Derating of Induction Motors Operating With a Combination of Unbalanced Voltages and Over or Undervoltages

Pragasen Pillay, *Senior Member, IEEE*, Peter Hofmann, and Marubini Manyage

***Abstract*—This paper examines the proper application of induction machines when supplied by unbalanced voltages in the presence of over- and undervoltages. Differences in the definition of voltage unbalance are also examined. The approach adopted is to use NEMA derating for unbalanced voltages as a basis to include the effects of undervoltages and overvoltages, through motor loss calculations.**

***Index Terms*—Equivalent circuit, negative sequence, positive sequence, unbalanced supplies.**

I. INTRODUCTION

THE proper application of induction motors to the power system to meet load requirements has been a subject of intense interest [1]–[13]. The majority of industrial motors in the US are designed for 460 V operation, yet the utility distribution system is designed for 480 V. The rationale here is that the cable voltdrop will allow the proper voltage of 460 V at the motor terminals. Measurements have shown that in spite of the cable drop, the motor terminal voltages can be substantially higher than 460 V in stiff industrial systems, while it may be well below the nominal voltage, when the system is heavily loaded in weak commercial or industrial systems.

Besides the overvoltage or undervoltage problem existing in the power system, the supply is never perfectly balanced. Usually, the level of unbalance is small enough so as not to affect the operation of the motors adversely; yet occasions arise when the level of unbalance must be accounted for in the proper application of the machine. This has been addressed by NEMA, using a definition of unbalance that differs from what is used in the power community. In addition, the unbalance assumes that the average value of the voltage is 460 V, a situation that rarely occurs in practice. It is the purpose of this paper therefore, to address the problem of the proper application of induction machines in the presence of a combination of unbalanced voltages and overvoltages or undervoltages. The differing definitions of voltage unbalance by the different communities are also addressed and the impact on the derating curve established.

II. DEFINITION OF VOLTAGE BALANCE

The definition of voltage unbalance used by the power community is the ratio of the negative sequence voltage to the positive sequence voltage. For a set of unbalanced voltages, V_{ab}, V_{bc}, V_{ca}, the positive and negative sequence voltages V_{ab1} and V_{ab2} are given by

$$V_{ab1} = \frac{V_{ab} + a^{*}V_{bc} + a^{2*}V_{ca}}{3}, \tag{1}$$

$$V_{ab2} = \frac{V_{ab} + a^{2*}V_{bc} + a^{*}V_{ca}}{3} \tag{2}$$

$$\text{where } a = -0.5 + j0.866 \text{ and } a^2 = -0.5 - j0.866. \tag{3}$$

For example, if the three unbalanced line to line voltages are $V_{ab} = 384$ at an angle of 82.8°, $V_{bc} = 576$ at an angle of $-41.4°$ and $V_{ca} = 480$ at an angle of 180°, then the positive sequence voltage V_{ab1} is 472.8 at an angle of 73.6° and the negative sequence voltage V_{ab2} is 112.8 at an angle of 220.3°. Therefore the "true" definition of % voltage unbalance is $(112.8/472.8)^{*}100 = 23.8\%$.

However the electrical machines' community in IEEE and NEMA use the following definition of voltage unbalance. NEMA MG1 for example, see (4) shown at the bottom of the next page.

In the previous example, the average is 480V and the maximum deviation from average is $576 - 480 = 96$. Therefore % voltage unbalance $= 100^{*}(96/480) = 20\%$. The IEEE, in the guideline for the testing of induction machines in IEEE 112, uses the same definition of voltage unbalance as NEMA, except that the phase voltages are used.

It is believed that the reason for using the above definitions of voltage unbalance is to avoid the use of complex algebra. A formula for calculating voltage unbalance which avoids the use of the complex algebra in symmetrical components, yet gives a good approximation of the true voltage unbalance is

$$\%\ \text{unbalance} = 82^{*}\frac{\sqrt{V_{abe}^2 + V_{bce}^2 + V_{cae}^2}}{\text{average line voltage}} \tag{5}$$

where V_{abe} = difference between the voltage V_{ab} and the average etc. In the above example, $V_{abe} = 480 - 384 = 96$, $V_{bce} = 576 - 480 = 96$ and $V_{cae} = 0$. Hence, % unbalance $= 23.2\%$, which is close to the actual unbalance of 23.8%. The induction machine will respond to the 23.8% unbalance, yet both NEMA and IEEE will be assuming a 20% unbalance for the same set of voltages.

Manuscript received June 18, 2001; revised March 1, 2002.

P. Pillay is with Clarkson University, Potsdam, NY 13699 USA.

P. Hofmann is with Consolidated Edison of New York, Manhattan, NY 10017 USA.

M. Manyage is with the Department of Electrical Engineering, University of Cape Town, Cape Town, South Africa.

Digital Object Identifier 10.1109/TEC.2002.805228

In order to understand the implications of using the two different definitions of voltage unbalance, the following analysis is given. Suppose E_a, E_b, E_c are three unbalanced voltages with

$$\bar{E}_a = E_a\angle 0^\circ,\ \bar{E}_b = E_b\angle\theta_b \text{ and } \bar{E}_c = E_c\angle\theta_c. \tag{6}$$

For a given voltage unbalance based on the NEMA definition, say 5% and assuming an average voltage of 460 V and call the voltage with the largest deviation from the average, E_a. Then

$$E_a - 460 = 0.05^{*}\text{average},\ E_a = 483 \tag{7}$$

and

$$\frac{E_a + E_b + E_c}{3} = 460 \quad E_b + E_c = 897. \tag{8}$$

Now

$$|E_b - 460| < 23 \quad |E_c - 460| < 23$$

$$437 > E_b < 460 \quad 437 < E_c < 460.$$

From the fact that the vector sum of

$$\bar{E}_a + \bar{E}_b + \bar{E}_c = 0 \tag{9}$$

$$\begin{aligned}\Rightarrow 483 &+ E_b\cos\theta_b + E_b\sin\theta_b j\\ &+ (897 - E_b)\cos\theta_c + (897 - E_b)\sin\theta_c j = 0.\end{aligned} \tag{10}$$

So for a given E_b, θ_b and θ_c can be found. From this, the % unbalance based on the ratio of the negative sequence voltage to the positive sequence voltage is given by

$$ratio = \frac{E_n}{E_p} = \frac{483\angle 0^\circ + a^2 E_b\angle\theta_b + a(897 - E_b)\angle\theta_c}{483\angle 0^\circ + aE_b\angle\theta_b + a^2(897 - E_b)\angle\theta_c}. \tag{11}$$

From this analysis, it has been found that for a given % unbalance, based on the NEMA definition, there is a range of % unbalance, based on the ratio of negative sequence voltage to positive sequence voltage. This is shown in Fig. 1 for 2%, 5%, 10%, and 20% NEMA definition of unbalance. The x-axis is the magnitude of E_b in p.u. and the y-axis is the unbalance based on the ratio of negative sequence voltage to positive sequence voltage.

The range of the ratio of the negative sequence voltage to the positive sequence voltage will be from 5% to 5.8%. Similarly, for a 2% unbalance based on NEMA or IEEE, the true unbalance can range from 2% to 2.3%. For a 10% unbalance using the NEMA definition, the true unbalance can range from 10% to 11.6% and for a 20% deviation using the NEMA definition, the true unbalance can range from 20% to 23.8%.

Fig. 1 also shows how the magnitude of E_b in p.u varies with the "true" definition of voltage unbalance for the same NEMA unbalance. Since both magnitudes and angles are unbalanced, the variation of angles with the true definition can also be shown. This was done by choosing the values of θ_b instead of E_b such that (7)–(10) are satisfied.

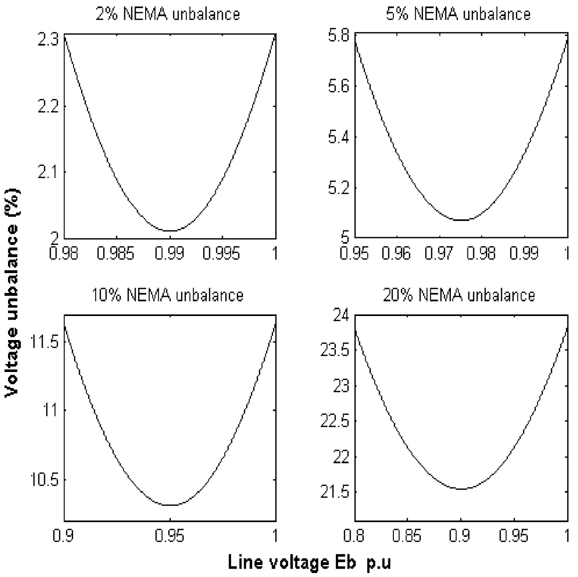

Fig. 1. Relationship between the "true" definition of voltage unbalance and the NEMA definition for different values of NEMA unbalance.

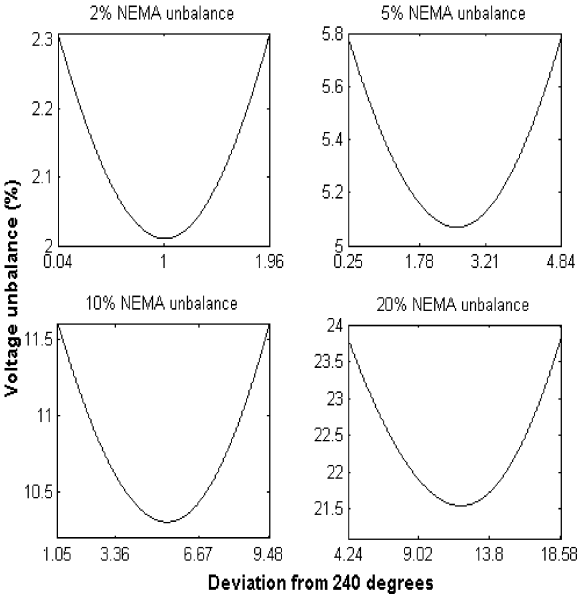

Fig. 2. Relationship of the "true" definition and NEMA definition of voltage unbalance.

Fig. 2 shows the relationship between NEMA and the true definition of voltage unbalance with angle variation. The x-axis represents the deviation from a balanced angle of 240° for 2%, 5%, 10%, and 20% NEMA unbalance. The y-axis is the range of unbalance based on the negative to positive sequence voltage ratio. For example, at 5% NEMA unbalance, the deviation from 240° is from 0.25° to 4.85°, therefore the true range of angles will be 239.75° to 235.15°. The deviation of angle θ_c from

$$\%\text{ voltage unbalance} = \frac{\text{maximum voltage deviation from average voltage}}{\text{average voltage}} * 100 \tag{4}$$

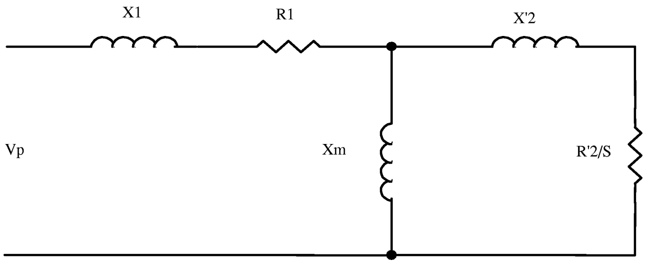

Fig. 3. Positive sequence equivalent circuit.

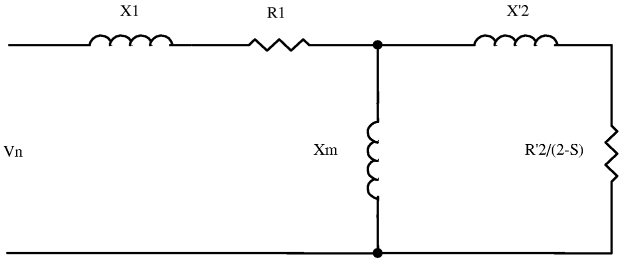

Fig. 4. Negative sequence equivalent circuit.

120 °C with unbalance can also be determined is the same way. These curves are the same as the curves in Fig. 1. That is, for a given NEMA % unbalance, there is a range of % unbalance, based on the "true" definition, which is the same range as in Fig. 1.

The difference between the NEMA definition of voltage unbalance and the true definition can differ substantially when the voltage unbalance is extremely high (say 20%) as shown in Fig. 1. At lower unbalance levels (say 5%) and when enforcing the condition that the average voltage must equal 460 V, the maximum deviation between the two definitions is only 0.8%. The question that remains then is whether this difference is significant in the derating of the machine. To answer this question, it is necessary to review the positive and negative sequence equivalent circuits of the induction machine, which is done in the next section.

III. POSITIVE AND NEGATIVE SEQUENCE EQUIVALENT CIRCUITS

Each set of positive and negative sequence voltages produce corresponding balanced currents in the IM 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 to the positive sequence voltage is essentially the same as for normal balanced operation. The negative sequence currents, however set up a reverse field, so that if the rotor slip is s with respect to the positive sequence field, it will be $(2-s)$ relative to the negative sequence field. The equivalent circuits of the induction motor for each sequence are shown in Figs. 3 and 4. 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. where

V_p	positive sequence voltage;
V_n	negative sequence voltage;
$X1$	stator reactance;
$X'2$	rotor reactance;
$R1$	stator resistance;
$R'2$	rotor resistance;
X_m	magnetizing reactance;
S	slip.

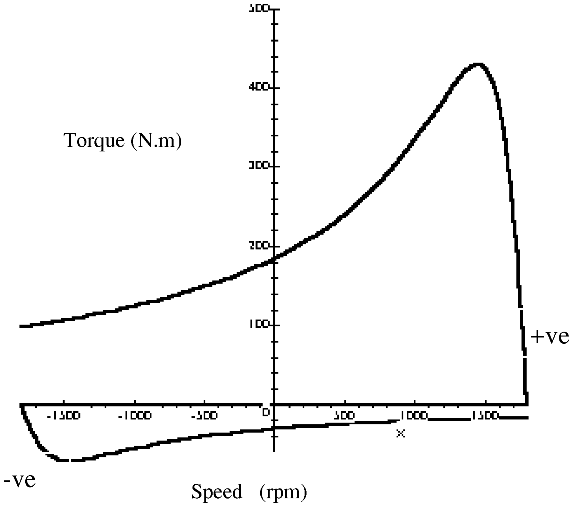

Fig. 5. Positive and negative sequence torques of the IM.

The total power output will be

$$P_m = I_p^2 r_2 \left[\frac{(1-s)}{s}\right] - I_n^2 r_2 \left[\frac{(1-s)}{(2-s)}\right] \; W.\text{per phase} \quad (12)$$

(note the reduction in the output power due to the negative sequence current) and the torque

$$T = r_2 \frac{\left[\frac{I_p^2}{s} - \frac{I_n^2}{(2-s)}\right]}{Wsyn.} \; \text{N.m per phase} \quad (13)$$

(note the reduction in output torque, due to the negative sequence current), where I_p is the positive sequence phase current, I_n is the negative sequence phase current and $Wsyn$ is the synchronous speed.

The positive and negative sequence currents are functions of their sequence voltages, the motor parameters and the slip s. Thus using the equation given below the currents I_p and I_n are obtained using the respective sequence voltages and motor parameters and including the dependence on the slip

$$I_p = \frac{V_p}{\sqrt{\left\{\left[r_1 + \left(\frac{r_2'}{s}\right)\right]^2 + (x_1 + x_2')^2\right\}}} \quad (14)$$

$$I_n = \frac{V_n}{\sqrt{\left[\frac{r_1 + r_2'}{(2-s)}\right]^2 + (x_1 + x_2')^2}}. \quad (15)$$

Thus the positive and negative sequence currents for an unbalanced supply can be obtained and used in analyzing the machine performance. Using these equivalent circuits, the positive and negative sequence torque-speed curves may be plotted as shown in Fig. 5. The upper curve is the positive sequence torque.

The positive sequence torque resembles the torque of an induction motor operating from a balanced supply. Normal operation is between zero speed and synchronous speed. This curve is typical of a class B machine. The counter rotating field produced by the negative sequence currents produces a negative torque, with a peak in the 3rd quadrant. The magnitude of the negative sequence torque is not negligible, so that the net shaft torque produced by the machine will be somewhat less than that produced by a balanced supply.

While the entire envelope of the torque-speed curve is reduced, by the presence of the negative sequence torque, three points on the curve of particular interest are the starting torque, breakdown torque and full load torque. Thus the important implication of Fig. 5 is that the motor will take longer to run up in the presence of unbalanced voltages. This increases the thermal stress in the machine and will lead to loss in life, if not early failure. This is due firstly to a reduction in the magnitude of the positive sequence voltage when compared to the unbalanced supply voltage. Secondly, the presence of the negative sequence current creates a negative sequence torque which subtracts from the positive sequence torque to yield a net torque that is even smaller. If full load is still demanded, then the motor will be forced to operate at a higher slip, thus increasing the rotor losses and heat dissipation. Premature failure can only be prevented by derating of the machine to allow it to operate within its thermal limitations. The reduction in the peak torque reduces the ability of the motor to ride through dips and sags, thus affecting the stability of the entire system.

This section has demonstrated the effects of the unbalanced voltage supply on the torque production in the machine. These circuits may be used to evaluate the derating of the machine from thermal considerations as well. In particular, the effect of the differing definitions of voltage unbalance can be examined. From Fig. 1, it is evident that for a 5% voltage unbalance based on the NEMA definition, the range of voltages based on the true definition is 0.05 to 0.058. The question is whether this is significant in terms of the motor's thermal rating. The procedure for determining this is to find the total losses with a 5% unbalance (based on the true definition), using the two circuits in Figs. 2 and 3. For the particular example under consideration, the total losses was 2160 W. With a 5.8% unbalance (based on the true definition), the losses increased to 2181 W, an increase of 1%

$$Efficiency = \frac{1 - Losses}{Input}. \tag{16}$$

For a motor efficiency of 0.85, the input is 14 400 W and the output is 12 240 W. With a 1% increase in the losses, the change in the efficiency is from 0.85 to 0.849 (for the same output) which is approximately 0.85 anyway. In other words, a 1% increase in the losses, does not require a corresponding decrease in the % output power. Thus the fact that NEMA and IEEE use a different definition of unbalance from the rest of the power community, does not result in a significant difference in the machine derating, up to an unbalance of 5%. It is therefore safe to use either definition when determining derating.

While the respective sequence networks may be used to establish derating, NEMA has also addressed this problem empirically by conducting tests on a number of machines. This method is used to establish the steady state derating curve given in the next section.

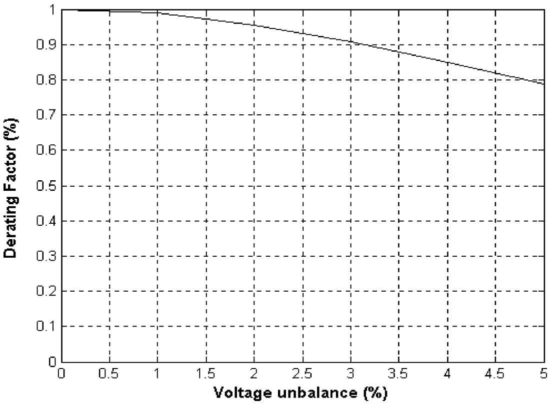

Fig. 6. Derating curve of the IM.

IV. DERATING CURVE FOR INDUCTION MOTORS

As per NEMA guidelines, operating a motor for any length of time at voltage unbalance above 5% "is not recommended." Any amount of unbalance makes a motor run hotter. The NEMA standard states that once unbalance reaches 5%, the temperature begins to rise so fast that protection from damage becomes impractical.

The simplest protection, as proposed by the NEMA standard, is to derate the motor—to reduce its output horsepower load so it can tolerate the extra heating imposed by the unbalanced supply. There are several ways to develop a derating curve. One of them which is based on many tests of a variety of motors, for balanced voltages, suggests that

$$1 + \frac{\text{percent increase in winding temprise}}{100} = \left(\frac{\text{percent load}}{100}\right)^{-1.7} \tag{17}$$

But information developed by NEMA and various researchers indicates that when voltages are unbalanced, the percent increase in temperature rise equals about twice the square of the percent voltage unbalance. This can be defined by the following relation:

$$1 + \frac{2(\text{percent unbalance})^2}{100} = \left(\frac{\text{percent load}}{100}\right)^{-1.7}. \tag{18}$$

The above relation can be used to find the percent load for operating under various unbalanced conditions (percent unbalance). In other words, the derating necessary to hold the temperature rise to the machine specifications can be determined. This derating curve for unbalance (NEMA definition) is given in Fig. 6. At 5% unbalance for example, the motor should not operate at more than 77% of its rated output.

V. INCLUSION OF OVERVOLTAGES AND UNDERVOLTAGES IN THE DERATING CURVE

In order to include overvoltages and undervoltages on the NEMA derating curve, the electrical and thermal models were developed. Fig. 7 shows the connection of the models. The electrical model is used to calculate motor losses. These losses are fed into the thermal model to predict the motor temperature rise.

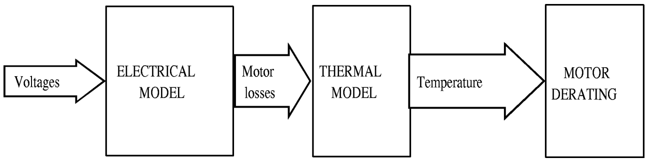

Fig. 7. Motor derating flow-chart.

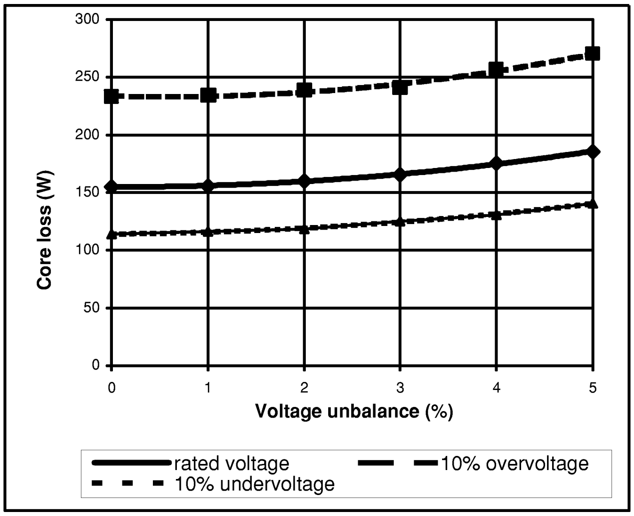

Fig. 8. Core loss variation with voltage unbalance.

Then, the derating factor is calculated depending on the temperature magnitude.

The electrical model is a combination of Figs. 3 and 4. The motor parameters were determined from no-load and locked rotor tests. The core losses were determined experimentally. Fig. 8 shows the core losses when the motor is supplied by unbalanced voltages, in combination with over- or undervoltages. The core loss increases with increase in voltage unbalance.

The thermal model presented in [12] was adopted. Simple tests were performed to determine thermal parameters through motor testing rather than from motor design data. From the model performance test, the thermal model worked with balanced voltages, unbalanced voltages, over and undervoltages. The model was able to predict both transient and steady state temperatures to an accuracy of $\pm 2^\circ$.

Fig. 9 shows the inclusion of overvoltages and undervoltage on the derating curve. The curves were obtained by running the following three cases: *Case 1*, a motor was supplied with unbalanced voltages at rated average voltage. In *Case 2*, a motor was supplied with 10% overvoltage in combination with unbalanced voltages up to 5%. In *Case 3*, a motor was supplied with 10% undervoltage in combination with unbalanced voltages up to 5%.

The motor rated temperature when supplied by balanced rated voltages at full-load was known. The chosen voltages were applied at the motor terminals. The stator winding temperature at full-load was predicted. For temperature values above rated, the motor output power was reduced so as to keep the temperature at rated. The derating factor was determined as the ratio of the calculated output power to the rated power.

The 100% curve in Fig. 9 shows the derating required to protect the motor when supplied with *Case 1* voltages. This curve is very close to the NEMA curve as expected. The 110% curve will protect the motor when supplied with *Case 2* voltages. Below 1% unbalance, the motor can be operated at full-load without being derated. This is the same as for the NEMA curve. At 5% unbalance, the motor cannot be operated above 71% of the rated power. The 90% curve shows the derating curve that will protect the motor winding from overheating when a motor is operated with *Case 3* voltages. If a motor is expected to run at full-load in the presence of 10% undervoltage, with or without voltage unbalance, the 90% curve suggests that the motor must be derated.

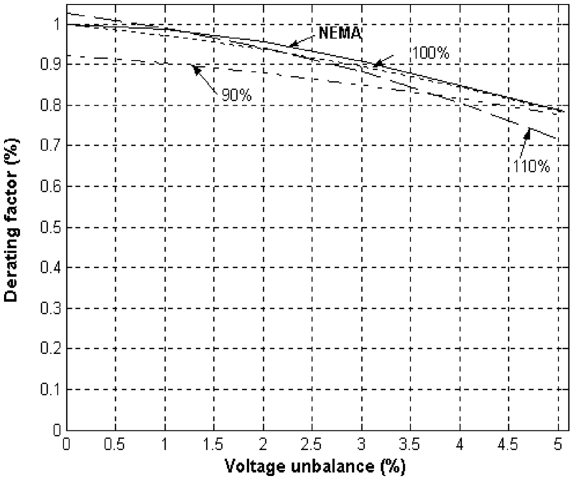

Fig. 9. Inclusion of overvoltages and undervoltages on the derating curve.

The 90% undervoltage and the 100% rated voltage curves have almost the same derating at 5% unbalance. This is believed to be due to the higher I^2R and lower core losses in the undervoltage case cancelling out with the lower I^2R and higher core losses for the rated case, hence giving the same derating at that point. The core loss for the 110% curve is the highest as shown in Fig. 8.

As an example of a motor, operating with a balanced voltage, yet with an undervoltage, consider Fig. 10, which has practical measurements for such a condition. The magnitude of the undervoltage is 200 V, while the machine rating is 230 V; this corresponds to a 0.87 undervoltage condition.

Using the 90% curve in Fig. 9, for 0% unbalance and 90% undervoltage, the derating can be read off directly as 0.92. Hence, the motor output should be derated so that its output is no more that 92% of the rated output and should be a little less, because the actual undervoltage is 87% and not 90%. Using the models in Fig. 7, the derating of this motor is about 90% of the rated output.

Fig. 11 has an example of a motor operating with an unbalanced voltage. Table I summarizes the voltage unbalance shown in Fig. 11.

The first column in Table I summarizes the unbalance in the period 10/28 through to 10/31 and the second column summarizes the unbalance from 10/31 through to 11/4. In the first period, the % unbalance is approximately 2%, while in the second period, it is approximately 0.78%. In addition, the average voltage during the unbalance in the first period is 213 V, i.e., 93% of rated, while in the second period, the average voltage is 215 V, i.e., 94% of rated. For the first case, the motor

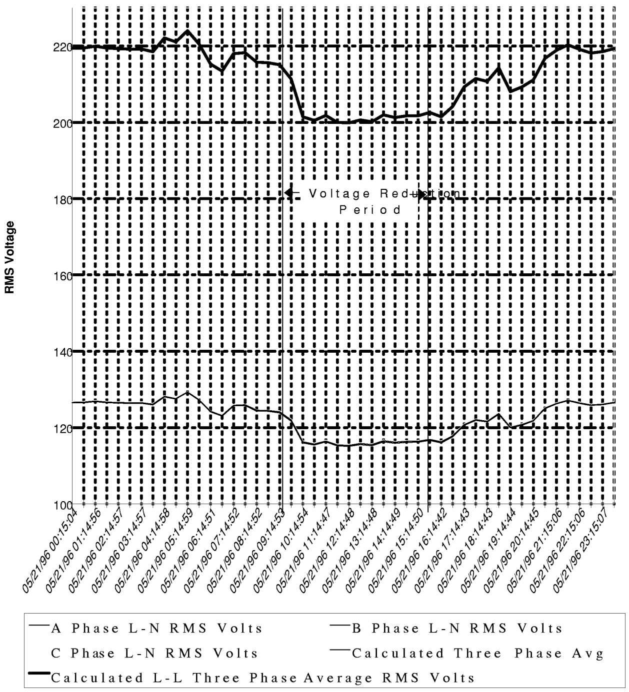

Fig. 10. Measured undervoltage.

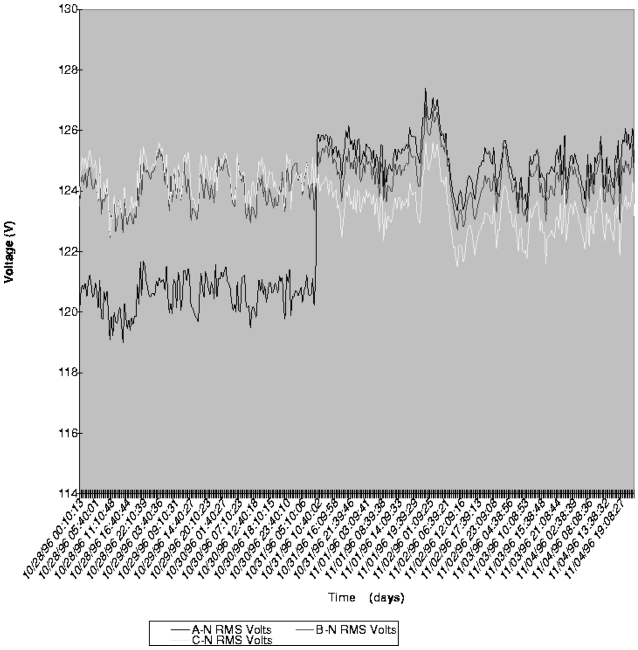

Fig. 11. Measured unbalanced voltage.

should be derated to at least 91% of the normal output. For the second case of 0.78% unbalance and 94% voltage, yields a derating of 92% of output.

The corresponding derating factors were obtained from models in Fig. 7. Fig. 9 presents the guidelines to motor derating when supplied by unbalanced voltages in combination with overvoltages or undervoltages.

TABLE I
VOLTAGE UNBALANCE

Period	10/28 - 10/31	10/31-11/4
Ave A-N	120.5795	125.0362
Ave B-N	124.0745	124.4744
Ave C-N	124.3826	123.3095
Average	123.0122	124.2734
Max	124.3826	125.0362
Min	120.5795	123.3095
Max-A	1.370424	0.762842
Ave-min	2.432732	0.963854
% unbal	1.977635	0.775592

VI. CONCLUSION

This paper has examined the derating of induction machines when supplied by unbalanced voltages, in combination with over- and undervoltages. An extensive analysis of the different definitions of unbalanced supply has revealed that the differences in the definitions do not result in significant derating differences when operated by unbalanced supplies in the 5% range.

Positive and negative sequence circuits were presented and the impact on the overall torque speed curve explained. The negative sequence torque reduces the starting, peak and full load rated torque, thus increasing starting time, reducing the ability to ride through sags and forces the motor to operate at a higher slip.

The NEMA curve for the derating of induction machines has been extended to cover overvoltages and undervoltages. The losses and temperature values for a machine operating with 10% overvoltage or 10% undervoltage have been calculated using the electrical and thermal models respectively. The derating factor was determined for safe operation. Two case studies were also included.

REFERENCES

[1] P. Pillay, "Practical considerations in applying energy efficient motors in the petrochemical industry," *IEEE IAS Mag.*, vol. 3, pp. 32–40, Jan./Feb. 1997.

[2] R. F. Woll, "Effect of unbalanced voltage on the operation of polyphase induction motors," *IEEE Trans. Ind. Applicat.*, vol. IA-11, pp. 38–42, Jan./Feb. 1975.

[3] ——, "Comparison of application capabilities of U and T rated motors," *IEEE Trans. Ind. Applicat.*, vol. IA-11, pp. 34–39, Jan./Feb. 1975.

[4] R. G. Harley, E. B. Makram, and E. G. Duran, "The effects of unbalanced networks and unbalanced faults on induction motor transient stability," *IEEE Trans. Energy Conv.*, vol. 3, pp. 398–403, June 1988.

[5] W. H. Kersting and W. H. Phillips, "Phase frame analysis of the effects of voltage unbalance on induction machines," *IEEE Trans. Ind. Applicat.*, vol. 33, pp. 415–420, Mar./Apr. 1997.

[6] J. E. Williams, "Operation of 3-phase induction motors on unbalanced voltages," *AIEE Trans. Power Apparat. Syst.*, pt. III, vol. 73, pp. 125–133, Apr. 1954.

[7] B. N. Gafford, W. C. Duesterhoeft Jr., and C. C. Mosher III, "Heating of induction motors on unbalanced voltages," *AIEE Trans. Power Apparat. Syst.*, pt. III-A, vol. 78, pp. 282–297, June 1959.

[8] M. M. Berndt and N. L. schmitz, "Derating of polyphase induction motors operated with unbalanced line voltages," *AIEE Trans. Power Apparat. Syst.*, vol. 81, pp. 680–686, Feb. 1963.

[9] N. Rama Rao and P. A. D. Jyothi Rao, "Rerating factors of polyphase induction motors under unbalanced line voltage conditions," *IEEE Trans. Power Apparat. Syst.*, vol. 87, pp. 240–249, Jan. 1968.

[10] P. B. Cummings, J. R. Dunki-Jacobs, and R. H. Kerr, "Protection of induction motors against unbalanced voltage operation," *IEEE Trans. Ind. Applicat.*, vol. IA-21, May/June 1985.

[11] C.-Y. Lee, “Effects of unbalanced voltage on the operation performance of a three-phase induction motor,” *IEEE Trans. Energy Conv.*, vol. 14, pp. 202–208, June 1999.

[12] O. C. N. Souto, J. C. de Oliveira, and L. M. Neto, “O impacto da qualidade da energia no comportamento termico e na vida util de motors de inductao trifasicos,” in *Proc. Sobre Qualidade da Energia Eletrica Seminar*, Aug. 1999.

[13] R. Nailen, *Managing Motors*. New York: Barks Books, 1991.

Pragasen Pillay (S’84–M’87–SM’92) received the B.S. degree from the University of Durban, Westville, South Africa, in 1981, the M.S. degree from the University of Natal, South Africa, in 1983, and the Ph.D. degree from the Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, in 1987.

From January 1988 to August 1990, he was with the University of Newcastle upon Tyne, U.K. From August 1990 to August 1995, he was with the University of New Orleans, New Orleans, LA. Currently, he is with Clarkson University, Potsdam, NY, where he is a Professor in the Department of Electrical and Computer Engineering and holds the Jean Newell Distinguished Professorship in Engineering. He has organized and taught short courses in electric drives at the Annual Meeting of the Industry Applications Society. His research and teaching interests are in modeling, design and control of electric motors and drives for industrial and alternate energy applications.

Dr. Pillay received the Fulbright Scholarship while at Virginia Tech. He is a Fellow of the IEE and a Chartered Electrical Engineer. He is a member of the IEEE Power Engineering, Industry Applications, Industrial Electronics, and Power Electronics Societies. He is a member of the Electric Machines Committee, Past-Chairman of the Industrial Drives within the Industry Applications Society and Chairman of Induction Machinery Sub-Committee in the Power Engineering Society.

Peter Hofmann received the B.S.M.E. degree from Newark College of Engineering, Newark, NJ.

He is a Senior Engineer with the Customer Service Power Quality Group, Con Edison, Manhattan, NY. During his eleven years at Con Edison, he has had distribution engineering and operations experience in both overhead and underground network systems.

Marubini Manyage was born in Venda, South Africa, in 1978. He received the B.S. degree in electrical engineering from the University of Cape Town, South Africa, in 1999, where he is currently pursuing the M.S. degree in electrical engineering.

He visited Clarkson University, Potsdam, NY, as a Research Assistant from August to December 2000. His field of interest is electric machines and drives.