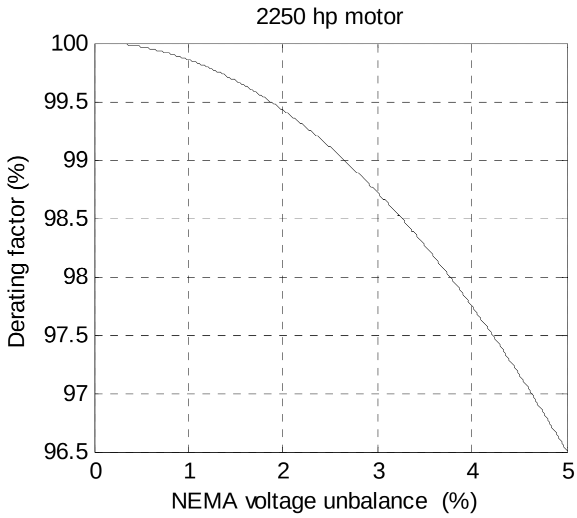


Fig.4.52 Derating curve for a 2250 hp motor (case 2)

4.5.5.3 Case 3 voltage unbalance

In this case the unbalanced voltages are chosen such that: the line voltages V_{ab} and V_{bc} are decreased by the same deviation but the line voltage V_{ca} is increased with the average line voltages is equal to the rated line voltage.

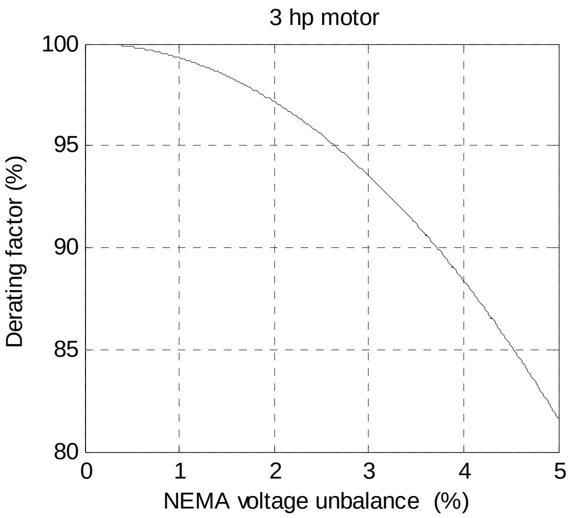


Fig.4.53 Derating curve for a 3 hp motor (case 3)

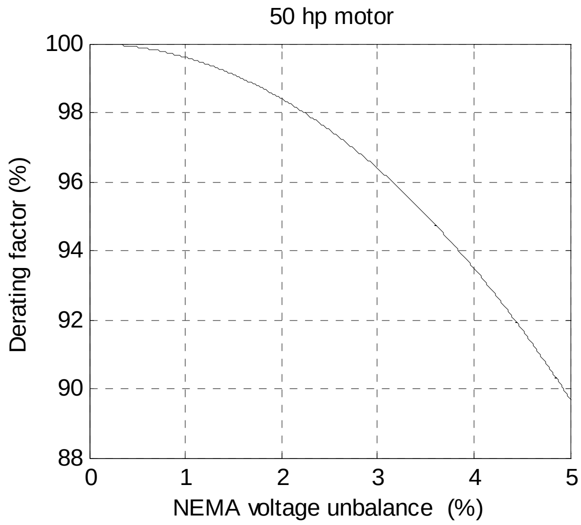


Fig.4.54 Derating curve for a 50 hp motor (case 3)

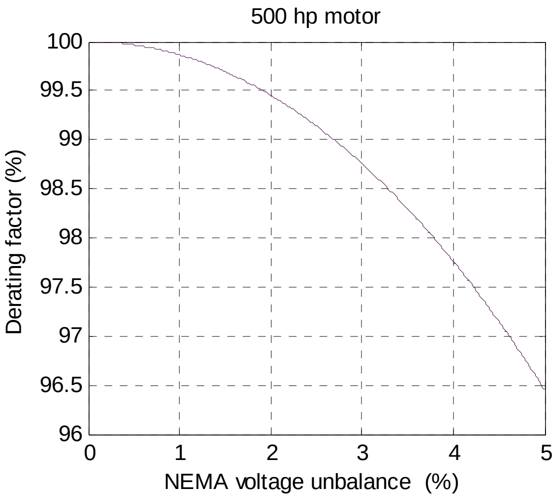


Fig.4.55 Derating curve for a 500 hp motor (Case 3)

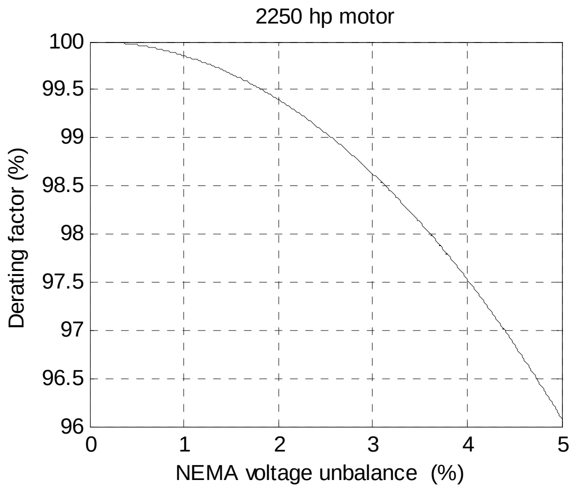


Fig.4.56 Derating curve for a 2250 hp motor (Case 3)

4.5.6 Effects of unbalanced voltage on temperature rise

The extra heating by negative sequence currents leads to uneven partial distribution of heat and, consequently, to high temperatures and hot spots. Hence, in the presence of unbalanced voltages, the load on the motor must be reduced below the rated load so as to limit the temperature rise to the normal value. For example a **3.5%** increase in voltage unbalance leads to a **25%** increase in operating temperature.

According to references [32], [33], [34], [35], a rise of only **10^{o}C** in temperature will reduce the expected insulation life by half. The temperature limits of induction motors depend on the motor insulation classes.

The plots in figures 4.57 through 4.68 show the temperature rise caused by the voltage unbalance, they are computed according to equation (4.29) which relates between the derating and the percent temperature rise under unbalanced supply at rated full load operation. The figures 4.57 through to 4.60 show the percent temperature rise of the induction motors, with the NEMA definition of voltage unbalance (case 1) on the right and those with IEC definition on the left of the page. Figures 4.61 through to 4.64 illustrate the percent temperature rises of the four machines using the NEMA definition of voltage unbalance with second case of the terminal voltages, and those of the third case are given in figures 4.65 through to 4.68.

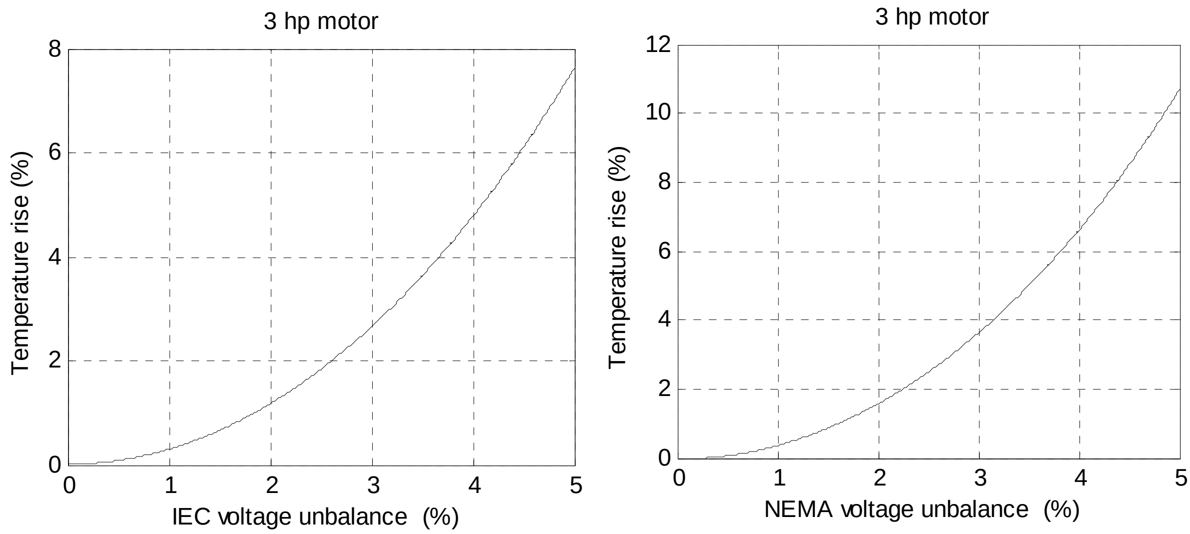


Fig. 4.57 Percent temperature rise with unbalanced voltages (case 1) for a 3 hp motor.

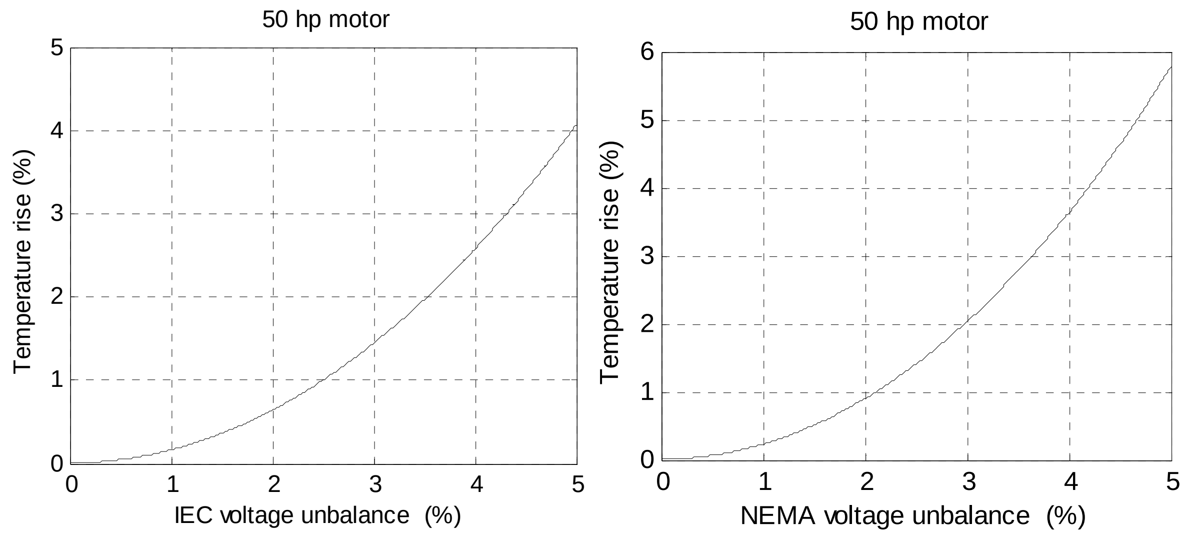


Fig. 4.58 Percent temperature rise with unbalanced voltages (case 1) for a 50 hp motor.

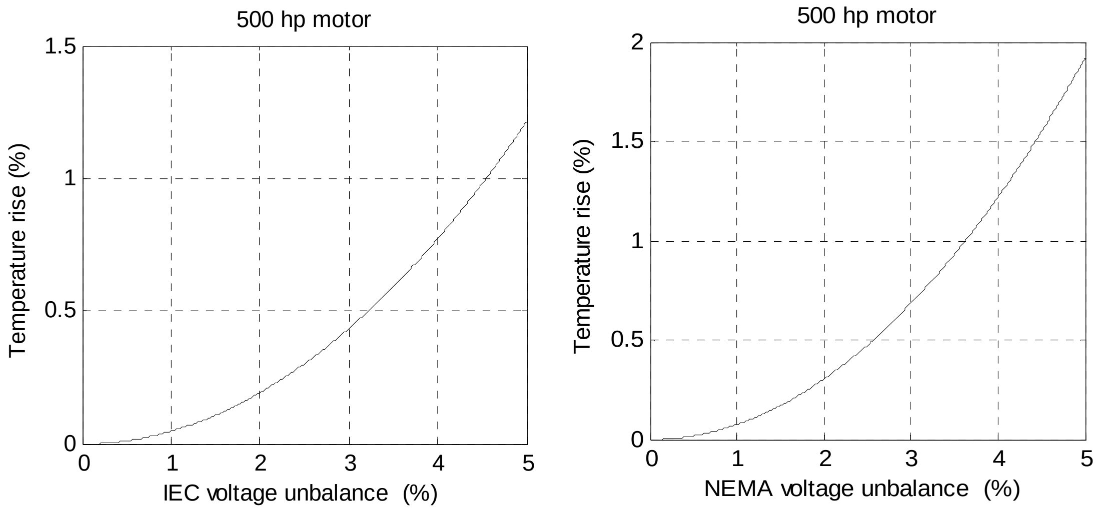


Fig. 4.59 Percent temperature rise with unbalanced voltages (case 1) for a 500 hp motor.

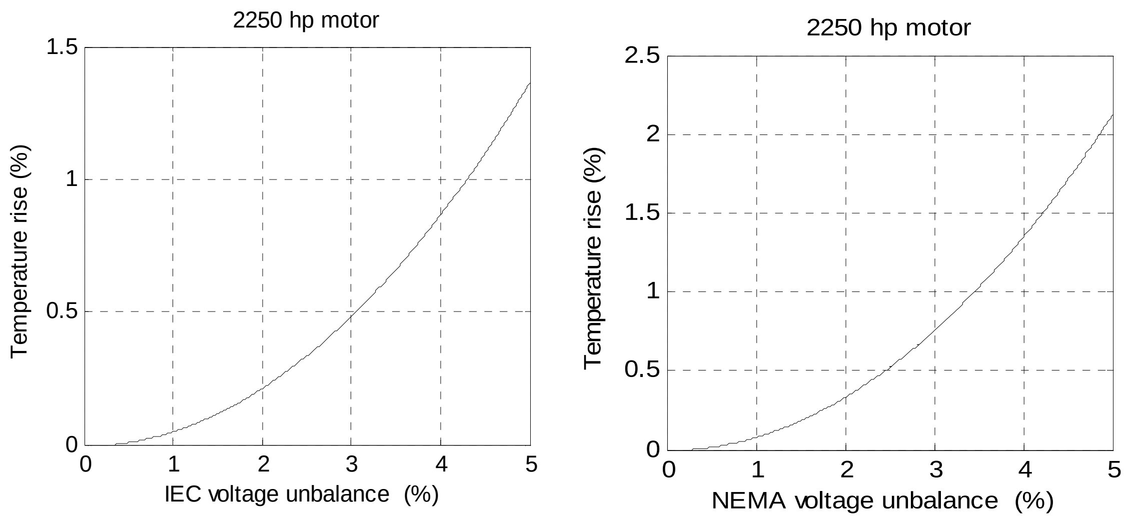


Fig. 4.60 Percent temperature rise with unbalanced voltages (case 1) for a 2250 hp motor.

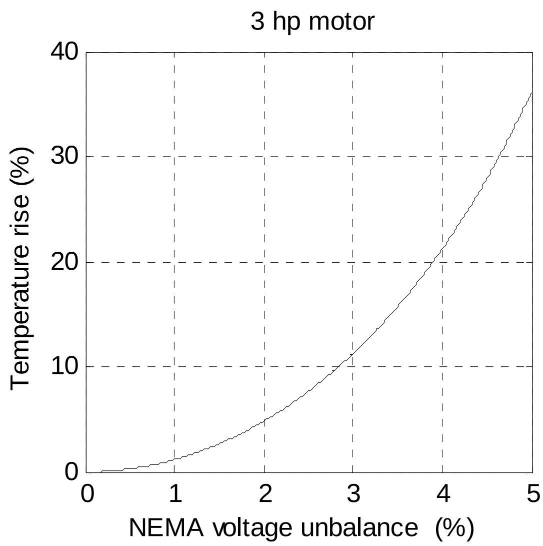


Fig. 4.61 Percent temperature rise versus unbalanced voltage (case 2) for a 3hp motor.

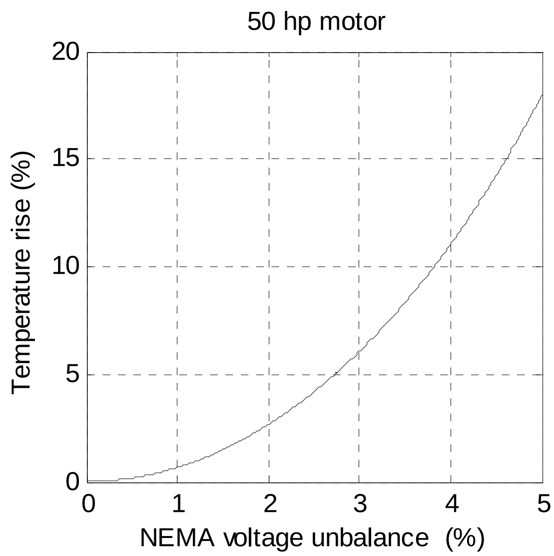


Fig. 4.62 Percent temperature rise versus unbalanced voltage (case 2) for a 50 hp motor.

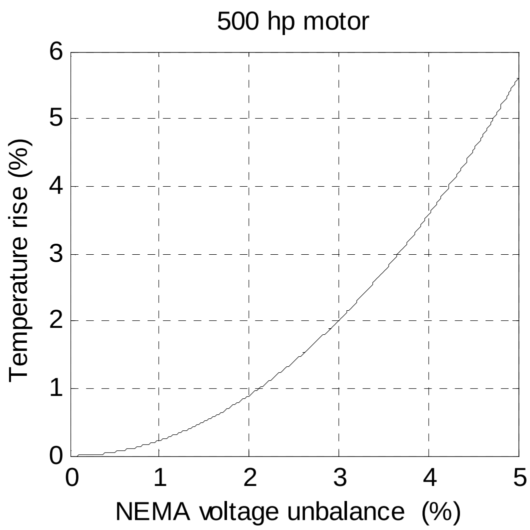


Fig 4.63 Percent temperature rise versus unbalanced voltage (case 2) for a 500 hp motor

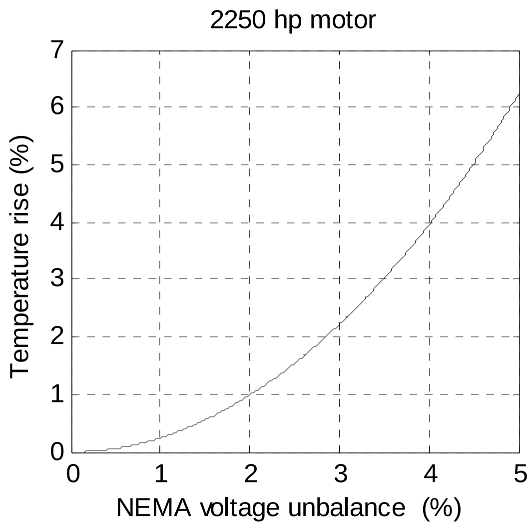


Fig 4.64 Percent temperature rise versus voltage (case 2) for a 2250 hp motor.

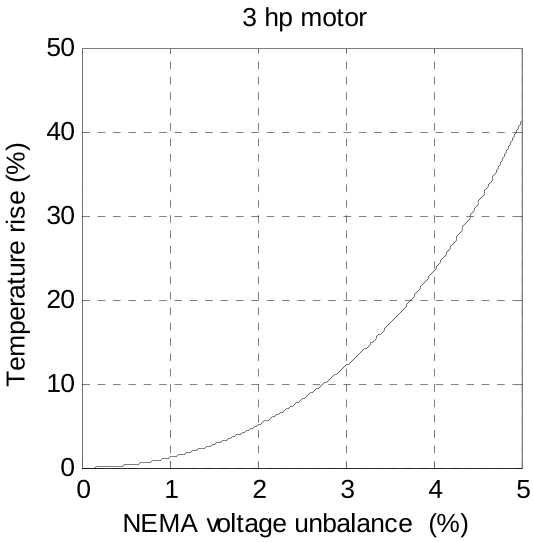


Fig. 4.65 Percent temperature rise versus unbalanced voltage (case 3) for a 3 hp motor.

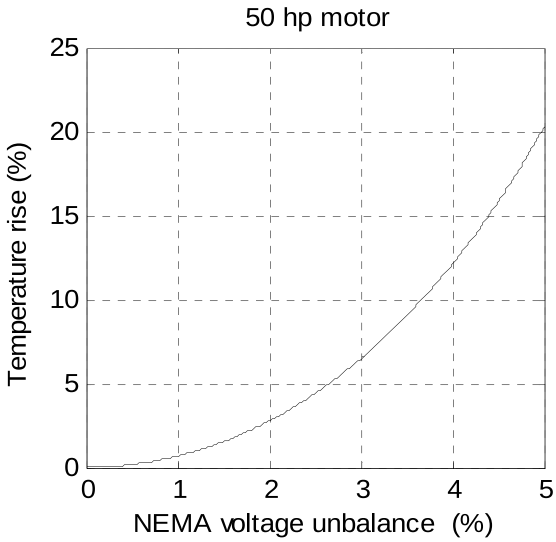


Fig. 4.66 Percent temperature rise versus unbalanced voltage (case 3) for a 50 hp motor.

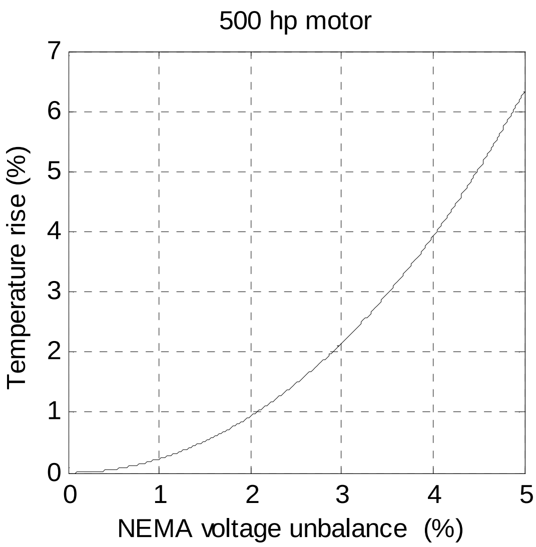


Fig. 4.67 Percent temperature rise versus unbalanced voltage (case 3) for a 500 hp motor.

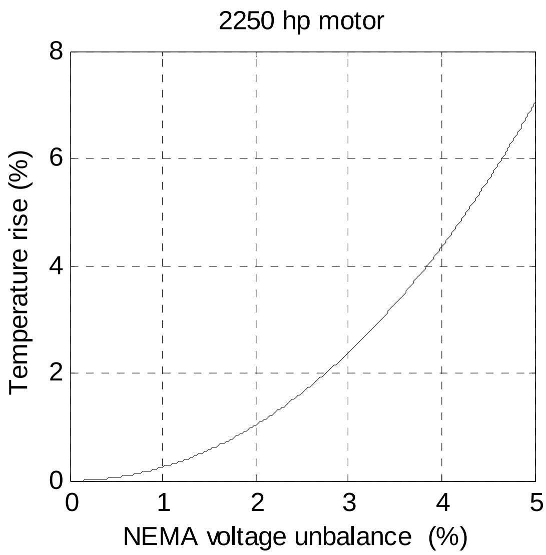


Fig. 4.68 Percent temperature rise versus unbalanced voltage (case 3) for a 2250 hp motor.

The following tables summarize the effect of 5% unbalanced voltages on the induction motor torque, current, losses, efficiency and derating factor for the four analyzed motors:

Balanced supply condition	3 hp	50 hp	500 hp	2250 hp
Line voltages (volts)				
V_{ab}	220/127	460/265.6	2300/1328	2300/1328
V_{bc}	220/127	460/265.6	2300/1328	2300/1328
V_{ca}	220/127	460/265.6	2300/1328	2300/1328
Phase sequence voltages (volts)				
V_p	127	265.6	1328	1328
V_n	0	0	0	0
Stator current (amps)				
I_s	7.64	51.7	45.42	138.9
Rotor current (amps)				
I_r	5.93	46.83	38.06	94.91
Losses Watts				
Stator	76.19	697.6	1622	1679
Rotor	85.68	1500	803	591.7
Total	161.9	2197	2425	2271
Efficiency (%)	88.81	89.80	97.8	99.23
rated torque (Nm)	11.36	189.4	774.6	1962
Power factor (%)	76.19	88.38	81.58	67.11

Table 4.1 Balanced Steady State Performances at Rated Condition.

IEC (5%) VUF	3 hp	50 hp	500 hp	2250 hp
Line voltages (volts)	220	460	2300	2300
Phase sequence voltages (volts)				
V_p	127	265.6	1328	1328
V_n	6.35	13.28	66.4	66.4
Stator currents (amps)				
I_a	11.2	68.49	67.45	260.3
I_b	5.31	32.01	19.78	53.69
I_c	7.93	60.29	59.35	206.7
Rotor currents (amps)				
I_a	8.45	61.1	50.87	172.1
I_b	2.31	26.39	14.71	59.7
I_c	8.21	58.49	60.55	216.8
Losses (per unit)				
Stator	1.237	1.166	1.367	1.958
Rotor	1.373	1.193	1.507	2.981
Total	1.309	1.185	1.413	2.225
Efficiency (%)	85.1	87.88	96.84	98.16
Torque (Nm)	11.27	188.7	773.5	1959
Power factor (%)	72.43	86.63	77.29	54.84
Derating (%)	95.77	97.68	99.29	99.22

Table 4. 2 Unbalanced Steady State Performances at 5 % VUF using IEC definition.

NEMA (5%) VUF	3 hp	50 hp	500 hp	2250 hp
Line voltages (volts)				
V_{ab}	220	460	2300	2300
V_{bc}	231	483	2415	2415
V_{ca}	209	437	2185	2185
Phase sequence voltages (volts)				
V_p	126.91	265.35	1326.8	1326.8
V_n	7.34	15.34	76.73	76.73
Stator currents (amps)				
I_a	11.76	71.26	71.19	280.3
I_b	5.1	29.08	16.32	60.47
I_c	8.12	62.13	62.31	222.9
Rotor currents (amps)				
I_a	8.9	60.70	53.81	189.8
I_b	1.75	23.19	12.54	76.99
I_c	8.64	63.56	64.35	236.8
Copper Losses (per unit)				
Stator	1.315	1.2	1.489	2.278
Rotor	1.497	1.232	1.675	3.645
Total copper losses	1.411	1.222	1.551	2.634
Efficiency (%)	83.87	87.25	96.52	97.81
Torque (Nm)	11.23	188	771.8	1954
Power factor (%)	71.66	86.19	75.77	50.67
Derating case 1 (%)	94.21	96.75	98.89	98.77
Temperature rise case1 (%)	10.68	5.77	1.91	2.12

Table 4.3 Unbalanced Steady State Performances at 5 % VUF using NEMA definition.

NEMA (5%) VUF	3 hp	50 hp	500 hp	2250 hp
Derating case 1 (%)	94.21	96.75	98.89	98.77
Derating case 2 (%)	83.42	90.74	96.84	96.51
Derating case 3 (%)	81.6	89.71	96.45	96.08
Temperature rise case1 (%)	10.68	5.77	1.91	2.12
Temperature rise case 2 (%)	36.09	17.96	5.6	6.22
Temperature rise case 3 (%)	41.19	20.28	6.33	7.03

Table 4.4 Derating and percent temperature rise at 5 % VUF using NEMA definition with different unbalanced voltage cases

4.6 Conclusion

According to NEMA definition of voltage unbalance, the predicted additional losses are higher for all motors. This is expected, as **5 %** voltage unbalance with NEMA definition can be proved to be equivalent to **5.8%** voltage unbalance according to IEC definition.

Due to the negative sequence current component under unbalanced condition, the stator and rotor maximum phase currents at rated speed are greater than the nominal rated one with balanced condition. Also the starting current is higher at **5%** voltage unbalance than that at balanced supply ranging from **4.5%** to **5.7%**.

From a mechanical point of view, an effect on torque developed is negligibly small. The electromagnetic torque is decreasing only very slightly with the voltage unbalance normally tolerated (up to **5%** voltage unbalance).However, severe voltage unbalance at starting can put the motor at risk of thermal damage as the available accelerating torque at starting is seriously weakened for low power motors. Figures 4.4 to 4.7 show the torque speed characteristics of the induction motors under balanced and unbalanced supply condition at **5%** and **20%** voltage unbalance using the NEMA definition where the mechanical effects remain negligible. This should not occult thermal effects which remain basically important and potentially damaging.

The additional per unit loss is increasing with power level and is maximum for the highest power motor **2250 hp**, reaching a **163%** loss increase at **5%** voltage unbalance. It must be noted that losses calculated are only the copper losses. It therefore appears plausible, that heating loss is important but also can actually be higher as other components of losses have not been included in the calculations of tables 4.2 and 4.3.

Efficiency figures are typical of standards efficiency motors, and increase with power level as expected. According to NEMA definition of voltage unbalance, efficiency figures obtained are more conservative for reasons indicated above.

The power factor calculations have been done at **5%** voltage unbalance showing that the case is that of using the NEMA definition compared with that of IEC definition, with the lowest value of **50.67%** for the 2250 hp motor.

There is a definite amount of derating required because of unbalanced supply condition. This derating varies depending on the power of the induction motor; the attainable power ranging from **94.21%** up to **98.89%** for the higher horse power motors which is seen to indicate that derating of highest power level induction motors is negligible, this obtained by keeping one phase voltage constant at the rated value with the other two varying such that the average voltage is equal to the rated one. This is the first case unbalance.

Two other unbalanced cases have been studied to illustrate the effects of unbalanced voltages on the induction motor derating. The second case is chosen by increasing two line voltages and the other one is decreased such that the average line voltages is equal to the rated voltage. The third unbalanced case is obtained by decreasing two line voltages and the other one is increased such that the average line voltages is equal to the rated voltage.

A derating factor curve recommended by NEMA gives factors only as a function of the voltage unbalance percent without considering an unbalanced terminal voltages condition. Actually, many voltage unbalance cases with the same voltage unbalance factor may have quite different derating curves.

The third case represents the worst case unbalance. The temperature rise is high for the motors less than **500 hp** power level. The temperature rise at maximum tolerated voltage unbalance of **5%**, can reach **42%**. According to NEMA rule of thumb, the temperature rise deduced from measurements would be **50%**. This lower conservative prediction of **42%** can be explained by the fact that we have assumed that the supply average value is constant at its rated value.

All insulating materials will undergo varying degrees of aging or deteriorating under normal and abnormal operating conditions. The rate of aging will be contingent upon the magnitude of the electrical, thermal, and mechanical stresses to which the material is subjected [36]. The useful life of an insulating system will thus be determined by a given aging variables. For example, the thermal stress depends on the upper and lower ambient temperatures, the temperature gradient in the insulation, and the maximum permissible operating temperature.

Not all parts of the motor windings operate at the same temperature. The temperature at the center of the coil is the hottest and is referred to as the hot spot temperature [5]. The hot spot temperature is the basis for establishing the insulation class rating.

With the same voltage unbalanced factor, each voltage unbalance case would lead to a different degree of temperature rise of the induction motors. This means that the way the terminal voltages are unbalanced has an important effect on the induction motor temperature rise.

5

CHAPTER 5
INDUCTION MOTOR UNDER SINGLE PHASING CONDITION

5.1 Introduction

Single phasing can be regarded to be an extreme case of unbalanced operation. It is not a common condition but may be considered during a fault situation following a loss of one phase of the three phase supply or even when it is intentionally desired to connect a three phase motor to a single phase supply. This condition is known as “single phasing”.

If a three-phase motor is running when the single phase condition occurs, it will attempt to deliver its full horsepower enough to drive the load. The motor will continue to try to drive the load until the motor burns out or the protection elements take the motor off the line. Single phasing results in an increase of the phase currents and the overheating caused by these currents often destroys the motor [37].

The loss of a phase on a three-phase line may be due to a downed line or a blown pole top fuse on the utility system. Loss of a single phase may also result from a single-phase overload condition causing one fuse to blow, or an equipment failure within the end-user's facility.

5.2 Effect of single-phasing on three-phase motors

The majority of stator winding damage of a three-phase induction motor is due to overheating caused by the disconnection of one of the supply phases. Under these circumstances the load on the shaft does not usually change, and therefore the currents in the stator windings increase and the overheating caused by these currents often destroys the isolation. They vary for different parts of an induction motor and influence the stator winding temperature rise in different ways.

If single-phasing occurs when a motor is rotating, the torque produced by the remaining two positively rotating fields continues to rotate the motor and develop the torque demanded by the load, but this motor is not capable of starting on a single phase.

For lightly loaded three-phase motors, say **70%** of normal full-load amperes, the phase current will increase by the square root of three **(**$\sqrt{3}$**)** of the rated current under balanced conditions [38], [39], [40]. This will result in a current draw of approximately **20%** more than the nameplate full load current [38].

5.3 Open phase model

The following figure illustrates the open phase condition. Where phase “a” has been opened [41].

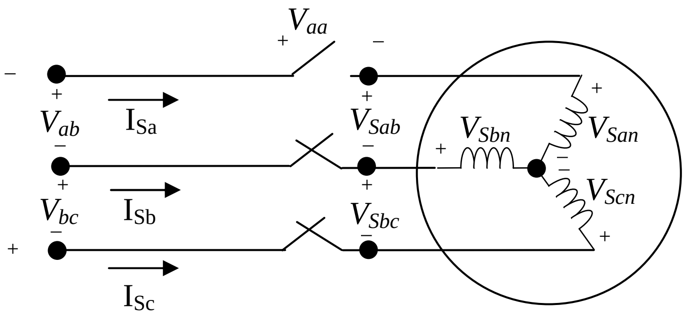


Fig 5.1 Open phase-a serving an induction motor

V_{ab} ; V_{bc} ; V_{ca} are system line-to-line voltages.

V_{Sab}; V_{Sbc}; V_{Sca} are the operating line-to-line voltages at the motor terminals.

V_{San}; V_{Sbn}; V_{Scn} are the stator line-to-neutral voltages.

I_{Sa}; I_{Sb}; I_{Sc} are the line currents.

For this operating condition the line currents must satisfy:

$$\begin{aligned} I_{Sa} &= 0 \\ I_{Sc} &= -I_{Sb} \end{aligned} \tag{5.1}$$

The symmetrical component sequence currents therefore are:

$$\begin{aligned} \begin{bmatrix} I_{S0} \\ I_{Sp} \\ I_{Sn} \end{bmatrix} &= \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} . \begin{bmatrix} 0 \\ I_{Sb} \\ -I_{Sb} \end{bmatrix} \\ &= \begin{bmatrix} 0 \\ (a-a^2).I_{Sb} \\ (a^2-a).I_{Sb} \end{bmatrix} = \begin{bmatrix} 0 \\ j\sqrt{3}.I_{Sa} \\ -j\sqrt{3}.I_{Sa} \end{bmatrix} \end{aligned} \tag{5.2}$$

From equation (5.2), it is noticed that

$$I_{Sn} = -I_{Sp} \tag{5.3}$$

In order to satisfy equation (5.3), the positive and negative sequence networks for the induction motor must be connected as shown in Figure (5.2).

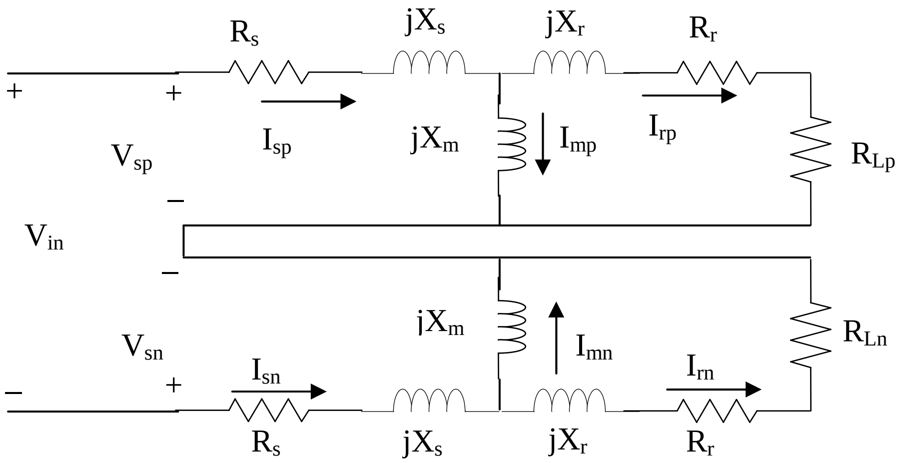


Fig 5.2 Sequence network connection

In figure **5.2**, the input voltage is given by

$$V_{in} = V_{Sp} - V_{Sn} \tag{5.4}$$

Substituting the expansion of the positive and negative sequence voltages in terms of the phase line-to-neutral voltages

$$V_{Sp} = \frac{1}{3}(V_{San} + a.V_{Sbn} + a^2 V_{Scn})$$
$$V_{Sn} = \frac{1}{3}(V_{San} + a^2.V_{Sbn} + a\ V_{Scn})$$
$$V_{in} = \frac{1}{3}(V_{San} - V_{San} + (a - a^2).V_{Sbn} + (a^2 - a).V_{Sbn}\ ) \tag{5.5}$$
$$V_{in} = \frac{1}{3}(j\sqrt{3}.V_{Sbn} - j\sqrt{3}.V_{Scn}) = j\frac{\sqrt{3}}{3}(V_{Sbn} - V_{Scn})$$
$$V_{in} = j\frac{V_{Sbc}}{\sqrt{3}}.$$

5.4 Equivalent circuit analysis

The analysis of the circuit of figure 5.2 is best accomplished by first computing the equivalent positive and negative sequence impedances at the terminals of the networks. In order to do this, a value of slip must be assumed.

Assume the positive sequence slip is s_1. Then the negative sequence slip is given by

$$s_n = 2 - s_p \tag{5.6}$$

The load resistances of the two networks are:

$$R_{Lp} = \frac{1 - s_p}{sp}.R_r$$

$$R_{Ln} = \frac{1 - s_n}{s_n}.R_r \quad = \frac{-1 + s_p}{2 - s_p}.R_r \tag{5.7}$$

Note in equation (5.7) that the negative sequence load resistance will be negative since the positive sequence slip is always a value of one or less.

The general equation for the input equivalent impedance at the terminals of the networks is given by:

$$Z_{eqi} = Z_{si} + \frac{Z_r + R_{Li}}{jX_m + Z_r + R_{Li}} \tag{5.8}$$

Where, i is p for positive sequence.

i is n for negative sequence.

Z_{si} is the stator impedance.

Z_r is the rotor impedance.

The stator sequence currents are then,

$$I_{sp} = \frac{V_{in}}{Z_{eqp} + Z_{eqn}}$$

$$I_{sn} = -I_{sp} \tag{5.9}$$

$$I_{s0} = 0.$$

The stator input line currents are computed as:

$$\begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} . \begin{bmatrix} I_{s0} \\ I_{sp} \\ I_{sn} \end{bmatrix} \tag{5.10}$$

Where a is the Fortescue operator, is given by: $a = \exp\left(\frac{j2\pi}{3}\right)$

In a general form, equation (5.10) can be written as:

$$[Is_{abc}] = [A] \lfloor Is_{0pn} \rfloor \tag{5.11}$$

The sequence rotor currents are given by

$$I_{ri} = I_{si} \cdot \frac{jX_m}{jX_m + Z_r + R_{Li}} \tag{5.12}$$

The sequence line-to-neutral stator voltages are

$$V_{s0} = 0 \tag{5.13}$$

$$V_{si} = Z_{eqi} \; .I_{si} \tag{5.14}$$

Where, i is p or n.
The equivalent line-to-neutral stator terminal voltages are

$$\begin{bmatrix} V_{san} \\ V_{sbn} \\ V_{scn} \end{bmatrix} = [A] \; . \; \begin{bmatrix} V_{s0} \\ V_{sp} \\ V_{sn} \end{bmatrix} \tag{5.15a}$$

or

$$\lfloor V_{LN\, s_{abc}} \rfloor \; = \; [A] \; \lfloor Vs_{0\,pn} \rfloor \tag{5.15b}$$

The line-to-line stator voltages are:

$$\begin{bmatrix} V_{sab} \\ V_{sbc} \\ V_{sca} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \; . \; \begin{bmatrix} V_{san} \\ V_{sbn} \\ V_{scn} \end{bmatrix} \tag{5.16a}$$

Or

$$\lfloor V_{LL\, s_{abc}} \rfloor \; = \; [D] \; \lfloor V_{LN\, s_{abc}} \rfloor \tag{5.16b}$$

The stator line-to-line voltages will not be the same as the secondary line-to-line voltages. Because of this, a voltage V_{aa} will appear across the switch (fuse), which is given by

$$V_{aa} = \; V_{ab} - Vs_{ab} \tag{5.17}$$

The total converted sequence powers are given by

$$P_{conv_i} = 3.\left|I_{ri}\right|^2 .R_{Li} \tag{5.18}$$

Where $i = p \;\; or \;\; n$.

The negative sequence load resistance is a negative number so that the converted negative sequence power will be negative, which adds to the effective rotor power loss.

The total converted power is

$$P_{conv_{total}} = P_{convp} + P_{convn} \tag{5.19}$$

The total stator and rotor power losses are respectively

$$P_{Loss\ stator} = 3.\left(\left|I_{sp}\right|^2 + \left|I_{sn}\right|^2\right).R_s \tag{5.20}$$

$$P_{Loss\ rotor} = 3.\left(\left|I_{rp}\right|^2 + \left|I_{rn}\right|^2\right).R_r \tag{5.21}$$

5.5 Computed performance under single phasing results and discussion

The above analysis is now used to illustrate the effects of single phasing on the induction motor, the four motors whose parameters are given in appendix A, they are analysed with phase "a" opened. Table 5.1 summarizes the results of the performance calculations for the induction motors operating under steady state conditions.

Parameters	3 hp	50 hp	500 hp	2250 hp
Line voltages (volt)				
V_{ab}	194.73	390.11	2084.1	2210.9
V_{bc}	219.97	460.03	2300.2	2300.2
V_{ca}	186.92	399.97	2105.5	2171.5
L-N voltages (volt)				
V_{an}	103.99	214.14	1167.3	1243.5
V_{bn}	123.68	251.14	1283.9	1318.4
V_{cn}	119.60	256.26	1295.5	1296.3
Stator currents (amps)				
I_a	0	0	0	0
I_b	11.63	77.07	71.56	205.02
I_c	11.63	77.07	71.56	205.02
Rotor currents (amps)				
I_a	11.34	83.69	73.05	168.36
I_b	2.84	28.09	19.65	50.93
I_c	8.95	55.89	54.68	158.54
Losses Watts				
Stator	117.84	1033.6	2684	3028.2
Rotor	144.80	2312.1	1394.3	1250.5
Total	262.65	3345.7	4078.3	4278.7
Converted power KVA	1.7255	27.744	122.710	255.490
Torque (Nm)	9.03	146.59	650.26	1353.3

Table 5.1 Summary of induction motor parameters under single-phasing operation

The computation results show the increase in the stator currents compared to the balanced condition. The rotor currents also increase in phase "a" and phase "c" but a decrease in phase "b".

The copper losses have greatly increased by up to **68%** in comparison with normal healthy condition. Whereas the mechanical torque developed by the motor has decreased by up to **31%**.

The torque speed characteristics of the four induction motors under single phasing and balanced healthy cases of different power levels are shown in figures 5.3 through to 5.6. The shape of the torque speed characteristics over the remaining operating part has changed drastically; the pull out torque has greatly decreased down to a maximum of **70%** and moved to a higher slip value.

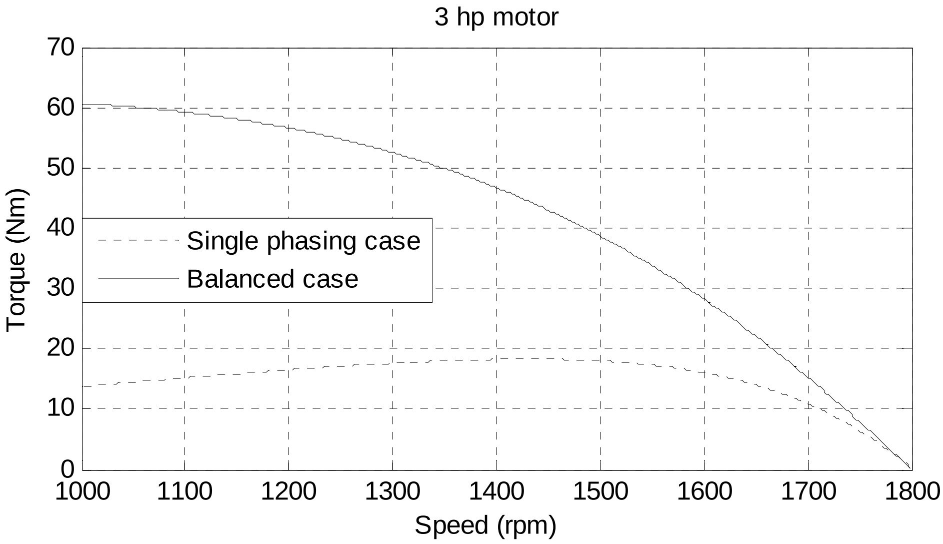


Fig 5.3 Torque speed characteristics under single phasing condition for a 3 hp motor.

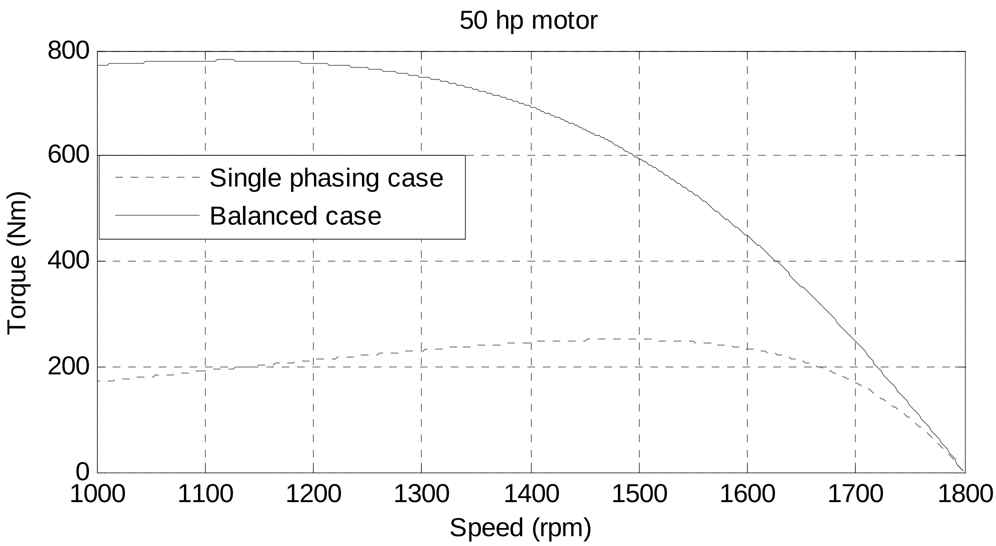


Fig 5.4 Torque speed characteristics under single phasing condition for a 50 hp motor.

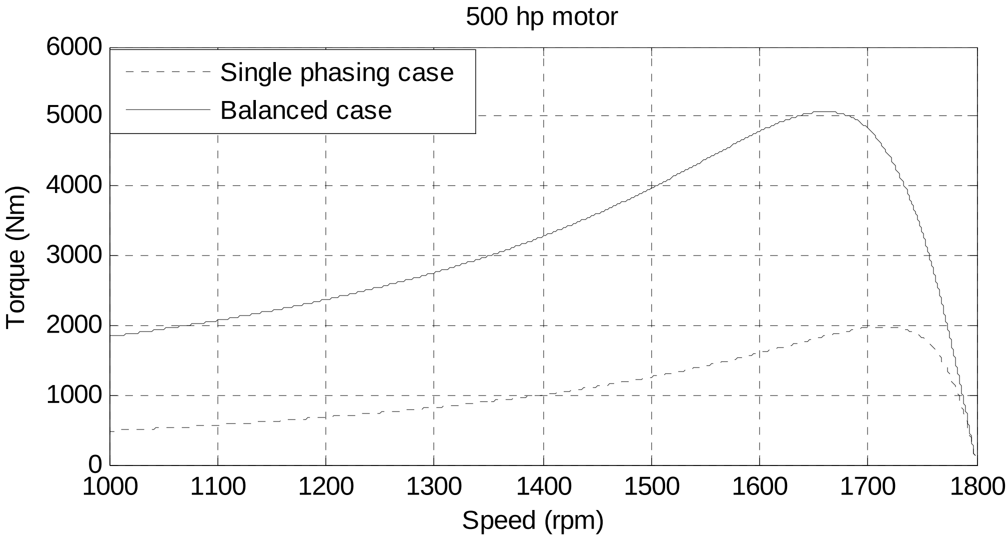


Fig 5.5 Torque speed characteristics under single phasing condition for a 500 hp motor.

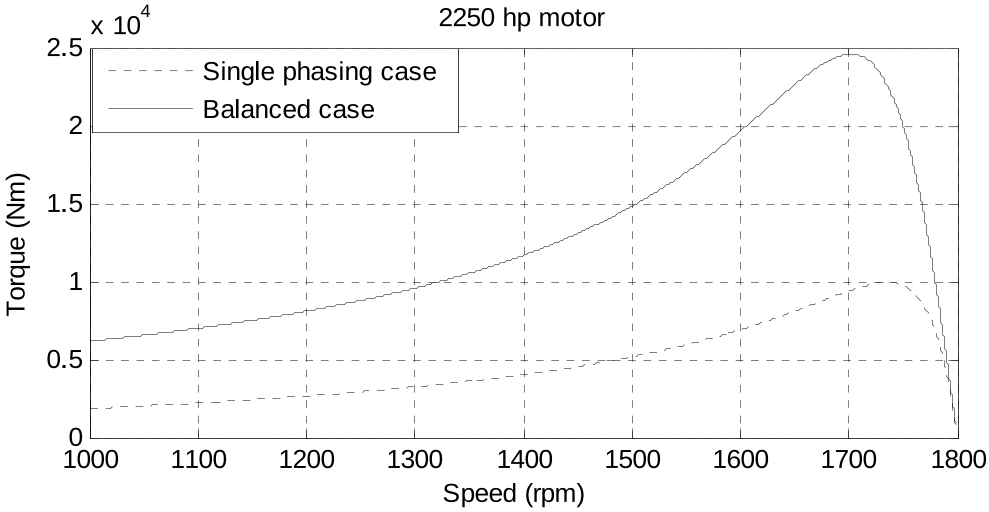


Fig 5.6 Torque speed characteristics under single phasing condition for a 2250 hp motor.

The motor will draw much higher currents in the healthy phases, to supplement the lost phase, as well as to compensate for the higher slip losses this is putting motors under heavy thermal stress. It may even stall if it was operating at more than **70%** of the rated torque at the time of single phasing [42]. Again because of no electrical to mechanical power conversion, thermal stress will be excessive and rapid motor disconnection becomes mandatory.

Furthermore, if the motor is switched on, in a single phasing condition, it will not rotate because of the absence of the rotating field the starting torque being zero. This will make thermal stress even less tolerable requiring immediate disconnection of the motor.

5.6 Conclusion

Single phasing represents an extreme condition of unbalanced voltage operation. A three-phase induction motor operating in the steady-state will continue to operate with a single phasing condition. The motor windings overheat due primarily to the flow of negative-sequence current, a condition that exists anytime there is a phase voltage unbalance. Under single phasing, induction motors may continue to run (but will not start) if one of the three-phase supply lines is disconnected. Speed will drop slightly, but currents, heating effects also noise (vibration) will greatly increase as well as the losses, hence an important decrease in efficiency.

The computed results of the problem are summarized in table 5.1. These results illustrate the very important decrease in motor developed torque; the great increase in motors currents, hence an increase in winding losses exceeding those incurred under the maximum voltage unbalance tolerated as expected. This will result in an operating condition that produces excessive heating in the motor, requiring an adequate, efficient protective scheme that will disconnect the motor from the system before it gets permanently damaged.

CONCLUSION

The voltage unbalance is a problem that affects induction motor performance in terms of higher losses and higher winding temperatures decreasing therefore machine efficiency and putting more thermal stress of machine insulation, hence accelerating the material fatigue and shortening machine nominal life time. Voltage unbalance is therefore detrimental to motor efficiency and reliability by causing higher losses and higher temperatures.

Under real operating conditions, the supply voltage is far from being perfect and balanced. It is assumed in this study that though the supply is sinusoidal, it is not balanced i.e. a given percentage of voltage unbalance is assumed.

The induction motor steady state analysis has first been carried out assuming balanced three phase sinusoidal supply system, the per phase equivalent circuit used to compute the steady state performance of the essential machine parameters of four induction motors in terms of:

- The developed torque
- The stator current
- The efficiency
- The power factor

Calculations have shown the relative magnitudes of the parameters in particular the torque speed characteristics being function of the type of the machine design.

Assuming the induction motors being fed from a three phase sinusoidal supply, the two most important definitions of voltage unbalance have been studied and compared in terms of their implications. The NEMA definition of voltage unbalance is less pessimistic.

Calculations show that a **5%** NEMA definition of voltage unbalance is equivalent to **5.8%** of voltage unbalance using the IEC definition. According to NEMA definition of voltage unbalance the average of the terminal voltages is assumed to be equal to the rated voltage of the supply. The positive sequence voltage is assumed to be equal to the phase rated voltage used with the IEC definition of voltage unbalance.

The theory of symmetrical components is used as a tool in the analysis of the effects of unbalanced supply voltages on the induction motors using the two definitions of voltage unbalance given above. This analysis also stresses on the NEMA definition of voltage unbalance with different terminal voltages but same average voltage which is taken to be the rated supply voltage.

It has been found that an excessive level of voltage unbalance can have serious impacts on induction motors. The level of current unbalance that is present is several times the level of voltage unbalance. The current unbalance factor when correlated to a given voltage unbalance factor is maximum at full load operation.

The results show that starting torque and pull out torques are only slightly affected (less by **0.5 %** decrease for the maximum tolerable value of voltage unbalance under steady state operation) with the effect on full load torque negligibly small. At an abnormally high value of voltage unbalance (faulty condition) the motor is exposed to a risk of damage, a lower starting torque due to excessive voltage unbalance will put the motor under higher mechanical and thermal stress as the acceleration time will be longer to build up to full load steady state speed.

For the maximum value of voltage unbalance tolerated (nominally 5% according to NEMA standards) the current effects can be quite important; the maximum phase currents at rated speed are greater than those at balanced sinusoidal supply condition by as much as **40%** due to the negative sequence currents. Because of these currents, the total stator and rotor additional losses increase considerably with unbalance voltage which leads to an important decrease in motors efficiency.

Also the power factor deteriorates with the supply voltage unbalance, calculations showing the worst case for the lower power rating motor.

For a same percent voltage unbalance figure, the two definitions of voltage unbalance will yield calculated results that are very close. The percent voltage unbalance can be the results of different combinations of terminal voltage magnitude. Depending on the particular combinations of terminal voltage magnitudes, effects can be widely different i.e. the percent voltage unbalance factor need to be further specified in terms of values for each phase voltage, as the same percentage voltage unbalance taken on its own will imply various combinations whose effects will be very different yielding higher losses and temperature therefore entailing higher motor derating.

Furthermore the study indicates that the percentage voltage unbalance figure is not enough by itself. The results indicate that for a tolerated **5%** voltage unbalance, relative losses depend on the motor power rating; they can be increased from **22.2%** up to **163%** for highest power rating machines.

As for the amount of derating required, results indicate that it is higher for lower power rating machine, derating factor of **81.6%**, they decrease with increasing machine power rating. The results will appear somewhat more optimistic on the basis of the NEMA standards.

The induction motor under unbalanced voltage supply can not meet the load requirements; this is because of the decreasing developed torque on the one hand and increased motor currents on the other. Derating becomes necessary in order to avoid excessive heating and additional losses, the figure of required derating arrived at in this study although slightly more optimistic, basically agree with various published figures (NEMA standards), they depend on motor power rating and can reach up to **25%** derating for motor population below 500 hp.

The study indicates that the predicted temperature rise is maximum for the lowest power rating machines.

Under single phasing condition the motor windings overheat due primarily to the flow of negative-sequence current. The current is increasing to a maximum of order of $\sqrt{3}$ times greater than that at the normal conditions. The three-phase motors may continue to run, but they are not capable of starting under single phasing condition.

Suggestions for further work

In the perspective of comparison predicted and real performance it is suggested a field study of induction motors operating in industry under their real load condition with on site measurement of voltage unbalance, efficiency and additional losses.

REFERENCES

[1] J. Oyama, F. Profumo, E. Muldjadi and T. A. Lipo “A Digital Voltage Controller for Reducing Induction Motor Phase Unbalance”. *Wisconsin Electric Machines and Power Electronics Consortium*. U.S.A. September 1988.

[2] NEMA Standard Publication MG-1, 1993, “Motors and Generators,” *National Electrical Manufacturers Association*, Washington, D.C.

[3] H.Austin Bonnett,” Operating Temperature Considerations and Performance Characteristics for IEEE 841 Motors”. *Copyright Material IEEE*, paper no. PCIC- 2000-08.

[4] Energy Tips, “Motor tips”. *Office of Industrial Technologies*, Energy *Efficiency and Renewable Energy*. U.S. January, 2000.

[5] Engineering data, “Integral AC Motor Selection and Application Guide for Fans”, *Information and Recommendations for the Engineer*,1999.

[6] Yaw-Juen Wang “Analysis of Effects of Three-Phase Voltage Unbalance on Induction Motors with Emphasis on the Angle of the Complex Voltage Unbalance Factor” *IEEE Trans. Energy Conversion*, vol.16, no.3, pp. 270-275, September 2001.

[7] K. Bimal Bose “Moderns Power Electronics and AC Drives” *Prentice Hall, USA.* 2002.

[8] Sanna Pöyhönen, “Support Vector Machine based Classification in Condition Monitoring of Induction Motors” *Helsinki University of Technology Control Engineering Laboratory*, 2004.

[9] S.A.Nasar and L.E. Unnewehr, “Electromechanics and electric Machines”, second edition, *JOHN WILLEY & SONS*. 1979.

[10] NEMA Standards Publication MG 10-2001 “Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors”. 2001.

[11] Rakesh Parekh, “AC Induction Motor Fundamentals“. *Microchip Technology Inc*. 1999.

[12] D.P.SenGupta, T.W.Lynn, “electric machines dynamics”, *Macmillan Press Ltd.*, *Hong Kong*, (1880).

[13] Licon electric Company, “Fundamentals of Poly-phase Electric Motors”, CLEVELAND, OHIO 44117-2525 U.S.A. December 1995.

[14] Vic Gosbell, Sarath Perera, Vic Smith, “Voltage unbalance”, *The Integral Energy Power Quality Centre of Electrical, Computer and Telecommunications Engineering at the University of Wollongong*. Technical Note No. 6, pp 1-10, October 2002.

[15] Pragasen Pillay, Peter Hofmann, and Marubini Manyage, “Derating of Induction Motors Operating With a Combination of Unbalanced Voltages and Over or Undervoltages” *IEEE Trans. Energy Conversion, vol. 17, no. 4,* December 2002.

[16] M. JOHN Macheler, “Motor /Drives Systems Specialist in Support of DOE’s Industries of the Future“, *MACRO International Inc. July 1998.*

[17] P. Pillay and M. Manyage, “Definitions of voltage unbalance,” *IEEE Power Eng. Rev. Mag.*, vol. 5, pp. 50-51, May 2001.

[18] Annette von Jouanne and Basudeb (Ben) Banerjee, “Assessment of Voltage Unbalance”. *IEEE Trans. Power delivery*,vol 16.no.4, pp 782-790, October2001.

[19] A. L. Jozef Ghijselen, P. M. Alex Van den Bossche, “Exact Voltage Unbalance Assessment without Phase Measurements”. *IEEE Trans. Power systems,* vol. 20, no. 1, pp. 519-520, February 2005

[20] Yaw-Juen Wang, “Analysis of Effects of Three-Phase Voltage Unbalance on Induction Motors with Emphasis on the Angle of the Complex Voltage Unbalance Factor” *IEEE Trans. Energy Conversion,* vol.16, no.3, pp. 270-275, September 2001.

[21] C.Brian Mann, G. T. Heydt, “Accuracy Improvement Strategies for Problematic Power System Measurements and Their Effect on State Estimation” *PSERC Publication 06-XX*, July 2006.

[22]W. H Kersting and W. H Phillips**,** "Phase frame analysis of the effects of voltage unbalance on induction machines," IEEE Transactions on Industry Applications, Vol. 33, No. 2, March /April 1997, pp 415-420.

[23] Jawad Faiz, “Influence of unbalanced voltage on the steady state performance of a three phase squirrel cage induction motor” *IEEE Trans. Energy Conversion,* vol.19,

No. 4, December 2004.

[24] Y. J. Wang, “An analytical study on steady-state performance of an induction motor connected to unbalanced three-phase voltage,” in *2000 IEEE Power Engineering Society Winter Meeting*, Singapore, Jan. 23–27, 2000.

[25] J.R. Linders, “Effects of power supply Variations on AC Motor Characteristics,” *IEEE Trans. on Industry Applications*, vol. 8, pp. 383-400, July/ Aug., 1972.

[26] L. Reffoufi, H. Bentarzi, F. Z.Dekhandji “Voltage Unbalance Effects on Induction Motor Performance”, *Proc. 6th WSEAS Inter. Conf. on Simulation, Modelling and Optimization*, Lisbon, Portugal, September 22-24, 2006.

[27] C. Y. Lee, “Effects of unbalanced voltage on the operation performance of a three-phase induction motor,” *IEEE Trans. Energy Conversion*, vol. 14, no. 2, pp. 202–208, June 1999.

[28] “Power Quality Solutions for Industrial Customers”, A Guidebook by the *California Energy Commission,*. August 2000.

[29] Pragasen Pillay, Peter Hofmann, and Marubini Manyage, “Derating of Induction Motors Operating With a Combination of Unbalanced Voltages and Over or Undervoltages” *IEEE Trans. Energy Conversion, vol. 17, no. 4,* December 2002.

[30] “Information Guide for General Purpose Industrial AC Small and Medium Squirrel-Cage Induction Motor Standards”, *NEMA Std Publication MG1*, 2002.

[31] P. B. Cummins, J. R. Dunki-Jacobs, and R. H. Kerr, “Protection of induction motors against unbalanced voltage operation,” *IEEE Trans. Industry Applications*, vol. IA-21, no. 4, pp. 778–792, May/June 1985.

[32] J. Brandolino and R.D. Findlay “Practical measurement of symmetrical component currents in induction motors”, *McMaster University*, Hamilton, Ontario.

[33] H. Austin Bonnett, and George C. Soukup,“Cause and Analysis of Stator and Rotor Failures in Three-Phase Squirrel-Cage Induction Motors”. *IEEE Trans. Industry Applications*, vol. 28, no. 4, July/August 1992.

[34] Hashem Oraee, “A Quantitative Approach to Estimate the Life Expectancy of Motor Insulation Systems”. *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 7, no.6, December 2000.

[35] H. Austin Bonnett,” Operating Temperature Considerations and Performance Characteristics for IEEE 841 Motors”. *Copyright Material IEEE,* paper no. PCIC-2000-08

[36] Chan, Shu-Park , The Electrical Engineering Handbook, *2nd* Ed. Richard C. Dorf Boca Raton: CRC Press LLC, 2000.

[37] E. M. Sebastiano de Oliveira," Operation of Three-Phase Induction Motors Connected to one Phase supply" *IEEE Trans. Energy Conversion, vol*. 5, no. 4, December, 1990.

[38] SUNILS.RAO, "Switchgear and Protection", 1992.

[39] COOPER Bussmann "Motor Protection against Single Phasing". Cooper Industries, Inc., Bussmann Division, U.S.A, May 1993.

[40] "IEEE Guide for AC Motor Protection", *IEEE Power Engineering Society,*U.S.A., 2000.

[41] W. H. Kersting, "Causes and Effects of Single-Phasing Induction Motors" *IEEE Trans. Industry Applications*, vol. 41, No. 6, pp 1499-1505, November/December 2005.

[42] K.C. Agrawal, "Industrial Power Engineering and Applications Handbook", *Newness Power Engineering Series*, 2001.

[43] M.G.Say, Alternating current machines, *Longman Singapore Publishers*, (1983).

[44] Paul Turnbull, John Kuo, Roy Schultz and Bruce Turner, "Thermal Analysis of an Electric Machine for a Hybrid Vehicle "*SAE technical paper series* 2004-01-05652004

[45] Chapman S. "Electric Machinery Fundamentals", 3rd Edition, *McGraw Hill, USA*, 1999.

[46]" Understanding Energy Efficient Motors". *EASA Reliable solution today*.

[47] F. Emad," Symmetrical Components and Unbalanced Faults". *ENEE 474, Electric Power Systems*, 2003.

[48] A. Robert Gannett, "Control Strategies for high Power four-leg Voltage Source Inverter" Master thesis in Electrical Engineering, *Blacksburg, Virginia*, July 30th, 2001.

APPENDICES

Appendix A

Specifications and characteristics of the induction motors used for torque, currents, power factor and efficiency speed characteristic under balanced sinusoidal operation. They are used also to show the effects of the unbalanced voltages on the induction motors.

The Three-phase, Y connected induction motors are:

1. 10 hp (7.5 KW) , 220 volts, 60 Hz, 6 poles, synchronous speed $\omega_s = 1800 \ rpm$, rotor speed, $R'_r = 0.144 \ \Omega$, $Rs = 0.294 \ \Omega$, $X_r = 0.209 \ \Omega$, $X_s = 0.503 \ \Omega$, $X_m = 13.25 \ \Omega$.

The parameters of the 3 hp, 50 hp, 500 hp and 2250 hp [43] are given by:

2. 3 hp (2.2 KW), 220 volts, 60 Hz, 4 poles, synchronous speed $\omega_s = 1800 \ rpm$, rotor speed $\omega_m = 1728 \ rpm$, $R'_r = 0.816 \ \Omega$, $Rs = 0.435 \ \Omega$, $X_r = 0.754 \ \Omega$, $X_s = 0.754 \ \Omega$. $X_m = 26.13 \ \Omega$.

3. 50 hp (37.3 KW), 460 volts, 60 Hz, 4 poles, synchronous speed $\omega_s = 1800\ rpm$, rotor speed $\omega_m = 1724\ rpm$, $R'_r = 0.228\ \Omega$, $Rs = 0.087\ \Omega$, $X_r = 0.302\ \Omega$, $X_s = 0.302\ \Omega$ $X_m = 13.08\ \Omega$.
4. 500 hp (373 KW), 2300 volts, 60 Hz, 4 poles, synchronous speed $\omega_s = 1800\ rpm$, rotor speed $\omega_m = 1790\ rpm$, $R'_r = 0.187\ \Omega$, $Rs = 0.262\ \Omega$, $X_r = 1.206\ \Omega$, $X_s = 1.206\ \Omega$. $X_m = 54.02\ \Omega$.
5. 2250 hp (1678.5 KW), 2300 volts, 60 Hz, 4 poles, synchronous speed $\omega_s = 1800\ rpm$, rotor speed $\omega_m = 1797\ rpm$, $R'_r = 0.022\ \Omega$, $Rs = 0.029\ \Omega$, $X_r = 0.226\ \Omega$, $X_s = 0.226\ \Omega$. $X_m = 13.04\ \Omega$.

Appendix B

Induction Motor Losses

The induction motor is essentially a conversion device, designed to accept an electrical three phase input, and produce a mechanical output in the form of torque from the rotor.

During the conversion from electrical power to mechanical power, there exist losses in the process that are impossible to avoid. They are generally described as follows:

a) Electrical stator Losses:

These originate at the stator windings, and are known as the stator copper losses (P_{SCL}). Since the stator windings are constructed of a copper conductor, current flowing through the conductor causes I^2R losses.

b) Iron (core) Losses (essentially independent of load):

There are additional power losses in the stator known as core losses (P_{core}) which comprise of hysteresis and eddy current losses. These losses can be described using Faradays law, and originate from a time changing magnetic flux inducing a voltage in a ferromagnetic core. However the magnitude of the voltage is not constant over the area of the iron, hence creating a potential difference between point points resulting in a current flow. The current flow more than often is in the shape of a swirl and this current flow is known as eddy currents. These currents in a resistive element produce losses in the form of heat. Hysteresis losses can be summarized as being are those encountered during each phase of the AC cycle whilst aligning magnetic domains in the core material. These losses occur in both the stator and the rotor and therefore can be represented at either point in the power flow diagram. For this case they are assumed to be on the stator side as displayed in figure 1.

The core losses in Watts/kg of iron can be expressed as follows, where the first term represents hysteresis losses, and the second term eddy current losses [44];

$$P_{core} = K_h f \, B_m{}^2 + K_e (f \, \tau \, B_m)^2$$

Where; k_e = variable dependant on properties of core material

k_h = variable dependant on properties of core material

B = maximum flux density in machine

Appendix B

f = frequency of supply

τ = laminations thickness

The flux in a rotating machine can be defined as

$$B_m = \frac{\phi_m}{A} = \frac{E}{4.44 f \; N \; A} = \frac{C_m E}{f}$$

Where E = air gap RMS voltage. N = number of turns,

A = Cross sectional area. C_m = Machine constant.

Substituting the above equation into the core loss equation gives;

$$P_{core} = \left[K_h \left(\frac{1}{f} \right) + K_e \tau^2 \right] (E \; C_m)$$

This equation relates to the fundamental frequency of 60Hz only, and all losses are given in Watts.

c) **Electrical rotor Losses** [45]:

The rotor copper losses (P_{RCL}) encountered in conversion are due to the flow of induced current in the rotor. Which are proportional to the current squared times the rotor resistance (I^2R). The remainder of the power after the rotor copper losses is converted from electrical to mechanical power and is known at this stage as power converted (P_{conv}). The stator and rotor copper losses constitute the bulk of the electrical losses associated with induction motor performance (up to 60%).

Appendix B

d) Mechanical (friction and windage) Losses (independent of load):

The mechanical rotational losses caused by friction of the shaft in contact with the ball bearings, windage losses (cause by cooling fans). These losses are generally small in open, low speed motors, but may be appreciable in large, high-speed or totally-enclosed fan-cooled motors.

e) Stray Load Losses:

The additional fundamental and high-frequency losses in the iron; strand and circulating-current losses in the stator winding; and harmonic losses in the rotor conductors under load. The stray losses are subtracted from the power converted (P_{conv}) and the output power can be determined. The mechanical losses ($P_{F\&W}$ and P_{stray}) are approximately proportional to the square of the speed and the contact surface area.

Figure (1) shows diagrammatically the power flow diagram of an induction motor, and how losses are distributed.

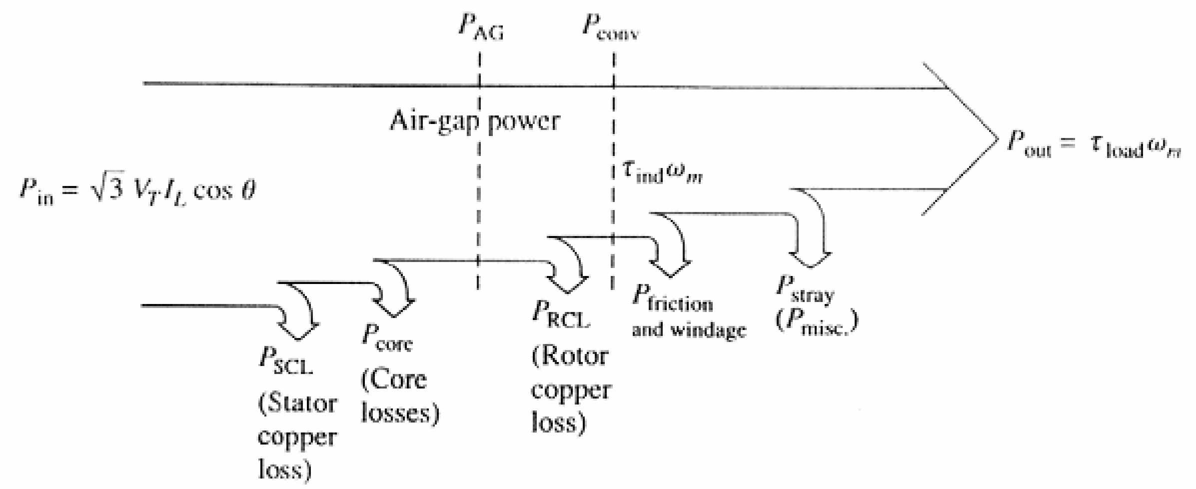


Fig 1. Power flow diagram

The figure above shows the typical losses concerned in the conversion of electrical to mechanical energy in a three phase induction motor. Core losses are displayed in this diagram is being on the stator side of the motor, however as mentioned previously core losses occur in both the rotor bars and stator windings

Appendix B

Listed below are the motor loss components, with the typical percent of the total motor losses they represent, and the design and construction factors which influence their magnitude [10], [46].

losses	**Typical Percent of Losses 4-Poles Motors**	**Factors Affecting These Losses**
Stator Losses	35 to 40	Stator conductor size and material
Rotor Losses	15 to 20	Rotor conductor size and material
Core Losses	15 to 20	Type and quantity of magnetic material
Stray Load Losses	10 to 15	Primarily manufacturing and design methods
Friction and Windage	5 to 10	Selection/design of fans and bearings

Appendix C

1. Symmetrical Components

When an unbalanced three-phase fault occurs, we can solve the three-phase circuit using ordinary circuit theory. This is much more numerically complicated than the single phase circuit normally used in balanced three phase circuits. The degree of difficulty increases with the third power of the system size. For this reason, it is apparent that if we were to solve three different single-phase circuits, it would be numerically simpler than solving the one three-phase circuit in one set of equations.

2. Fundamentals of Symmetrical Components

It was Fortescue in 1918 that developed the idea of breaking up asymmetrical three-phase voltages and currents into three sets of symmetrical components. These three basic components are [47]:

(1) The positive sequence currents and voltages (known also as the "abc" and often denoted by the superscript “p”, “1” or “+”) shown in fig.(c.1). Note this is the regular three-phase balanced phasors.

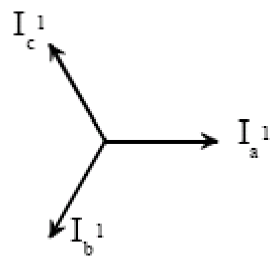


Fig C.1 The positive sequence currents

(2) The negative sequence currents and voltages (known also as the "acb" and often denoted by the superscript “n”,”2” or “-“). These are the regular balanced negative sequence components. Note the sequence of the phasors is the opposite direction from the positive sequence (acb instead of abc.)

Appendix C

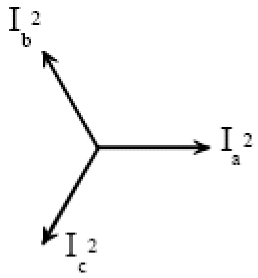


Fig C.2 The negative sequence currents

(3) The zero sequence components of currents and voltages (often denoted by the superscript "0".) These components are shown on the right. Note that these zero sequence phasors are all in-phase and equal in magnitude.

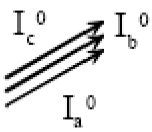


Fig C.3 The zero sequence currents

3. Symmetrical components transformations

3.1 Fortescue operator:

$a = 1\angle 120^{o}$, which is a unit vector at an angle of 120 degrees. It is easy to see that

$$a^2 = a^* = 1\angle 240^{o} = 1\angle -120^{o}$$

and

$$a^2 = 1$$

It is also clear that $1 + a + a^2 = 0.$

3.2 Positive sequence:

$$I^1{}_a = I^1{}_a\angle 0^\circ = I^1{}_a$$
$$I^1{}_b = I^1{}_b\angle 240^\circ = a^2\ I^1{}_a$$
$$I^1{}_c = I^1 c\angle 120^\circ = a\ I^1{}_a$$

Appendix C

3.3 Negative sequence:

$$I^2{}_a = I^2{}_a\angle 0^\circ = I^2{}_a$$
$$I^2{}_b = I^2{}_b\angle 240^\circ = a^2\ I^2{}_a$$
$$I^2{}_c = I^2 c\angle 120^\circ = a\ I^2{}_a$$

3.4 Zero sequence:

$$I^o{}_a = I^o{}_b = I^o c$$

The three-phase unbalanced set of currents I_a, I_b, and I_c is shown in the figure (C.4). Note that the vectors are arbitrary in length and direction.

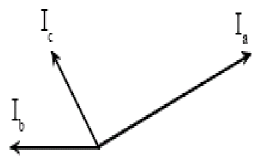


Fig C.4 The negative sequence currents

The same argument would hold if these were voltages instead of currents. These "abc" currents can be expressed in terms of the symmetrical components currents as follows:

$$I_a = I^o{}_a + I^1{}_a + I^2{}_a$$
$$I_b = I^o{}_b + I^1{}_b + I^2{}_b$$
$$I_c = I^o c + I^1{}_c + I^2{}_c$$

And we know that all the currents can be expressed in terms of the "a" components, thus:

$$I_a = I^o{}_a + I^1{}_a + I^2{}_a$$
$$I_b = I^o{}_a + a^2 I^1{}_a + a\ I^2{}_a$$
$$I_c = I^o{}_a + a\ I^1{}_a + a^2 I^2{}_a$$

Appendix C

Or in matrix form:

$$\begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \begin{pmatrix} I^o{}_a \\ I^1{}_a \\ I^2{}_a \end{pmatrix}$$

Which can be written as a single matrix equation as:

$$I^{abc} = A\ I^{012}{}_a$$

Where A is known as the symmetrical components transformation matrix [48], which transforms the currents I^{abc} into component currents $I^{012}{}_a$

$$A = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix}$$

Note that $A^T = A$ thus the A-matrix is symmetric.

Using matrix inversion we have:

$$I^{012}{}_a = A^{-1}\ I^{abc}$$

and the inverse matrix is given by:

$$A^{-1} = \frac{1}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}$$

And since

$$a^2 = a^*$$

We see that

$$A^{-1} = \frac{1}{3} A^*$$

Using the above equation it is seen that:

Appendix C

$$\begin{pmatrix} I^o{}_a \\ I^1{}_a \\ I^2{}_a \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}\begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix}$$

Or in detail:

$$I^o{}_a = \frac{1}{3}(I_a + I_b + I_c)$$
$$I^1{}_a = \frac{1}{3}\left(I_a + aI_b + a^2 I_c\right)$$
$$I^2{}_a = \frac{1}{3}\left(I_a + a^2 I_b + aI_c\right)$$

It is noted that $I^o{}_a$ is the sum of the three "abc" components, thus if the abc components are balanced, their sum is zero, hence the zero-sequence component is also zero.

The exact similar expressions are valid for voltages V^{abc} and $V^{012}{}_a$. These equations need not be repeated here.

Often it is understood that the quantities with superscript "0", "1", or "2" will have subscript "a" and the "a" is omitted. Thus instead of $I^o{}_a$ we use I^o and instead of $I^1{}_a$ we use I^1 and so on…

The three phase complex power is

$$S_{(3\phi)} = V^{abc^T} I^{abc^*}$$

The equation for complex power may be expressed in terms of symmetrical components thus:

$$S_{(3\phi)} = \left(AV^{012}{}_a\right)^T \left(AI^{012}{}_a\right)^*$$

And dropping the subscript "a" these may be written as:

$$S_{(3\phi)} = \left(AV^{012}\right)^T \left(AI^{012}\right)^*$$

$$= V^{012^T} A^T A^* I^{012^*}$$

Appendix C

Keeping in mind that "A" is symmetric and $A^T A^* = 3$ we have:

$$S_{(3\phi)} = 3\left(V^{012}\right)^T \left(I^{012}\right)^*$$

$$= 3V^o I^{o^*} + 3V^1 I^{1^*} + 3V^2 I^{2^*}$$

The last equation shows that the total unbalanced three-phase power is equal to the sum of the three symmetrical component powers. Note that in the above equations the subscript "a" was dropped from all those terms having superscript "012," "0," "1," or "2."

Appendix D

1. Insulation

An electric motor's insulation system is an assembly of insulating materials which separate electrical components from each other and prevent short circuits and winding burnout and failure. The endurance of the insulation system is affected by many factors such as temperature, electrical and mechanical stresses, vibration, harmful atmosphere and chemicals, moisture, and dirt, etc. Because temperature is very often the dominating ageing factor on insulating materials and insulation system of electric motors, the insulation systems are divided into classes according to their thermal endurance of the system for temperature rating purposes.

The stator winding insulation is one of the most important parts in large motor. It is always subjected to the combined thermal, mechanical, electrical and environmental stresses during the long-term operation. It is hence concluded that the residual life of large motor is decided by the life of stator insulation system to a great extent. Therefore it is very important for the safe operation of motor to inspect insulation condition and evaluate the residual life of stator wingding insulation.

Four classes of insulation systems are used in motor; namely, classes A, B, F, and H. Insulation Class Maximum Winding Temperature Rise Tatung standard motors are designed to have class F insulation with class B temperature rise. This gives an extra 25° C thermal safe margin. There is a rule of thumb that says a 10° C rise reduces the insulation life by half, while a 10°C decrease doubles the insulation life [32], [33], [35]. Thus such design will significantly extend the insulation life.

1.1 Class A:

A Class A insulation system is one which by experience or accepted test can be shown to have suitable thermal endurance when operated at the limiting Class A temperature of 105°C. Typical materials used include cotton, paper, cellulous acetate films, enamel-coated wire, and similar organic materials impregnated with suitable substances.

1.2Class B:

A Class B insulation system is one which by experience or accepted tests can be shown to have suitable thermal endurance when operated at the limiting Class B temperature of 130°C.

Typical materials include mica, glass fiber, asbestos and other materials, not necessarily inorganic, with compatible bonding substances having suitable thermal stability.

1.3 Class F:

A Class F insulation system is one which by experience or accepted test can be shown to have suitable thermal endurance when operating at the limiting Class F temperature of 155°C. Typical materials include mica, glass fiber, asbestos and other materials, not necessarily inorganic, with compatible bonding substances having suitable thermal stability.

1.4 Class H:

A Class H insulation system is one which by experience or accepted test can be shown to have suitable thermal endurance when operated at the limiting Class H temperature of 180°C. Typical materials used include mica, glass fiber, asbestos, silicone plasterers, and other materials, not necessarily inorganic, with compatible bonding substances, such as silicone resins, having suitable thermal stability.