Computer Analysis Of 3-Phase Induction Motor Operation On Rural Open-Delta Distribution Systems

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Abstract—Open-delta/open-delta and open-wye/open-delta transformer banks are often used as an economic means of supplying simultaneous single-phase and 3-phase loads in rural areas. If the 3-phase load is an induction motor, the inherent voltage unbalance causes increased losses and uneven heating that may lead to motor failure. Often these motors are submersible or deep well pump motors located in remote unattended areas or air conditioning motors which may not have sufficient over-design to handle the voltage unbalance. The theory analyzing the open-delta distribution system has existed for many years, however, because of the tedious and almost infinite differences in distribution topology, the problem has been neglected. The purpose in this endeavor is to present a simple general approach to the solution of the problem by utilizing existing motor and network concepts and theories. Two previously published theories are used to predict motor heating and the motor derating that is necessary to prevent insulation failure due to the unbalanced voltages. A general motor model has been developed. Motor heating and derating are obtained from the model through a generalized digital computer program.

INTRODUCTION

GROWTH of 3-phase water pumping applications and air conditioning loads in rural and suburban areas that were previously single-phase has prompted the utilities to seek a satisfactory method of installing 3-phase service. Although a separate 3-phase system could be built, a method that is economically attractive to the utilities is to supply both single-phase and 3-phase loads from the same transformer bank. Often the old system can be expanded to 3-phase service by simply adding a second transformer to form either an open-delta/open-delta or open-wye/open-delta transformer bank.

Both leading and lagging open-delta connections are used. They are defined as follows.

1) In the open-delta leading connection, the voltages across the transformer supplying the single-phase load leads the voltage across the other transformer by 120 degrees.
2) In the open-delta lagging connection, the voltage across the transformer supplying the single-phase load lags the voltage across the other transformer by 120 degrees.

The circuit and phasor diagrams of Fig. 1 describe the above connections.

Unfortunately, the secondary voltages of the open-delta systems are subject to voltage unbalance caused by unequal loading and unequal transformer impedances. Section 14.34 of NEMA Standard MG1-1972 defines this unbalance as

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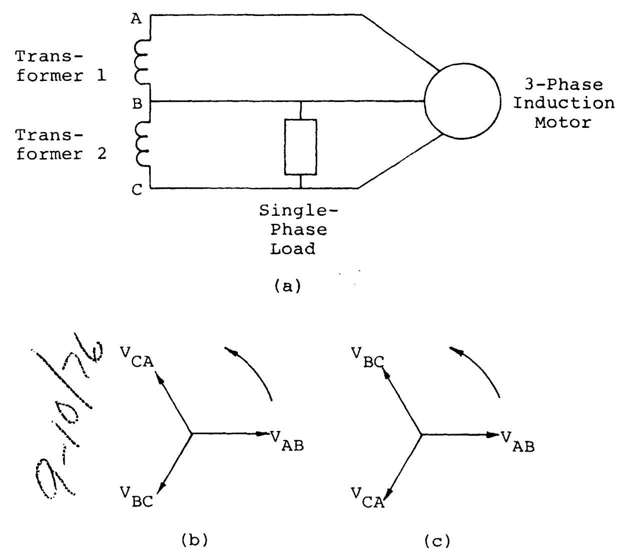

Fig. 1. Open-delta distribution system. (a) Wiring diagram. (b) Phase sequence for open-delta lagging connection. (c) Phase sequence for open-delta leading connection.

$$\text{percent voltage unbalance} = \frac{\begin{array}{c}\text{maximum deviation from}\\ \text{average voltage}\end{array}}{\text{average voltage}}.$$

Voltage unbalance is usually small. However, it can become quite serious when the 3-phase load is an induction motor. Unbalance in the 3-phase voltage reduces starting and breakdown torques, even if these torques are sufficient to handle the load, excessive motor heating caused by the unbalanced conditions may eventually lead to insulation failure. The amount of voltage unbalance which a motor can constantly withstand without damage varies with induction motor design. Winding insulation, winding pitch, type of rotor, and ventilation details may all affect the maximum winding temperature. To prevent insulation failure, the motor load should be derated until the maximum winding temperature does not exceed that of rated conditions. Present methods of calculating the exact amount of derating are cumbersome.

The purpose of this paper is to develop a computer program capable of analyzing an open-delta distribution system, predicting motor heating, and determining the amount of derating necessary to prevent motor failure. Necessary background analysis of the open-delta system and the methods used to predict winding temperatures and to derate motor loads are presented. Laboratory testing was performed to verify the modeling procedure, analysis, and digital program.

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An open-delta distribution system, which serves a single-phase load and 3-phase induction motor, was analyzed by Anderson and Ruete [2] and by Bankus and Gerngross [3] in papers written in 1954. Voltage unbalance on open-delta systems was discussed in both papers. Anderson and Ruete derived general equations which could be used to calculate voltage unbalance. Bankus and Gerngross recommended transformer sizing that would result in a low voltage unbalance and in maximum utilization of transformer kVA. In a later paper, Bankus and Gerngross [4] compared the advantages and disadvantages of using either the open-delta leading or open-delta lagging transformer connections.

Williams [10] analyzed the effects of voltage unbalance on motor operation and concluded that the unbalanced voltages cause increased motor losses and uneven heating. Gafford *et al.* [7] attributed the rise in motor temperature under unbalanced conditions to increased copper losses and unbalanced spatial distribution of stator heating.

More recently, investigations have been made on the spatial distribution within the motor of the heat resulting from unbalanced voltages, and methods of derating motor loads to prevent insulation failure have been proposed. The two extremes for determining the amount of derating necessary are presented in discussion by Lee [5, pp. 684-685] and the paper by Berndt and Schmitz [5]. Lee assumed that the thermal impedance between stator windings was negligible; therefore, any additional heating caused by unbalanced voltages is evenly distributed among all three windings. Therefore, Lee concluded to prevent insulation failure, the motor load should be derated until the total losses in the stator windings do not exceed the losses under rated conditions. On the other hand, Berndt and Schmitz assumed that the thermal impedance between windings was infinite. According to their theory, the motor load should be derated until the maximum current in any phase is equal to or less than rated current. Whereas Lee presented an optimistic derating of the motor load, Berndt and Schmitz were overly pessimistic. Later, Rao and Rao [8] presented two additional methods of motor derating by taking into account winding and insulation details. Because the methods of motor derating presented by Lee and Berndt and Schmitz require a minimum knowledge of motor construction, they were considered in this paper.

DERIVATION OF THE COMPUTER MOTOR MODEL

Determining the exact amount of motor derating requires an accurate analysis of the open-delta system. The unbalanced voltages must be calculated and their effect on motor operation determined. The unbalanced conditions make these calculations laborious. A generalized computer program, which is capable of analyzing the open-delta system, predicting motor heating, and determining necessary derating, would be timesaving. Such a program has been written and is in the files of the Power Section of the Electrical Engineering Department at the University of Missouri-Rolla [9]. The derivation of the system equations and the analysis of motor heating which are used in the program are presented below.

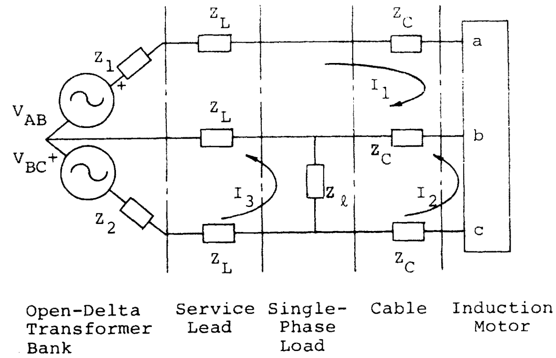

Fig. 2. Model of open-delta distribution system.

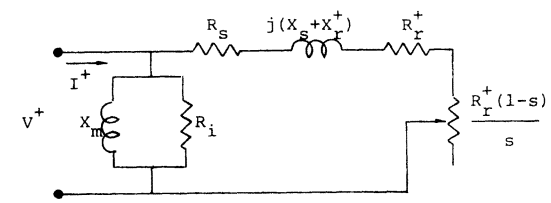

Fig. 3. Positive sequence model of one phase of the induction motor.

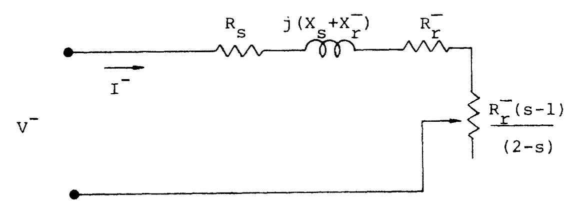

Fig. 4. Negative sequence model of one phase of the induction motor.

A. System Equations

An equivalent circuit of an open-delta system that includes transformer secondaries, service leads and cables, single-phase load, and 3-phase induction motor is shown in Fig. 2. By writing Kirchhoff's voltage equations for the circuit, the voltages at the motor terminals can be expressed as

$$\begin{bmatrix} v_{ab} \\ v_{bc} \end{bmatrix} = \begin{bmatrix} (Z_1 + 2Z_L + 2Z_C) & Z_C & Z_L \\ Z_C & (Z_l + 2Z_C) & Z_l \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} + \begin{bmatrix} V_{AB} \\ 0 \end{bmatrix}. \tag{1}$$

For simplicity, (1) can be written

$$\bar{V}_t = [Z]\bar{I} + \bar{V}. \tag{2}$$

The stator of the induction motor is assumed to be delta-connected. Each phase of the motor can be modeled by its positive and negative sequence circuits shown in Fig. 3 and Fig. 4 [7]. The zero sequence circuit is not considered because of the assumed delta connection. The total positive sequence impedance, Z^+, and negative sequence impedance, Z^-, can be

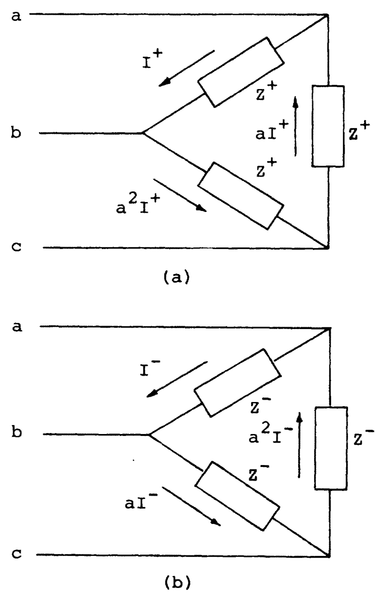

Fig. 5. Three-phase sequence models of an induction motor. (a) Positive sequence model. (b) Negative sequence model.

derived from Fig. 3 and Fig. 4 to be

$$Z^+ = \frac{z\,[R_s + R_r{}^+/s + j(X_s + X_r{}^+)]}{z + R_s + R_r{}^+/s + j(X_s + X_r{}^+)} \tag{3}$$

in which

$$z = \frac{jR_i X_m}{(R_i + jX_m)}$$

and

$$Z^- = R_s + \frac{R_r{}^-}{(2-s)} + j(X_s + X_r{}^-). \tag{4}$$

From Fig. 5, the positive and negative sequence voltages at the motor terminals are

$$\begin{bmatrix} v_{ab}{}^+ \\ v_{ab}{}^- \end{bmatrix} = \begin{bmatrix} Z^+ & 0 \\ 0 & Z^- \end{bmatrix} \begin{bmatrix} I^+ \\ I^- \end{bmatrix} \tag{5}$$

or

$$\bar{V}_s = [Z_s]\,\bar{I}_s. \tag{6}$$

The phase sequence is assumed to be v_{ab}, v_{bc}, v_{ca}. The symmetrical components transformation can be applied to the voltages at the motor terminals to obtain

$$\begin{bmatrix} v_{ab}{}^+ \\ v_{ab}{}^- \\ v_{ab}{}^0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix} \tag{7}$$

where

$$a = 1\underline{/120^\circ}.$$

Because the zero sequence impedance is infinite, the zero sequence voltage is zero. The terminal voltage v_{ca} can be eliminated from (7) to yield

$$\begin{bmatrix} v_{ab}{}^+ \\ v_{ab}{}^- \end{bmatrix} = \begin{bmatrix} (1-a^2)/3 & (a-a^2)/3 \\ (1-a)/3 & (a^2-a)/3 \end{bmatrix} \begin{bmatrix} v_{ab} \\ v_{bc} \end{bmatrix}. \tag{8}$$

Equation (8) can be rewritten as

$$\bar{V}_s = [A]\,\bar{V}_t. \tag{9}$$

Substitution of (2) and (6) for $\bar{V}_t$ and $\bar{V}_s$ in (9) gives

$$[Z_s]\,\bar{I}_s = [A]\,[Z]\bar{I} + [A]\,\bar{V}. \tag{10}$$

Application of Kirchhoff's current law to the circuits in Fig. 5 and the summation of both positive and negative sequence components of the line currents I_1 and I_2 (see Fig. 1) result in the following two equations:

$$I_1 = (1-a)I^+ + (1-a^2)I^- \tag{11}$$

and

$$I_2 = (a-a^2)I^+ + (a^2-a)I^-. \tag{12}$$

A third equation is obtained by applying Kirchhoff's voltage law to loop 3 (see Fig. 2). Substitution of (11) and (12) for I_1 and I_2 in this equation and a rearrangement of the terms results in

$$I_3 = \frac{-Z_L(1-a) + Z_l(a-a^2)}{(Z_2 + 2Z_L + Z_l)}\,I^+ + \frac{-Z_L(1-a^2) + Z_l(a^2-a)}{(Z_2 + 2Z_L + Z_l)}\,I^- - \frac{V_{BC}}{(Z_2 + 2Z_L + Z_l)}. \tag{13}$$

In matrix form, these three current equations are

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} (1-a) & (1-a^2) \\ (a-a^2) & (a^2-a) \\ \dfrac{-Z_L(1-a)+Z_l(a-a^2)}{(Z_2+2A_L+Z_l)} & \dfrac{-Z_L(1-a^2)+Z_l(a^2-a)}{(Z_2+2Z_L+Z_l)} \end{bmatrix} \cdot \begin{bmatrix} I^+ \\ \\ I^- \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dfrac{-V_{BC}}{(Z_2+2Z_L+Z_l)} \end{bmatrix} \tag{14}$$

or

$$\bar{I} = [W]\,\bar{I}_s + \bar{I}_{t2}. \tag{15}$$

By inserting (15) into (10) and solving for the currents in the motor sequence models $\bar{I}_s$ one obtains

$$\bar{I}_s = ([Z_s] - [A][Z][W])^{-1}([A][Z]\bar{I}_{t2} + [A]\bar{V}). \qquad (16)$$

With a knowledge of the input voltages and circuit elements, (16) can be solved for the currents in the motor sequence models. The line currents at the motor terminals can then be calculated from (15). The sequence voltages at the motor terminals $\bar{V}_s$ are determined by inserting the values of $\bar{I}_s$ into (5). The line to line terminal voltages are then calculated by rearranging (9) to obtain

$$\bar{V}_t = [A]^{-1}\bar{V}_s. \qquad (17)$$

Knowledge of the voltages and currents in the motor sequence models permits the calculation of the motor losses.

B. Motor Losses

The prediction of the spatial distribution of heat in an induction motor is an extremely difficult problem. The wide variety of induction motors make any general analysis difficult by requiring intricate details of motor construction.

To keep the computer program in this study as general as possible and to keep to a minimum the amount of knowledge of motor construction required, the two methods of derating presented by Lee [5, pp. 684-685] and Berndt and Schmitz [5] were considered. Neither method can predict the exact amount of derating necessary, but they do determine the bounds which should be considered. These restrictions and considerations, along with experience and engineering judgment, can then be employed to determine proper derating.

Unbalanced voltages cause an increase in rotor copper loss [7], [9]. This loss can be calculated by adding the powers dissipated in R_r^+ and R_r^- for all three phases (see Figs. 3 and 4). In some cases, such as machines having deep bar or double cage rotors, this loss can become significant in determining the critical temperature [5], [7], [9]. Both derating methods presented by Lee and Berndt and Schmitz assume that the rotor copper loss has a neglgible effect on motor operation.

In many motors, the stator copper loss is the determining factor for derating the motor load [5], [8]. The losses in R_s (the resistance of each of the stator windings) can be calculated from circuit theory (see Figs. 3 and 4). As a result of the unbalanced line currents, these losses are not equal in each winding. It is here that the two theories presented by Lee and by Berndt and Schmitz differ. Lee assumed that the thermal impedance between stator windings is negligible; therefore, the temperatures of all three phases are equal and proportional to the average of the powers dissipated in the stator windings. On the other hand, Berndt and Schmitz assumed that the thermal impedance is infinite and that overheating will result in the phase dissipating the most power. Neither theory is completely correct. The actual critical temperature lies between the two estimates.

Past evidence has shown that for approximately each 10°C rise in winding temperature, the insulation life is roughly halved [1]. To estimate the effects of the unbalanced voltages on motor life, the temperature rise in the motor is calculated. The rise in winding temperature ΔT above ambient is assumed to be directly proportional to the power dissipated in the winding. The proportionality constant k is calculated by dividing the designed stator temperature rise, $\Delta T_{\text{designed}}$, above an assumed 40°C ambient temperature by the power dissipated per phase in the stator under balanced rated conditions, or

$$\Delta T = k I_s^2 R_s \qquad (18)$$

in which

$$I_s = \text{total current in } R_s \qquad (19)$$
(see Figs. 3 and 4)

and

$$k = \frac{\Delta T_{\text{designed}}}{I_{s_{\text{rated}}}^2 R_s}. \qquad (20)$$

To protect the motor, the maximum winding temperature should not be allowed to exceed the temperature under balanced rated conditions. The motor load should be derated until the stator temperature is within safe limits. Bounds on the amount of derating necessary can be obtained from the two theories presented above.

Refinements of these two methods to include rotor heating, type of winding insulation, and winding pitch could be made to obtain better accuracy. Although the derivation of the program presented in this paper is derived for two specific methods of derating, minor changes can make it applicable to any other derating theory.

C. Implementation of System Equations and Motor Heating in a Computer Model

By using the system equations and derating methods discussed above, a computer program was written. The program determines the unbalanced voltages on an open-delta system, predicts motor heating, and determines load derating limits. To make the program easier to use and more generalized, the modifications which follow are included in the program.

It is noted that the impedance of the single-phase load is required to solve (16). Usually, the data given for the single-phase load are the total power, kVA, and the power factor (PF). As a result of the voltage unbalance, the voltage across the single-phase load is not explicitly known prior to the analysis; therefore, the exact value of Z_l cannot be calculated before solving (16). An iteration technique was, therefore, introduced to adjust the impedance of Z_l until the desired single-phase load is obtained. The initial guess of Z_l is calculated by assuming that the voltage across the single-phase load V_l is V_{AB}. Each subsequent guess is made by solving (16), determining a new value of V_l, and recalculating a new guess of the single-phase load Z_l^{k+1} by

$$|Z_l^{k+1}| = \frac{(V_l^k)^2}{\text{kVA}} \qquad (21)$$

and

$$Z_l^{k+1} = |Z_l^{k+1}| (\mathrm{PF}) + j |Z_l^{k+1}| (1 - \mathrm{PF}^2)^{1/2} \qquad (22)$$

in which $|Z_l^{k+1}|$ is the magnitude of the kth + 1 guess of Z_l. The iteration loop is executed until the single-phase load is within a specified tolerance of the kVA and power factor desired.

In addition to knowing the impedance of the single-phase load, (16) also requires that the slip of the induction motor be specified. This is impractical because the programmer may not always know the value of slip when the motor is operated at other than the rated load or under unbalanced conditions. A more reasonable quantity to specify is the output horsepower of the motor. To achieve this, a second iteration loop is included in the program. Equation (16) is originally solved by using the value of slip the motor would have when operating at nameplate speed. The power output of the motor P is then determined by summing the power outputs of the motor sequence models to give

$$P = 3 |I_r^+|^2 R^+ \left(\frac{1-s}{s}\right) + 3 |I_r^-|^2 R^- \left(\frac{s-1}{2-s}\right) \qquad (23)$$

in which $|I_r^+|$ and $|I_r^-|$ are the magnitudes of the currents in the rotor resistance R_r^+ and R_r^-, respectively (see Figs. 3 and 4). This power is compared with the desired output power of the motor. If the error exceeds a specified tolerance, the slip is adjusted in a direction to minimize the error. The error criterion used is

$$E = 746 \, (\mathrm{hp}) - P \qquad (24)$$

in which hp is the desired horsepower of the motor. The new guess of slip s^{k+1} can be determined by

$$s^{k+1} = s^k - E/(\partial E/\partial s) \qquad (25)$$

in which

$$\frac{\partial E}{\partial s} = 3 |I_r^+|^2 R_r^+ \left[-\frac{1}{s} - \frac{(1-s)}{s^2} \right] + 3 |I_r^-|^2 R_r^- \left[\frac{1}{(2-s)} - \frac{(s-1)}{(2-s)^2} \right]. \qquad (26)$$

The iterations are continued until the power output calculated in the program is within a specified tolerance of the horsepower desired.

The program is capable of analyzing both open-delta leading and lagging connections. The difference between the two is the phase sequence of the voltages at the transformer terminals as shown in Fig. 1. The system equations derived in Section A assume a phase sequence of V_{AB}, V_{BC}, V_{CA}; therefore, the system is a lagging open-delta connection. To analyze a leading connection, the phase sequence must be changed to V_{AB}, V_{CA}, V_{BC}. This will result in changing (7) and (8). These two equations will retain their same form; however,

$$a = 1\angle 240^\circ .$$

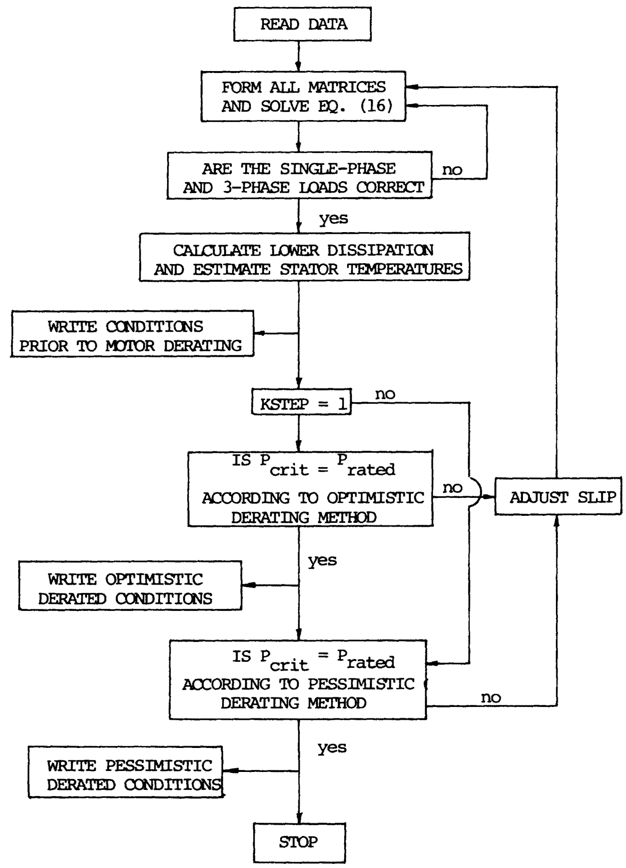

Fig. 6. Flowchart for comptuer analysis.

A program written for a lagging connection can also be used to analyze a leading connection by simply changing the value of a.

After these modifications, (16) can be solved for each leading and lagging connections and for specific single-phase and 3-phase loads. Unbalanced conditions can then be determined, and the power dissipated in each stator winding can be calculated. By using the analysis presented in Section B, the effects of the unbalanced voltages on motor operation can be estimated.

To obtain the derated value of motor load hp_d a third iteration loop is required in the program. The horsepower is adjusted until the critical stator power predicted by either of the derating methods is equal to the power dissipated per phase in the stator under balanced rated conditions, i.e.,

$$P_{\mathrm{crit}} = P_{\mathrm{rated}}. \qquad (27)$$

The initial guess of the derated horsepower $\mathrm{hp}_d{}^0$ is the rated horsepower of the motor. The new estimate of the derated motor load $\mathrm{hp}_d{}^{k+1}$ is determined each time for the following expression:

$$\mathrm{hp}_d{}^{k+1} = \mathrm{hp}_d{}^k - \mathrm{hp}_d{}^k \frac{(P_{\mathrm{crit}} - P_{\mathrm{rated}})}{(P_{\mathrm{crit}} + P_{\mathrm{rated}})} \qquad (28)$$

in which

$$P_{\mathrm{rated}} = R_s (I_{s_{\mathrm{rated}}})^2 \qquad (29)$$

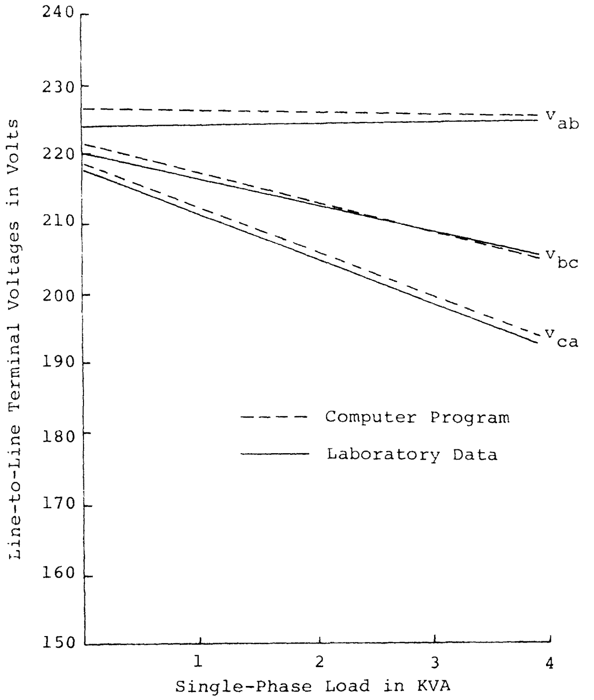

Fig. 7. Comparison of measured and predicted terminal voltages versus single-phase kVA.

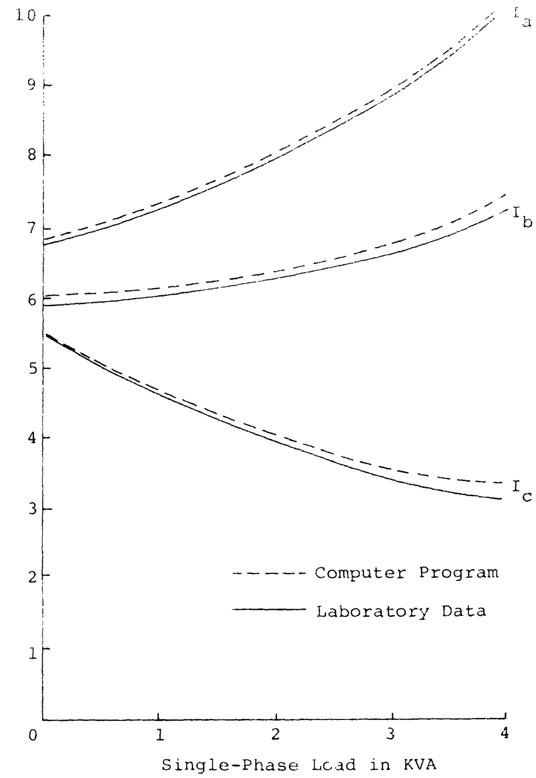

Fig. 8. Comparison of measured and predicted currents at the motor terminals versus single-phase load.

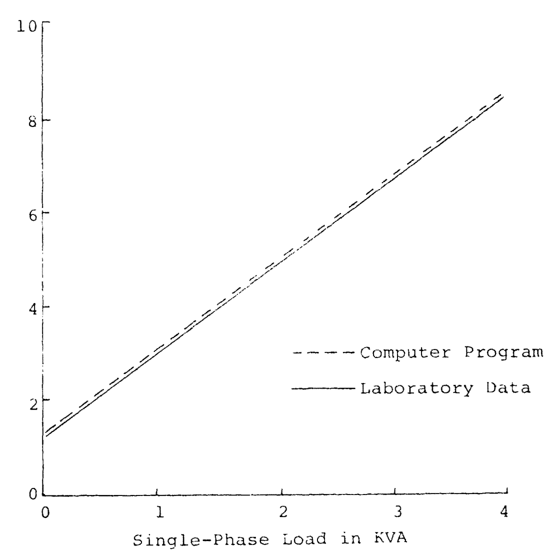

Fig. 9. Comparison of measured and predicted NEMA voltage unbalance at motor terminals versus single-phase kVA.

$I_{s_{\text{rated}}}$ is the magnitude of the current in R_s under balanced rated conditions and is determined from the positive sequence model (see Fig. 3). When the predicted critical stator power is within a specified tolerance of the stator heating under rated conditions, an exit from the iteration loop occurs. This iteration loop is executed twice to obtain values for both derating methods presented in Section B.

The above derating procedures assume that the service factor of the induction motor is unity. For motors having service factors other than unity, derating limits can be approximated by determining the values of the derated load from the above procedure and then multiplying these values by the service factor. A flow chart of the digital program is shown in Fig. 6.

VERIFICATION OF THE SYSTEM MODEL

An open-delta distribution system was simulated in the laboratory. Two 5-kVA transformers were used in a lagging open-delta transformer bank to supply both a single-phase load and 3-phase induction motor.

The 3-phase motor load was a 220 V, 4 pole, 60 Hz, 3 hp induction motor having a wye-connected stator and was of deep bar squirrel-cage rotor construction. The elements in the sequence models of the motor (Figs. 3 and 4) were determined to be

$$R_s = 0.850 \text{ ohm per phase}$$
$$R_i = 227. \text{ ohms per phase}$$
$$R_r^+ = 0.390 \text{ ohm per phase}$$
$$R_r^- = 0.780 \text{ ohm per phase}$$
$$X_m = 27.1 \text{ ohms per phase}$$
$$X_s + X_r^+ = 2.54 \text{ ohms per phase}$$
$$X_s + X_r^- = 2.36 \text{ ohms per phase.}$$

The impedance of the lines were negligible; therefore, a 1.35 ohm resistor was added in series with transformer 2 (Fig. 1) to obtain sizable voltage unbalances for reasonable values of single-phase loads.

With a motor load of 1.5 hp, the unity power factor single-phase load was varied between 0 and 4 kVA. The resulting unbalanced conditions were recorded for several values of single-phase loads in this range. The same system was then analyzed in the computer program and the results were compared and are shown in Figs. 7 through 9. The voltage

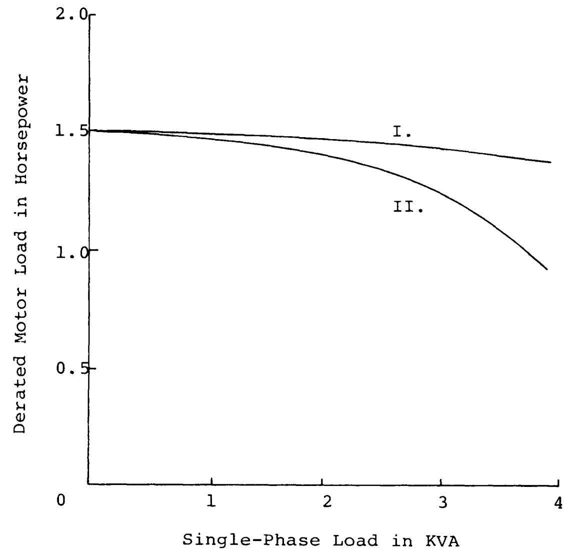

Fig. 10. Motor derating limits versus single-phase load for test motor assuming rated load of 1.5 hp.

unbalance in Fig. 9 was calculated using the definition of voltage unbalance given in Section 14.34 of NEMA Standard MG1-1972.

Assuming that the motor was rated at 1.5 hp instead of 3 hp, the motor load was derated to keep the critical winding temperature equal to the winding temperature when the motor is operated under balanced conditions at 1.5 hp. Derating limits were predicted by the computer program for several values of single-phase loads and are shown in Fig. 10.

EXAMPLE OF AN APPLICATION OF THE COMPUTER PROGRAM

A theoretical system was analyzed in a computer program with the analysis presented in this paper. The system consisted of a leading open-delta transformer bank serving a single-phase load and 3-phase induction motor. Transformer ratings were assumed to be 5 and 37.5 kVA, respectively. The single-phase load was assumed to be 20 kVA at 0.9 power factor and supplied by the larger of the two transformers. The 3-phase induction motor was a 10 hp, 240 V, 4 pole, 60 Hz motor having class B winding insulation. Motor constants were assumed to be

$$R_s = 0.153 \text{ ohm per phase}$$
$$R_r^+ = 0.188 \text{ ohm per phase}$$
$$R_r^- = 0.507 \text{ ohm per phase}$$
$$X_m = 14.3 \text{ ohms per phase}$$
$$X_s + X_r^+ = 1.26 \text{ ohms per phase}$$
$$X_s + X_r^- = 0.982 \text{ ohm per phase.}$$

Service leads and cables were each assumed to be 200 ft of number 2 AWG copper wire.

Without derating the motor load, the computer program predicted that the following conditions would occur:

Voltage unbalance	1.7 percent
Maximum stator heating (optimistic)	60 W
Estimated temperature (optimistic)	124°C
Maximum stator heating (pessimistic)	72 W
Estimated temperature (pessimistic)	142°C.

Under balanced rated conditions, the power dissipated as heat in each of the stator windings is 57 W at 120°C.

According to the derating method presented by Lee [5, pp. 684-685], the motor load should be derated to 9.7 hp. This would reduce the average power dissipation per phase in the stator windings to 57 W. The derating method presented by Berndt and Schmitz [5] would derate the motor load to 8.9 hp and reduce the maximum power dissipated in any of the stator windings to 57 W.

For this theoretical system, the effects of the unbalanced voltages on motor operation have been determined. To prevent insulation failure, the motor load should be derated to a value between 8.9 and 9.7 hp.

RESULTS AND CONCLUSIONS

This paper has summarized the background necessary to analyze an open-delta distribution system, predict motor heating, and determine derating limits. Suggestions have been made to combine the analysis of the open-delta system and the motor heating into one computer program. This computer program can then be used to estimate the effects of the voltage unbalance on motor operation and to determine the amount of derating necessary.

Motor heating and unbalanced conditions do not lend themselves to easy solutions. Computer simulation is perhaps the best approach to this problem. Such a program, as presented in this paper, would be helpful in both field applications and future research.

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Peak Shaving—A Way to Fight Rising Costs

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Abstract—**The background of rising costs in the production, transmission, and distribution of electric power and energy is discussed and, in particular, the significant increases in the cost of generation. It discusses the adverse annual load pattern experienced by Buckeye Power, Inc. and the electric water heater control program of load management adopted by Buckeye to fight the rising costs of providing electric service.**

The Buckeye peak shaving system is described, involving the use of radio switches installed on electric water heaters which are activated through the use of an automatic central computer control scheme. The system operating results are discussed and other electric power systems are admonished to consider controlling deferrable loads.

BACKGROUND

I DOUBT that anyone representing the rural electric power industry has escaped the wrath of dissident electric consumers and their never-ending complaints about high electric bills. Because our industry is highly technical, it is extremely difficult to give short explanations of why costs are rising in such unprecedented proportions. Unfortunately, we cannot escape the fact that practically everything involved in getting central station electric power and energy from the generating plant to the consumer has fallen victim to unbelieveable increases in costs during the past five or six years. Large coal-fired generating plants which could be constructed for less than \$150/kW six years ago now are in the \$400–\$500/kW cost range. Transformers and other substation equipment as well as transmission lines, distribution substations, distribution lines, and everything else right up to and including the service entrance of a consumer's home have increased in cost by a similar order of magnitude.

These cost increases only relate to the physical plant. The fuel required to produce a kilowatthour of electricity has increased in cost over the past six years in far greater proportions. Six years ago most of us were of the opinion that a 20¢/million Btu fuel cost was quite high. We are extremely lucky nowadays to secure the same fuel for \$1/million Btu.

There was a day when we did not worry very much about peak loads, load factors, power factors, or, in fact, our overall efficiency in providing electric energy to consumers. We did not worry because facilities and fuel were relatively cheap and, in addition, our big problem was competing with alternative energy sources. In most cases our toughest competition came from natural gas. Now that natural gas is not available to serve new consumers in most areas and alternative fuels are either relatively unavailable or very high in price, suddenly we find ourselves providing the principal energy source to turn the wheels of industry and commerce and to operate the appliances and comfort conditioning for a high percentage of the people in this country.

I believe that all of this adds up to an escalation in peak loads, declining load factors, increased peak load losses, and generally an adverse effect upon the cost of providing electricity to consumers. Confronted with such drastic cost increases, we can no longer afford the luxury of inefficiency in our resource utilization.

This reiteration of facts of which you are all aware will help to provide some general background for the main thrust of this paper, that being "peak shaving".

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