

Operating Guidance for Induction Motors During Unbalanced Voltage Conditions

Unbalanced Voltage Report

2017 TECHNICAL REPORT

Operating Guidance for Induction Motors During Unbalanced Voltage Conditions

Unbalanced Voltage Report

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ABSTRACT

Since the January 30, 2012 Byron Event, the Electrical Power Research Institute (EPRI) has been investigating the impact of open-phase conditions on nuclear plant operation. In this investigation, EPRI has evaluated several transformer configurations. It has been determined that some transformer types will have a certain amount of voltage unbalance depending on their loading [2, 3, 4].

This technical update examines the impact of these voltage unbalances on a large squirrel-cage induction motor, typical of those installed in nuclear plants. Because open-phase conditions result in voltage unbalances during loading conditions, the concern becomes “How long can motors withstand a certain amount of voltage unbalance?” The goal of this report is to provide guidance on the maximum allowable time an open-phase can exist before action is required to limit equipment damage.

Keywords

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Open phase

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PRIMARY AUDIENCE: Protection Engineers, Transformer Engineers, System Engineers

SECONDARY AUDIENCE: Operations personnel, Design engineers

KEY RESEARCH QUESTION

Current standards do not fully address the amount of time a motor can operate with unbalanced voltage conditions (i.e., the amount of time before there is thermal damage to the motor due to excessive heating) or the impact on starting and running torque – the type of conditions which could affect motor operation caused by an unbalanced voltage condition during an open phase event.

RESEARCH OVERVIEW

In January 2012, an open circuit occurred on a single phase of the three phase overhead conductors feeding the two station auxiliary transformers (SATs) at Byron Nuclear Station Unit 2. The open phase event caused unbalanced voltages and a significant plant transient. A number of plant motor loads were subjected to the unbalanced voltages before the open phase condition was isolated. Some equipment was exposed to abnormal heating. The purpose of this research project is to develop generic guidance and screening criteria for three phase induction motors operating under unbalance conditions. Both motor starting and running conditions will be addressed.

KEY FINDINGS

- Heating impact of electric motors has varying definitions with various ranges of assumed unbalance bias factors (K) which in turn, yield, a varying range of results
- There is no evidence to suggest that squirrel cage induction machines should trip faster than the locked-rotor thermal limits due to voltage unbalances
- It would be a conservative estimate to use the locked-rotor thermal limit to determine the exposure time for motors to unbalanced conditions
- It is recommended that motor should not be started when an open-phase condition exists on the system
- A motor exposed to locked-rotor currents for an excessive amount of time will take longer to start, if it is able to start at all

WHY THIS MATTERS

The developed guidance will help the industry determine precautions for operating large motors under unbalanced conditions to avoid unnecessary damage to the large motor assets due to overheating resulting from unbalanced voltages that occur during operation with an open phase condition

HOW TO APPLY RESULTS

The information in this report should be used along with motor manufacturer and other protection information when plants are in the process of making their open phase settings. The guidance will help avoid nuisance tripping while maintaining protection for electric motors.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Persons in the industry that are responsible for open phase protection settings.
- Industry groups that support open phase detection devices

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INTRODUCTION TO OPEN-PHASE STUDIES

1.1 Purpose

This report was prepared to address a question associated with the effects that an open-phase condition would have on motors fed from the associated power system. The question of “how long can a motor be exposed to an open phase” had been partially answered by work done by Gafford, et. Al [12]. However, previous work did not address timing information which is essential for providing guidance for setting protective devices that would limit the effect of an open-phase condition on operating equipment.

1.2 Background

Soon after the NRC published reference [1], the Nuclear Energy Institute established a Task Force to address the open-phase issue for the industry. Within the NEI Task Force, a working group was established to address the impact that an open-phase condition would have on electric motors connected to a system with unbalanced phase voltage. See Figure 1-1.

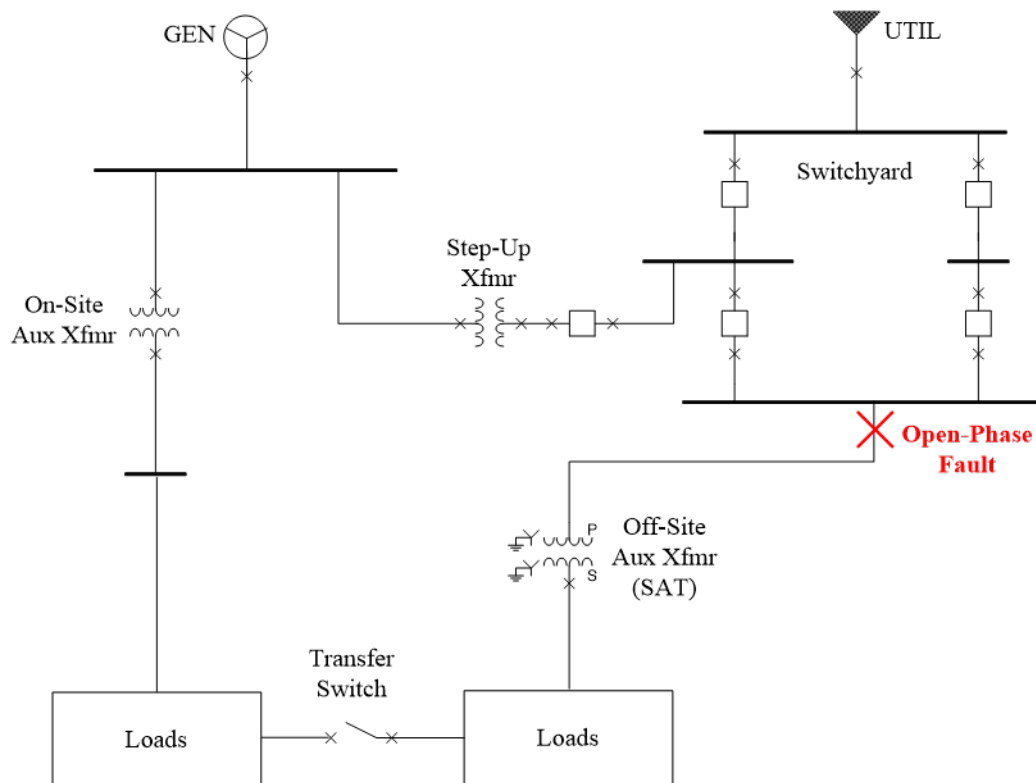


Figure 1-1
One-Line Diagram

1.3 Open Phase Problem Definition

References [2] and [4], illustrate the fact that the response to an open-conductor condition depends on transformer construction and/or configuration. The open phases discussed in these references, were open phases were on the primary side of the transformer under investigation as shown in Figure 1-1. For example, Table 1-1 shows the voltage response to an unloaded transformer for various transformer winding and core configurations with an open phase (Phase A in this case) on the transformer primary. As can be seen in the table, under no-load conditions, delta connected primaries and wye primary transformers that do not have a delta connection on their secondary/tertiary winding or are not constructed on a three-legged core, have a resultant low voltage on their primary and secondary windings. Alternatively, wye connected primaries that have a delta connection on their secondary/tertiary windings or are core-form transformers recreate the voltage to 1 per unit (pu) in the open phase as described in reference [2].

Table 1-1

Various Unloaded Transformer Responses to an Open Phase (Phase A) Condition (Line to Neutral Voltages) Those Transformers Highlighted are those Transformers that Re-Create the Voltage to 1-pu [4]

	Primary Voltage (pu)			Secondary Voltage (pu)		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Wye-Wye (Shell Core)	0	1.0	1.0	0	1.0	1.0
Wye-Wye (3-Single Phase Cores)	0	1.0	1.0	0	1.0	1.0
Wye-Wye* (5-Legged Core)	0.54	1.0	1.0	0.54	1.0	1.0
Delta-Wye (3-Legged Core)	0.5	1.0	1.0	0.5	1.0	0.5
Wye-Delta (Any core type)	1.0	1.0	1.0	1.0	1.0	1.0
Wye-Wye (3-Legged Core)	1.0	1.0	1.0	1.0	1.0	1.0
Wye-Delta-Wye (Shell Core with Buried Delta)	1.0	1.0	1.0	1.0	1.0	1.0

*An open in Phase B (inner leg) of the transformer, the voltage on Phase B becomes 0.43 pu.

Table 1-2 and Table 1-3 shows the results of the primary and secondary line-to-neutral voltages when the transformer is supplying a motor load. Table 1-2 shows the impact of an induction machine utilizing 10% of the transformer capacity and Table 1-3 shows the impact of an induction machine utilizing 64% of the transformer capacity. As shown in the tables, the addition of load results in unbalances of differing degree. Note: Modeling details can be obtained from references [2] and [4].

Table 1-2
Summary of Primary Current for Small Induction Motor Load (10% Transformer Rating) [4]

Table 1 2 Transformer Winding Type	Primary Voltage (pu) Phases			Secondary Voltage (pu) Phases		
	A	B	C	A	B	C
Wye-Wye (Shell Core)	0.67	0.99	0.99	0.67	0.99	0.99
Wye-Wye (5-Legged Core)	0.67	0.99	0.99	0.67	0.99	0.99
Delta-Wye (3-Legged Core)	0.64	0.99	0.99	0.89	0.73	0.98
Wye-Delta (3-Legged Core)	0.98	0.99	0.99	0.98	0.98	0.99
Wye-Wye (Shell Core with Buried Delta)	0.96	0.99	0.99	0.96	0.98	0.99

Table 1-3
Summary of Primary Current for Large Induction Motor Load (64% Transformer Rating) [4]

Transformer Winding Type	Primary Voltage (pu) Phases			Secondary Voltage (pu) Phases		
	A	B	C	A	B	C
Wye-Wye (Shell Core)	0.46	0.99	0.99	0.46	0.82	0.72
Wye-Wye (5-Legged Core)	0.44	0.99	0.99	0.43	0.89	0.82
Delta-Wye (3-Legged Core)	0.45	0.99	0.99	0.36	0.77	0.41
Wye-Delta (3-Legged Core)	0.89	0.99	0.99	0.94	0.88	0.95
Wye-Wye (Shell Core with Buried Delta)	0.80	0.99	0.99	0.80	0.90	0.94

As can be seen from the above tables taken from References [2] and [4], the degree of voltage unbalance during an open-conductor condition depends on transformer construction and/or configuration along with the loading.

Therefore, it is important to determine the impact of these voltage unbalances on motors and protect them from damage.

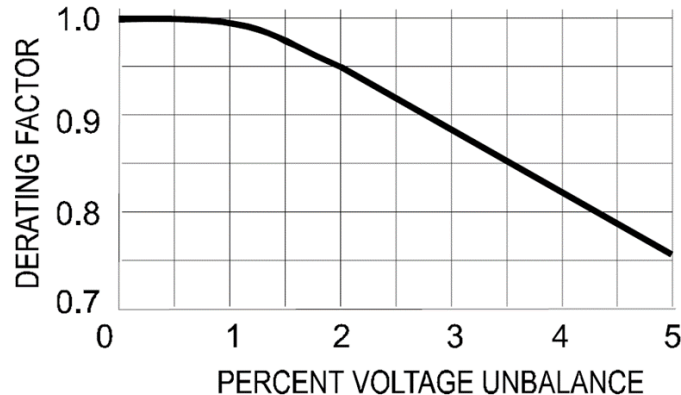
2

MOTOR UNBALANCE

As illustrated in the previous chapter, open-phase conditions can expose motor loads to unbalanced voltages. Even a small amount of voltage unbalance will result in a larger amount of current unbalance. Because of this phenomenon, the temperature rise of a motor operating under voltage unbalance conditions will be greater than for the motor operating under the same conditions with balanced voltages.

2.1 Background on Negative-Sequence Limits in Relaying

Because of this increased heating associated with voltage unbalance, the National Electrical Manufacturers Association (NEMA) provides derating guidance in NEMA MG-1 [11]. NEMA MG-1 also recommends against running a motor if the voltage unbalance is greater than 5% due to the resulting negative-sequence currents. Figure 2-1 gives the plot provided in NEMA MG-1 for the recommended derating factor depending upon the percentage voltage unbalance. The NEMA derating factor is an accepted derating value that can be applied to motors under unbalance voltage conditions. It is important to note that the NEMA MG-1 guide provides derating guidance assuming continuous operation with the motor appropriately loaded.



Source: NEMA MG-1-2011

Figure 2-1
NEMA MG-1-2011 Medium Motor Derating Factor Due to Unbalanced Voltage [11]

As alluded to earlier, the resulting negative-sequence currents from the unbalance voltage is what has the major impact in terms of motor heating. Reference [13] states that a typical relay setting of negative-sequence current is 8% for alarm and 12 to 15% for trip. However, in that reference, there was no time duration provided for these typical values.

Assuming a typical negative locked-rotor impedance of 0.16 pu and a negative-sequence current setting of 15% based on the trip level from reference [13], the corresponding negative-sequence voltage (V_2) can be calculated as follows:

$$V_2 := 0.15 \times 0.16$$

$$V_2 = 0.024$$

For this example, a 15% negative-sequence current setting corresponds to an approximate voltage unbalance of 2.4%, which is approximately half the NEMA recommended maximum.

Note: This condition would not result in excessive phase currents (stator currents) which highlights the fact that phase overcurrent relays will not be protecting a fully loaded motor against unbalance conditions.

Gafford, et al.[12], introduce the concept that the total heating is proportional to:

$$I_1^2 t + K * I_2^2 t$$

Where:

I_1 is the positive-sequence motor current

I_2 is the negative-sequence motor current

K is the unbalance bias factor that accounts for the excess heating caused by I_2

As stated by Blackburn [7], a conservative approximation of K is shown in Equation 2-1.

$$K = \frac{R_{r2}}{R_{r1}} = \frac{175}{I_{LR}^2} \quad \text{Eq. 2-1}$$

Where:

$\frac{R_{r2}}{R_{r1}}$ is the ratio of motor rotor negative-sequence resistance to positive sequence resistance

I_{LR} is the motor locked-rotor current in per-unit (i.e. $\frac{I_{aLR}}{I_{FL}}$), where I_{aLR} is the locked rotor current in amperes and I_{FL} is the full-load current

Using these expressions with the simple example below, a voltage unbalance of $V_2/V_1 = 3.5\%$ (V_1 = Positive-Sequence Voltage and V_2 = negative-sequence voltage) results in an almost 25% increase in motor temperature. Note, that NEMA recommends a derating of 15% at 3.5%¹ voltage unbalance.

¹ Note that NEMA uses the maximum line-voltage deviation from average line-voltage divided by the average line-voltage. This example uses V_2/V_1 as the definition of voltage unbalance. The difference between these two definitions below 5% voltage unbalance is negligible.

$V_2 := 0.035$ pu Negative Sequence Voltage

$R_{LR} := 0.15$ pu Locked-Rotor Impedance

$I_{LR} := 6.25$ pu Locked-Rotor Current

$I_2 := \frac{V_2}{R_{LR}}$ pu Negative Sequence Current

$I_{FL} := 1$ pu Full Load Current

$I_1 := 1$ pu Positive Sequence Current

$$I_1^2 + 175 \cdot \left(\frac{I_2 \cdot I_{FL}}{I_{LR}} \right)^2 = 124.391\% \quad \% \text{ Increase in temperature}$$

2.2 Equivalent Current Concept

An equivalent current concept takes into account the additional heating that is a result of the negative-sequence currents [9, 10]. The equivalent current concept can be used with the thermal limits of the induction motor. References [9] and [10] define the equivalent current as shown in Equation 2-2.

$$I_{EQ} = \sqrt{I_M^2 * \left[1 + K \left(\frac{I_2}{I_1} \right)^2 \right]} \quad \text{Eq. 2-2}$$

Where:

I_{EQ} is the equivalent motor heating current

I_M is the real motor current (assumed to mean maximum stator current)

I_1 is the positive-sequence component

I_2 is the negative-sequence component

K is the unbalance bias factor

Note that Reference [9] does not provide an adequate definition of I_M , but it is assumed from Reference [10] that it refers to the maximum worst-case stator current. In addition, both of these references introduce an even more conservative K -factor. For example, Reference [9] states Equation 2-3 as a conservative estimate.

$$K = \frac{230}{I_{LRC}^2} \quad \text{Eq. 2-3}$$

For this report, values were used from Blackburn [7], provided in Eq. 2-1.

The Nuclear Energy Institute (NEI) working group on unbalance voltage impact has recommended the following equivalent current [8] approach shown in Equations 2-4 and 2-5 based on references [7] [12]. In these equations, I_{EQ} , I_1 , and I_2 have the same meaning as they did for Equation 2-2 above. Again, as stated by Blackburn, a conservative approximation of K is shown above in Equation 2-1.

$$I_{EQ}^2 = I_1^2 + K * I_2^2 \quad \text{Eq. 2-4}$$

$$I_{EQ} = \sqrt{I_1^2 + K * I_2^2} \quad \text{Eq. 2-5}$$

The results for this I_{EQ} will render results in agreement with the example in Section 2.1 above showing that a 3.5% voltage unbalance will result in a 25% increase in motor temperature. It should be noted, as stated in Reference [12], that Equation 2-5 assumes the thermal conductance of the motor tends to balance the average temperatures of the stator windings even though the heat produced is extremely unbalanced in the stator windings due to the unbalance currents. Reference [12] also notes that this averaging of heat between the stator windings may be less in machines of a higher voltage rating due to the increased thickness of conductor insulation.

2.3 Thermal Limit for Induction Machines

The question still remains, based on the previous sections, of how long can the motor operate with unbalanced voltages and not be damaged. IEEE Std. 620 “IEEE Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Machines” [16] defines thermal limit curves for induction machines, establishes a standard procedure for the presentation of these curves, and provides guidance for the interpretation and use of these curves for thermal protection of a machine. Per the standard [16], the motor thermal limit is presented in the form of a time-current curve representing locked rotor, acceleration and running overload.

For example, the thermal damage curve for the Reactor Coolant Pump (RCP) in Reference [3], maps closely to that shown in Figure 2-2 taken from the IEEE Std. 620. Note that model details are provided in next section and Reference [3].

Using the example from Reference [3], one or two phases were opened upstream of the Station Auxiliary Transformer (SAT) to create an unbalance voltage condition at the terminals of the RCP.

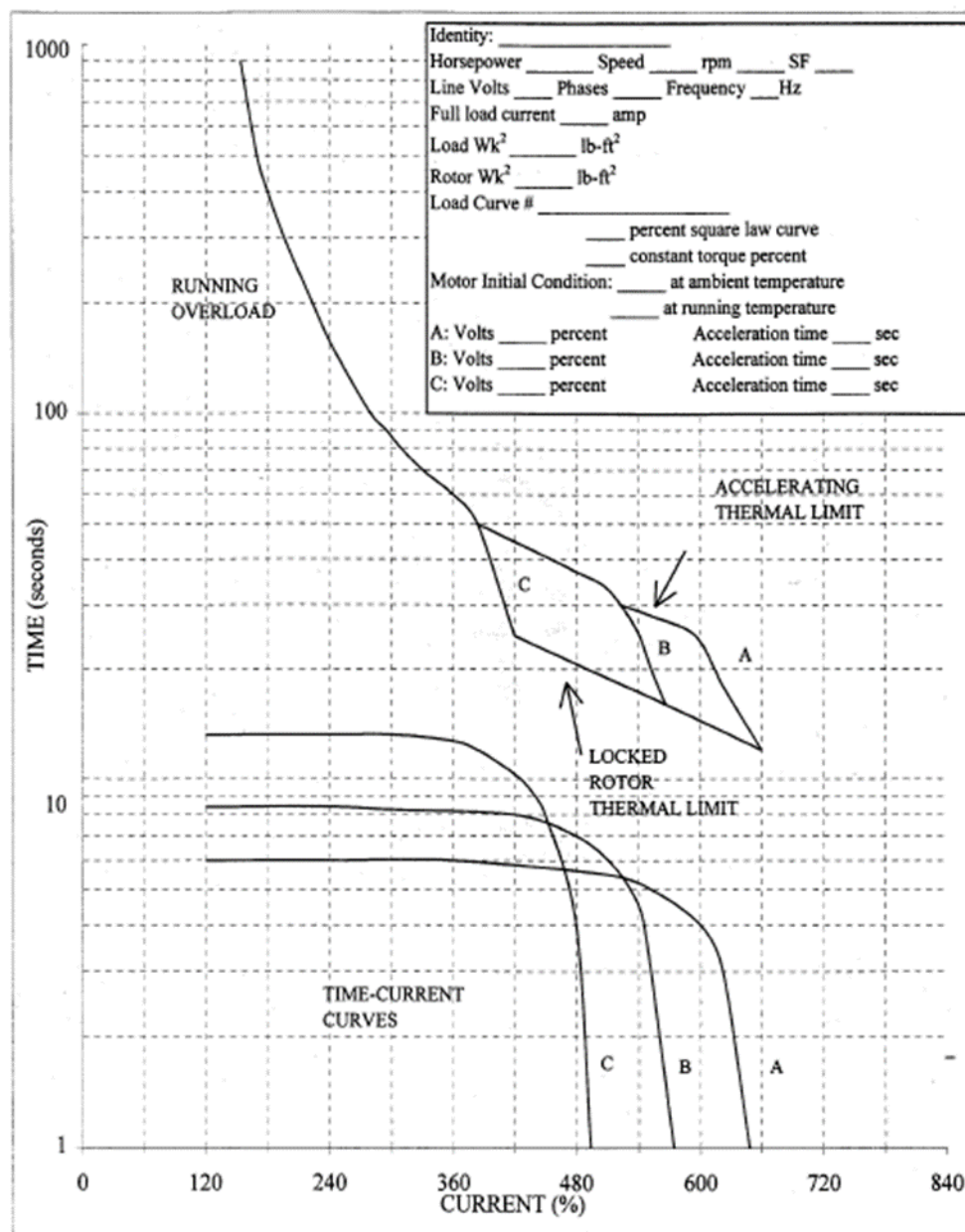


Figure 2-2
Typical Thermal Curve per IEEE 620-1996

Table 2-1 shows the results of these conditions. The table provides the following:

- Positive-sequence stator current (I_1),
- The negative-sequence stator current (I_2),
- The maximum of the 3-phase currents supplying the motor (stator current),

- Percentage voltage unbalance expressed as $\%V_2/V_1$,
- The equivalent motor heating current (I_{EQ}) based on equations 2-2 and 2-5, with a $K = 175/I_{LRC}$ (Blackburn), and the time to reach the damage threshold curve Figure 2-2 based on the results of I_{EQ} using both Equations 2-2 and 2-5.

Table 2-1

Responses for 6000 hp (4474 kW) RCP Motor in reference [3] to Unbalance Voltages as a Result of Open-Phase Conditions. Note: FLA is the Full Load Current of Motor

	I_1 (% FLA)	I_2 (% FLA)	Max Current on Phase (% FLA)	$\%V_2/V_1$	I_{EQ} (% FLA) Equation 2-7	I_{EQ} (% FLA) Equation 2-4	Time IEEE-620 Thermal Curve Figure 2-2
Single-Open Phase No Loads on Bus	101%	60%	152%	10%	161%	242%	120 sec – 800 sec
Single-Open Phase Bus Fully Loaded	117%	85%	178%	16%	211%	324%	60 sec – 250 sec
Double- Open Phase Bus Fully Loaded	140%	140%	288%	99%	327%	668%	10 sec (Locked Rotor Max) – 60 sec

As can be seen in Table 2-1, for the double open-phase case Equation 2-2 results in an I_{EQ} of 668% and Equation 2-5 results in an I_{EQ} of 327%. In this example, the maximum phase current is 288% of the full-load current (%FLA), well below the locked-rotor current rating of the machine (631%). Theoretically, the maximum current that will ever flow in the stator windings is the locked-rotor current. This can easily be examined by the sequence diagrams in Figure 2-3, where for all values of slip, the locked-rotor impedance is the lowest impedance ($s = 1$). Therefore, the locked-rotor limitation shown in Figure 2-2 of 10 seconds is a conservative estimate of the maximum allowable time to allow an open-phase condition to exist.

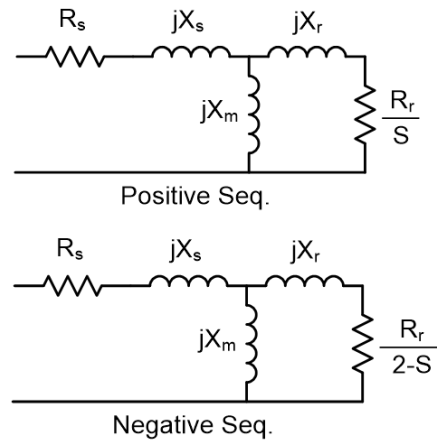


Figure 2-3
Positive- and Negative-Sequence Circuits of a Squirrel Cage Induction Machine

To examine this further, another example will be provided, but with a much lower source impedance compared to the previous case. In this example, the motor begins to spin down reducing the impact of the rotor heating on the stator windings, which is not considered in the assumptions of the K constant mode for Equations 2-2 or 2-5. ($K = 175/I_{LRC}$ (Blackburn [7])).

This next analysis investigates a wye-delta transformer case as shown in Figure 2-4. The wye winding is on the primary side of the transformer, i.e., the side where the open phase will be placed. The source impedance is dominated by the transformer impedance, which is:

- 230kV:4.16kV 25 MVA Delta – Grounded Wye
- Percent Load Loss = 0.2%
- % I magnetizing = 0.5%
- %No Load Loss=0.5%
- XHL = 10%

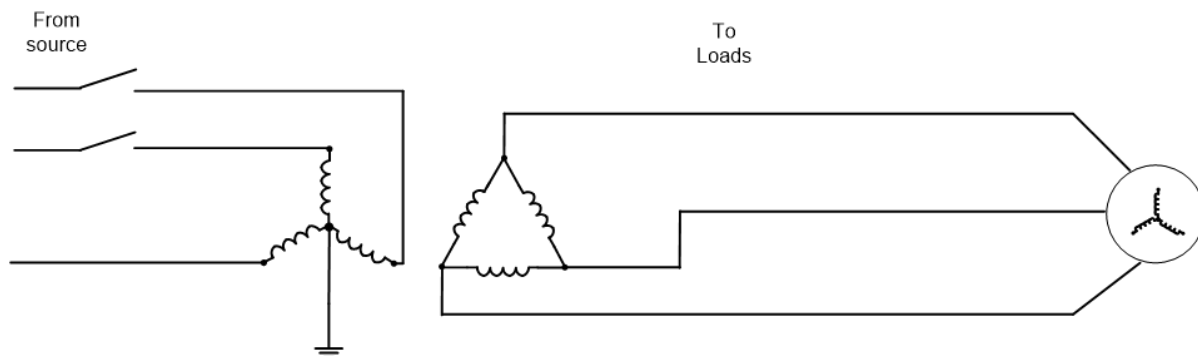


Figure 2-4
Wye-Delta Transformer

In this example, unlike the previous, the motor does not spin down and the slip increases from approximately 1% to 2%. Therefore, the motor is “single-phasing” and able to maintain rotation, albeit at a reduced speed. The results of this example are shown Table 2-2. As can be seen in the table, for the double open-phase case Equation 2-2 results in an I_{EQ} of 494% and Equation 2-5 results in an I_{EQ} of 300%. The maximum phase current is 213% of the Full-load Current (%FLA) which is well below the locked-rotor current rating (631%). Furthermore, if this condition is cleared by using the locked-rotor motor thermal limits (~10 sec), the negative-sequence heating effects on the stator associated with the rotor windings will be mitigated.

Table 2-2
Responses for 6000 hp (4474 kW) RCP Motor with a Reduced Source Impedance to Unbalance Voltages as a Result of Open-Phase Conditions. Note: FLA is the Full Load Current of Motor

	I_1 (% FLA)	I_2 (% FLA)	Max Current on Phase (% FLA)	% V_2/V_1	I_{EQ} (% FLA) Equation 2-7	I_{EQ} (% FLA) Equation 2-4	Time IEEE-620 Thermal Curve Figure 2-2
Double- Open Phase No Loads on Bus, Fed by a Y-D with Low Impedance	128%	128%	213%	24.4%	300%	494%	15 sec – 80 sec

It should be noted that if the induction machine is backfeeding static loads during an open-phase condition, then the heating of the rotor losses will increase and the unbalance in the stator windings will increase; however, the machine will see a reduction in speed and if this condition is cleared by using the locked-rotor motor thermal limits (~10 sec), the negative-sequence heating effects on the stator associated with the rotor windings will be mitigated. But again, the stator currents will not exceed the locked-rotor currents.

A more practical example would be to assume that the phase current is bound to the existing pick-up levels of the phase overcurrent. Assuming the pick-up levels are typically set to 150% of the FLA as shown in Table 2-3, assume the following:

Table 2-3
Bounding the Phase Pick-Up Overcurrent to 150% of FLA.

	I_1 (% FLA)	I_2 (% FLA)	Max Current on Phase (% FLA)	% V_2/V_1	I_{EQ} (% FLA) Equation 2-7	I_{EQ} (% FLA) Equation 2-4	Time IEEE-620 Thermal Curve Figure 2-2
Unbalance	140%	140%	150%	100%	327%	351%	60 – 70 sec

[Note: I_1 and I_2 assumed the worst case from the values simulated, in reality these values would be less.]

In this case, the phase currents (stator currents) are bounded by levels that would typically be detected by the phase overcurrents, Equation 2-2, it is found that I_{EQ} is equal to 351% and Equation 2-5, I_{EQ} is equal to 327%. Locating those values on the thermal curve in Figure 2-2, the approximate damage time is anywhere between 60 and 70 seconds. These values would correspond more closely to reference [15], which recommends using a negative voltage sequence relay with a timer with a range of up to 1 to 2 minutes.

All of the examples examined above were a “running motor” condition. As identified in Reference 14 and illustrated in Reference 3, for a motor that is started into an open phase condition it will take longer to start if it is able to start at all. The presence of the negative-sequence current creates a negative-sequence torque that counteracts the positive-sequence torque, resulting in a reduction of the net torque. In addition to this counteracting torque, the positive-sequence voltage will be reduced due to the larger stator currents. Therefore, the worst-case condition would be trying to start a motor under an open-phase condition and subjecting the stator winding to a prolonged exposure to the locked-rotor current.

2.4 Motor Data Used in Example

Simulations of Section 2-3 were performed using an Electromagnetic Transients Program (EMTP-RV) to model a 6000 hp (4474 kW) Reactor Coolant Pump (RCP). The motor parameters were estimated using available nameplate data. The parameters for the RCP motor are as follows:

- 4 kV – 6000 HP – 6 pole
- Assumed double cage rotor
- Steady State Slip = 0.92% (@ 1.0 p.u. load torque)
- F.L. Amps = 760.2
- L.R. Amps = 4800
- Efficiency = 92.5%, PF = 91.5%
- F.L. Torque = 26,500 Ft*Lbs (35,929 N*m)
- Starting Torque = 88% of F.L. (88,026 N*m)
- H of motor + load = 5.07 seconds
- Acceleration time @ 100% voltage ~ 15 seconds
- Acceleration time @ 80% voltage ~ 44 seconds

The acceleration times were determined from the curves of Figure 2-5.

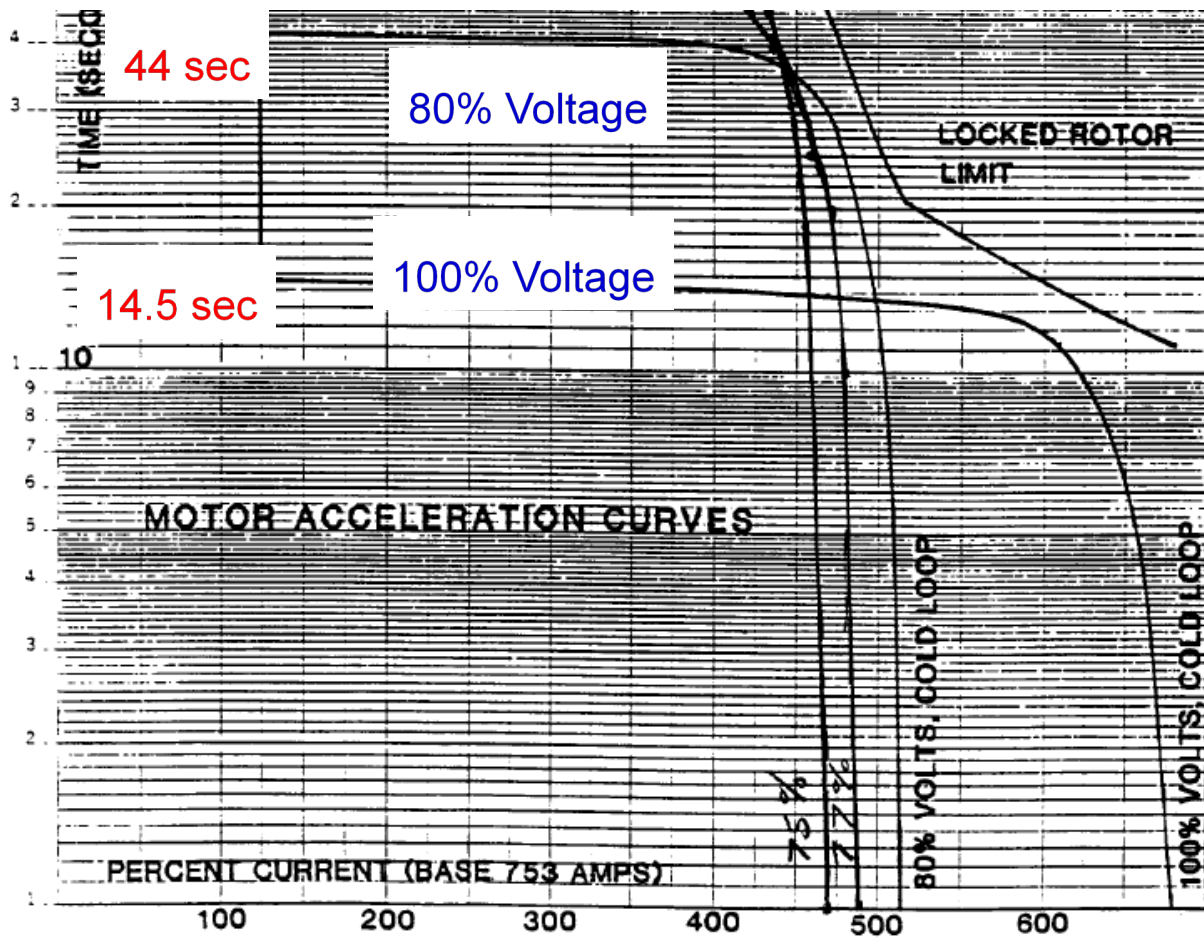


Figure 2-5
Motor Acceleration Curves for RCP Motor

3

SUMMARY

The purpose of this research is to recommend a maximum allowable time that an open phase should exist on a system before action is required.

The concern with voltage unbalance on motors is the additional heating that occurs because of negative sequence phase currents, when the condition goes undetected, causing the motor's temperature to continue to rise to levels which can damage motor insulations. These damaging levels can occur when the phase currents are below the pick-up levels of the phase overcurrent protection. Therefore, if additional protection is not in place, the condition will continue to exist. As discussed in Section 2, the heating impact on motors is dependent on many factors including the transformer winding type, the location of the open phase, the motor voltage rating, motor horse power, is the motor running, or starting, etc. Also, various ranges of assumed unbalance bias factors (K) will give a wide range of results.

As illustrated in Section 2, the stator current in an induction motor never exceeds the locked-rotor current for all voltage unbalance conditions examined. Therefore, it would be a conservative estimate to use the locked-rotor thermal limit to determine the exposure time for motors to unbalanced conditions. In most cases, this is approximately 10 seconds (IEEE Std. 620). However, each motor is different depending on its particular motor winding and ventilation configuration; therefore, it is recommended to use the motor specific damage curves provided by the manufacture to establish motor specific time settings.

It is important to note that these times only apply to a motor that is already running. The motor should not be started when an open-phase condition exists on the system. Both the locked-rotor torque and breakdown torque are decreased in the presence of negative-sequence voltage, and with the accompanying decrease in positive-sequence voltage, the motor will be exposed to locked-rotor currents for an excessive amount of time. Because of this, the motor will take longer to start, if it is able to start at all. [14].

4

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A

NEI OPAWG TASK GROUP REPORT: MOTOR NEGATIVE SEQUENCE CURRENT ACCEPTANCE CRITERIA

Purpose

An NEI Open Phase Analysis Working Group (OPAWG) Task Group has been reviewing industry documentation on the capability of motors to withstand negative sequence current during an open-phase event. The goal of this task group was to determine motor negative sequence current acceptance criteria. To achieve this goal, the following was required:

1. Identify a negative sequence current limit for induction motors, in terms of current and/or time, to prevent motor damage or loss of function due to overcurrent or other motor protective device tripping.
2. Determine a motor negative sequence current and/or time value for conditions when immediate protective action is not recommended or required.
3. Document references and assumptions associated with items 1 and 2.

Introduction

Unbalanced voltage conditions, on a three-phase power system, can cause undesirable effects on induction motors. Numerous studies have documented how increased current and decreased torque can occur in these conditions with increased rotor heating becoming an issue of concern.

Although small system unbalanced voltage conditions are a normal occurrence, there has been little and sometimes inconsistent guidance on how to protect motors and preserve safety functions once a voltage unbalance becomes significant. Due to the variety of motor specifications, general acceptance criteria for all induction motors could not be established. A method of calculating an equivalent current, from the effects of negative sequence current, was developed. Once the equivalent current is determined, existing motor damage curves can be utilized to ensure acceptable limits are not exceeded for individual motors.

Existing Guidance

NEMA MG-1 discusses voltage unbalance, which is the maximum deviation of a phase from the average of the three phase voltages. It states that 1% voltage unbalance is acceptable, but does not recommend motor operation above 5% voltage unbalance, and indicates a possible corresponding 30%-50% current unbalance will result. There is no guidance in MG-1 on what to do between 1% and 5%. More importantly, the NEMA standard contains no time criteria for any of these values. Time criteria are critical to prevent motor damage.

A more definitive measure of imbalance is represented in voltage and current sequence values (i.e. zero, positive and negative sequence). A negative sequence current value in particular can prescribe the unacceptable effect in a motor, but an acceptable level of negative sequence current for continuous operation has not been determined by the industry. There is little industry consensus on the values of motor negative sequence current that are detrimental and the time criteria for protection. In addition, there is no direct correlation between NEMA unbalance and negative sequence values.

IEEE C37.96-2012, Section 7.2.6.2 states that protection at 15% negative sequence current is typical.

Considerations for Acceptability

1. For unbalanced voltage conditions, where negative sequence current is low, there should not be any immediate detrimental effects on the loads. There is a need for protective guidance that considers the time for action.
2. The allowable time at a particular motor negative sequence value is a debatable point, because design must also consider what the motor overcurrent relaying response would be for the condition. It is entirely possible that motor overcurrent protection would prevent damage due to an unacceptable negative sequence current, but then loss of the load's function would be a concern.

References

Listed below are references related to defining motor thermal capability during operation with significant negative sequence currents.

1. Protection of 3-Phase Motors Against Single-Phase Operation, Transactions of the AIEE - Power Apparatus and Systems, Vol. 77, Issue 3, April 1958.
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Equivalent Current Formula Review

Formula #1

The Task Group has been investigating the validity and applicability of the following formula which typically reflects the existing industry guidance on the thermal heating effect of negative sequence current in a motor.

References 2, 4, and 5 provide a basis for the following equivalent current formula:

$$(A) \quad I_{EQ}^2 = I_1^2 + \left(\frac{R_{r2}}{R_{r1}} * I_2^2 \right)$$

Where:

I_1 = Positive sequence motor current in amperes

I_2 = Negative sequence motor current in amperes

$\frac{R_{r2}}{R_{r1}}$ = Ratio of motor rotor negative to positive sequence resistances

This can be re-written as:

$$(B) \quad I_{EQ}^2 = I_1^2 + (K * I_2^2)$$

Reference 4 shows K equal to:

$$(C) \quad K = \frac{175}{I_{LR}^2}$$

I_{LR} = Motor locked rotor current in per-unit (i.e. $\frac{I_{LR}}{I_{FL}}$)

Substituting equation (C) into equation (B) gives:

$$(D) \quad I_{EQ}^2 = I_1^2 + 175 * \left(\frac{I_2 * I_{FL}}{I_{LR}} \right)^2$$
$$I_{EQ} = \sqrt{I_1^2 + 175 * \left(\frac{I_2 * I_{FL}}{I_{LR}} \right)^2}$$

Formula #2

References 6 and 9 provide a slightly different version of Formula D:

$$(E) \quad I_{EQ}^2 = I^2 * \left[1 + K * \left(\frac{I_2}{I_1} \right)^2 \right]$$

Where:

I = Motor phase current in amperes

I_1 = Positive sequence motor current in amperes

I_2 = Negative sequence motor current in amperes

Substituting (C) into (E) gives:

$$(F) \quad I_{EQ}^2 = I^2 * \left[1 + 175 * \left(\frac{I_2}{I_1 * I_{LR}} \right)^2 \right]$$
$$I_{EQ}^2 = \left[I^2 + 175 * \left(\frac{I * I_2}{I_1 * I_{LR}} \right)^2 \right]$$

Recommendation

Since the negative sequence component results in rotor heating not sensed by the phase overcurrent relays, an equivalent current can be computed which takes into account the system unbalance effect.

Formula #1 is recommended to determine this equivalent current:

$$I_{EQ} = \sqrt{I_1^2 + 175 * \left(\frac{I_2 * I_{FL}}{I_{LR}} \right)^2}$$

Note all “I” values are in amperes.

Note: I_{EQ}/I_{FL} can be used as a per unit value to evaluate the effect of the negative sequence current and to determine motor protective requirements based on a comparison to typically available motor per-unit overcurrent limits.

Formula #2 could not be verified to accurately represent an equivalent current for the following reasons:

- The K value should be in per-unit as in equation (C), however this was not considered in the outlined references. Since this was not normalized, the portion in brackets is not a dimensionless quantity.
- The motor phase current (I) is not a definitive quantity like positive sequence motor current (I_1), since the magnitude of each phase current can be different.

While Formula #2 could not be verified to be correct as written, it was noted that if “K” is assumed to be a per-unit value and “ I_1 ” were substituted for “I” in equation (F), the formula reduces to the same as equation (D).

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