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

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***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.

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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.

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

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

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

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

and

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

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

$$\bar{E}_a + \bar{E}_b + \bar{E}_c = 0 \quad (9)$$

$$\Rightarrow 483 + E_b\cos\theta_b + E_b\sin\theta_b j + (897 - E_b)\cos\theta_c + (897 - E_b)\sin\theta_c j = 0. \quad (10)$$

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

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

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.

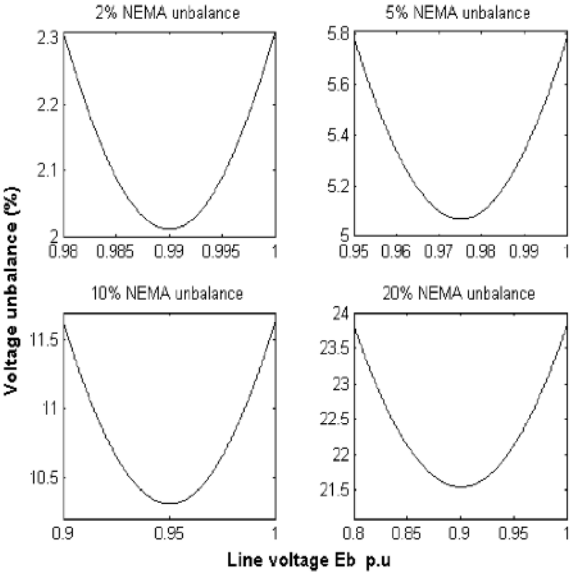

Fig. 1. Relationship between the "true" definition of voltage unbalance and the NEMA definition for different values of NEMA unbalance.

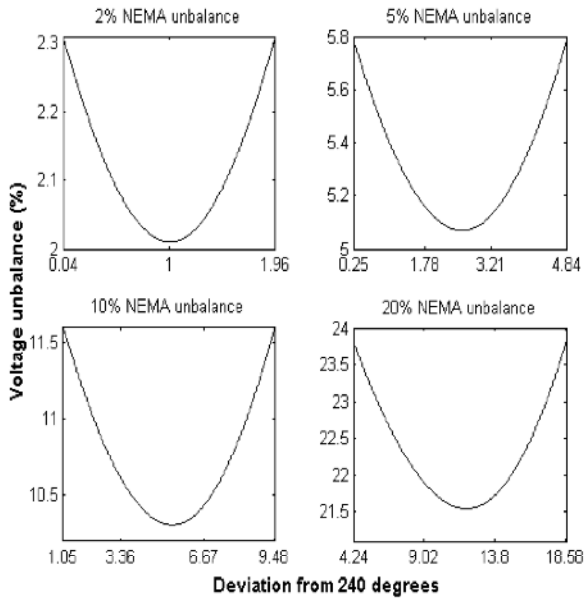

Fig. 2. Relationship of the "true" definition and NEMA definition of voltage unbalance.

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

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