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INVESTIGATION OF EFFECT OF SINGLE PHASE
ELECTRICAL FAULTS AT LOFT

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ABSTRACT

This LTR presents the general basic engineering facts related to an open phase fault in a three phase power system commonly referred to as a single phase condition. It describes the probable results to electrical motors and describes the LOFT system design factors which minimize the likelihood of such a fault occurring at LOFT. It recognizes that the hazard of such a fault is a realistic threat and notes the types of relays designed to provide protection.

Recommendations are made to perform a detailed engineering study to determine the most advantageous protective relay design, and to implement such a design by installation of the necessary devices and controls.

Subcontract K5146 Task 18 was awarded to Nuclear Services Corp. June 30, 1978 for examination of LOFT electrical design and construction relative to susceptibility to open phase faults. The initial report draft was received August 14, 1978. Final report is scheduled for Oct. 9, 1978.

Subcontract K5734 was awarded to Westinghouse Elec. Corp. to provide a mathematical analysis of the effects of an open phase fault on the LOFT electrical System and recommend necessary protective relaying. The subcontract is scheduled for completion Oct. 12, 1978.

Responsibility for the engineering study design and implementation of necessary protection lies with the LOFT Instrument and Electrical Design Branch. The WBS Task No. is 521847.

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CONTENTS

- I. Introduction
 - II. Definition of a Single Phase Condition
 - III. Causes of Single Open Phase Faults
 - IV. Specific Cases and Related Comments
 - V. Reaction of Three Phase Motors to Single Open Phase Faults
 - VI. Methods of Reducing Risk and Providing Protection
 - VII. Method of Analyzing Single Phase Faults
 - VIII. Effect of a Single Loss of Phase Fault on the LOFT Facility
 - XI. Recommendations
 - X. References
- Appendix A - Symptoms on the LOFT EPDS Indicating a Single Loss of Phase Fault
- Appendix B - Unbalance Protection and Phase Failure
(Extract from ANSI C37.96-1975.
"Guide for AC Motor Protection")

I. INTRODUCTION

Three phase power systems have been long established and recognized as the most efficient and economical means of transmitting electrical power to industrial loads which require usage of considerable numbers of large motors. Three phase motors are inherently designed with excellent starting torque and low in maintenance requirements even under adverse usage environments. The loss of one phase in a three phase system is a serious problem in many respects and particularly to three phase motors. The latter problem is addressed in this document.

II. DEFINITION OF A SINGLE PHASE CONDITION

Whenever one "line" or "phase" conductor only is opened in a three phase power system and the remaining two lines remain energized the term "single phased" or "open phased" is applied.

III. CAUSES OF OPEN PHASE FAULTS

An open phase fault for an individual motor or load may be caused by a loose connection in any of the phase conductors from the motor control center to the motor terminal box. Such a loose connection causes overheating and burns open when the necessary current and joint resistance conditions occur. Fuses in motor circuits are also a very susceptible cause. Any line to ground, or line to line, fault which does not trip the protective device and burns open will result in an open phase.

An open phase fault for a group of motors can result from the same circumstances as given above and can occur in other types of equipment as well. Examples are loosening and opening of connection joints in buses in MCCS, Switch gear, aerial buses in switchyards and aerial distribution and transmission lines. The failure of a contact within a circuit breaker (a rare occurrence) or a disconnect switch is another potential cause of a single phase condition.

IV. SPECIFIC CASES AND RELATED COMMENTS

Throughout the history of the INEL 132 kv power transmission system no single phase fault is known to have occurred. A very few faults of this type have occurred on 12.5 and 13.8 kv power lines, however, the details are not documented.

The General Electric office in Salt Lake City reported that in June of 1978, the REA Power Co. in Alliance, Nebraska experienced an open phase in a high voltage transmission line tap, which did not result in a ground or short and no tripping occurred. G.E. Co., also reported that in May 1960, the operating rod in a 138 kv oil circuit breaker failed, causing an open phase on a transmission system operated by a power company in Texas.

Inquires made to Utah Power Co., Idaho Power Co. and Montana Power Co. revealed that they have no specific records of open phase faults and consider them very unlikely. No specific relay protection for such faults is provided on their transmission systems. An Idaho Power spokesman stated that many of their 365 kv transformers are protected by both oil immersed fuses and differential relays. Although the fuses can trip before the relays, a single phase condition would exist for only a few cycles. The spokesman also stated that their contracts with industrial and agricultural users stipulate that the billing rate is contingent upon the user providing his own single phase protective relaying.

V. REACTION OF THREE PHASE MOTORS TO SINGLE PHASE FAULTS

(Note, material contained in Ref. 1 has been used extensively in preparation of this section, see Appendix B).

A. Induction Motors

Three phase induction motors which are running at the time that one supply phase is opened will continue to run at near rated speed. The slip may increase but the motor will seldom stall unless the remaining single phase voltage is reduced, or the shaftload is a high value. The line current will

increase to nearly twice normal value and internal losses will likewise increase. The losses occur mainly within the rotor. Negative sequence phase currents flow in the stator equal and opposite to the previous load current. These currents produce a flux that rotates in a direction opposite to rotor rotation. This flux cuts the rotor bars at a high speed and generates a voltage and a resulting high current in the rotor bars. Because of the high frequency of the induced current ($120 \pm \text{hz}$) a marked skin effect occurs in the rotor bars which greatly increases rotor resistance. Consequently excessive heating of the rotor occurs even with stator line currents less than rated.

All three phase voltages will continue to appear at the motor terminals although the faulted phase voltage will be reduced, and the value will depend on motor load and other loads in parallel with the motor. Three phase motors that may be called upon to start on a single phase supply will fail to do so and will draw a high inrush current in the energized phases.

B. Synchronous Motors

Most synchronous motors and generators are provided amortisseur windings which consist of a type of squirrel cage winding placed in the outer portion of the salient field poles. The purpose of this winding is to act as a starter winding to bring the field pole rotor up to rated rotation speed and also to dampen any minor speed oscillations while running at synchronous speed.

A synchronous motor running at rated load when one supply phase is lost will probably pull out of step. If lightly loaded it will continue in synchronism and with additional losses. Severe and immediate damage to the amortisseur winding will likely result for the same reasons discussed for induction motors.

VI. METHODS OF REDUCING RISK AND PROVIDING PROTECTION

A. Design, Arrangement and Preventive Maintenance (PM)

The use of "parallel" and "ring" distribution and transmission lines such as employed at INEL and LOFT greatly reduces the susceptibility of loads to experience such fault conditions.

The elimination of fuses for protection of transformers and lines, and equipment, also practiced at LOFT, removes another source of such faults.

A good PM program in which all connections are checked and tightened on a regular basis or in which an infra red scan is performed will greatly reduce the risk of such connections opening under load.

B. Protective Devices

The very rapid overheating (1 minute or less) within the rotors of induction motors and amortisseur winding of synchronous motors caused by negative sequence currents flowing in the stator is the factor which requires special protection for highly important plant motors. The thermal relays included in motor contactor units for normal overload protection at motors are generally too slow for the required protection. Thermal detectors imbedded in the stator offer some degree of protection but are not believed adequate to protect the rotor amortisseur windings. Current unbalance relays have been used but may cause nuisance tripping of large motors during phase fault disturbances remote from the motor.

Negative phase sequence relays are most suitable for motor protection from open phase faults, however even these have some drawbacks in that sensitivity varies for various motor load conditions.

General Electric Co. currently provides a NBV negative sequence voltage balance relay and a INC negative sequence current relay and a solid-state Lodtrak phase unbalance relay for motor protection. Westinghouse Corp. provides a CVQ negative sequence voltage relay and a CW phase balance relay. They also furnish a MOR modular overload relay which can provide motor starters a loss of phase protective feature.

VII. Method of Analyzing Open Phase Faults

Open phase networks are analyzed using a balanced system of vectors called "symmetrical components". Stated simply, any unbalanced three-phase system of vectors can be resolved into three balanced systems of vectors, namely:

1. A balanced system of three phase vectors having the same phase sequence as the original unbalanced system of vectors. This balanced system is called the "positive-sequence system".
2. A balanced system of three-phase vectors having a phase sequence which is opposite to that of the original unbalanced system of vectors. This balanced system is called the negative sequence system.
3. A system of three single phase vectors which are equal in magnitude and which have exactly the same time-phase position with respect to any given reference axis. This system of single-phase vectors is known as the Zero-sequence or uniphase system.

Fig. 1 - Unbalanced Vectors

Fig. 2 - Positive-Sequence Components of the Vectors in Fig. 1

Fig. 3 - Negative-Sequence Components of the Vectors in Fig. 1

Fig. 4 - Zero-Sequence Components of the Vectors in Fig. 1

Fig. 5 - Combination of the Three Symmetrical Component Sets of Vectors to Obtain The Unbalanced Vectors in Fig. 1

Extending the use of symmetrical components further, we can develop the positive, negative and zero sequence impedance networks. For the system under study, the positive, negative and zero sequence self and mutual impedances of transmission line, transformers and rotating machinery are combined to form the equivalent circuits shown in Figures 6, 7, and 8. The machine impedances to be used in the networks depend on when the fault currents and voltages are desired; if immediately after the fault occurs, in general, use sub-transient reactances; if a few cycles after the fault occurs, use transient reactances; and if steady state conditions are desired, use synchronous reactances.

Fig. 6 - Positive Sequence Network Equivalent Circuit

Fig. 7 - Negative Sequence Network Equivalent Circuit

Fig. 8 - Zero Sequence Network Equivalent Circuit

An open phase circuit can be represented by an interconnection between the equivalent sequence networks shown in Figure 9.

Fig. 9 Positive, Negative and Zero Sequence Networks for Phase A, Interconnected to represent Open Phase, note generated voltage, E_a , appears in positive sequence network only. It is assumed alternators will generate only positive-sequence voltages.

From the sequence networks shown, the equations for positive-negative and zero sequence components of current and voltage follow:

$$I_{1F} = \frac{E_{a1} (Z_2 + Z_0)}{Z_1 Z_2 + Z_1 Z_0 + Z_2 Z_0} \quad \text{Pos. Seq. Current}$$

$$I_{2F} = \frac{-Z_0 E_{a1}}{Z_1 Z_2 + Z_1 Z_0 + Z_2 Z_0} \quad \text{Neg. Seq.}$$

$$I_{0F} = \frac{-Z_2 E_{a1}}{Z_1 Z_2 + Z_1 Z_0 + Z_2 Z_0} \quad \text{Zero Seq.}$$

$$E_{1X} - E_{1Y} = E_{a1} - I_{1F} Z_1 = \frac{Z_2 Z_0 E_{a1}}{Z_1 Z_2 + Z_1 Z_0 + Z_2 Z_0} \quad \text{Pos. Seq.}$$

$$E_{2X} - E_{2Y} = I_{2F} Z_2 = \frac{-Z_2 Z_0 E_{a1}}{Z_1 Z_2 + Z_1 Z_0 + Z_2 Z_0} \quad \text{Neg. Seq.}$$

$$E_{0X} - E_{0Y} = -I_{0F} Z_0 = \frac{Z_2 Z_0 E_{a1}}{Z_1 Z_2 + Z_1 Z_0 + Z_2 Z_0} \quad \text{Zero Seq.}$$

From the definitions of symmetrical components, we can now calculate the phase currents and voltages at the point of the fault (assume Phase "A" open)

$$I_a = I_{0F} + I_{1F} + I_{2F} = 0$$

$$I_b = I_{0F} + a^2 I_1 + a I_2$$

$$I_c = I_{0F} + a I_1 + a^2 I_2$$

$$E_{aX} - E_{aY} = E_{0X} - E_{0Y} + E_{1X} - E_{1Y} + E_{2X} - E_{2Y}$$

$$E_{bX} - E_{bY} = E_{0X} - E_{0Y} + a^2 [E_{1X} - E_{1Y}] + a [E_{2X} - E_{2Y}]$$

$$E_{cX} - E_{cY} = E_{0X} - E_{0Y} + a [E_{1X} - E_{1Y}] + a^2 [E_{2X} - E_{2Y}]$$

Where a is the vector operator e^{j120°

Thus, we have the unbalanced phase currents and voltages for an open phase in a three phase power system. By maintaining a current flow convention, direction of currents can be calculated. From the following equation power can also be calculated:

$$P = 3[(E_{0X} - E_{0Y})I_{0F} \cos \theta_0 + (E_{1X} - E_{1Y})I_{1F} \cos \theta_1 + (E_{2X} - E_{2Y})I_{2F} \cos \theta_2] \quad (13)$$

VIII. EFFECT OF A SINGLE LOSS OF PHASE FAULT ON THE LOFT FACILITY

The effects of an open phase fault on LOFT are placed in two categories: those which result from faults in the commercial power system external from LOFT, and those which result from a fault within the LOFT EPDS.

A. Effects Caused by Faults External From LOFT

In order for such an external fault to effect the LOFT EPDS it would necessarily have to occur in a single transmission line supplying the INEL or in a segment of the INEL "ring" transmission system with some other segment of the ring completely open, ie; a parallel configuration of lines would not be in effect. If such were the case all LOFT electrical loads including both vital 480 volt buses and MG sets would be affected. A variety of symptoms and effects would occur. Single phase lighting circuits supplied by the faulted (open) phase would go out, switchgear control power transformers (single phase) which happened to be supplied from the faulted phase would be de-energized with consequent loss of indicator lights and control power. Motors already running would draw nearly twice rated current and would exhibit other symptoms as discussed in paragraph V-A and V-B. Correct overcurrent devices might afford limited protection by opening of motor contactors but protection of rotors from damage cannot be assured. Three phase motors called upon to start would fail to do so.

The vital 480 volt buses and MG sets could separate from commercial power by action of under voltage relays however there is no assurance that this would occur, consequently such tripping would be necessary by the operator.

B. Effects Caused by Faults Within the LOFT Facility

A single open phase fault within LOFT would cause a more limited effect than described above. Only one vital bus and MG set would be affected. Many of the symptoms described in VIII-A would occur but in a less extensive manner.

Use of switchgear volt meters and ammeters would enable the operators to locate and isolate the faulted area.

Appendix "A" discusses specific symptoms anticipated throughout LOFT in the event of a single loss of phase fault.

C. Probability of LOFT Being Affected by a Single Loss of Phase Fault

Because of the requirements of the LOFT Technical Specification for redundancy of incoming power lines the probability of a single phase fault is very low. Also experience has shown that such faults are usually coincident with, or develop into, phase to ground or line to line faults which are detected by standard protective devices. The devices then open all phases of the faulted circuit.

IX. RECOMMENDATIONS

A. Action Throughout Power Ascension

1. Prepare a LOFT procedure for recognizing the symptoms of a single loss of phase fault and provide recommended protective action.
2. Accept the risk of the possibility of a loss of phase realizing that the probability of such an occurrence is low, and satisfactory recovery or isolation from such a fault is favorable due to the two vital MG sets and diesel generators.

B. Final Corrective Action

1. Conduct a thorough and orderly analysis to determine the most effective and appropriate means of protecting the LOFT EPDS from the consequences of an open phase fault.
2. Implement the results of the analysis with addition of recommended protective relays or other modifications as recommended.

Note: Subcontract K5146 task order 18 with NSC was awarded June 30, 1978

for examination of LOFT EPDS design and construction to discover any points of susceptible open phase failures. Subcontract K5734 is currently being fulfilled by Westinghouse to provide a complete mathematical analysis of the effects on the LOFT vital power equipment and to recommend such protective relays as may be required.

X, REFERENCES

1. ANSI C37.96-1075, IEEE Std. 588-1976, American National Standard Guide for AC Motor Protection. Note, Paragraph 2.7.1.3 is included as Appendix B.

SYMPTOMS ON THE LOFT EPDS INDICATING
A SINGLE LOSS OF PHASE FAULT

A. SINGLE PHASE ON INCOMING COMMERCIAL POWER

1. Numerous 120 volt receptacle or lighting circuits will be de-energized or suffer low voltage while some others will remain normal. Lighting throughout the plant will vary in intensity. Switchgear control power may be lost in some instances.
2. Numerous three phase motors will shutdown due to action of over-current protective devices. The PSMG sets are expected to trip off if they are operating at rated or near rated load. If operating at light load they may not trip off. A check of motor current on the switchgear ammeters should reveal high currents in two phases and no current in the third phase. If such conditions are noted the motor circuit breakers should be tripped open.
3. Three phase motors called on to start will fail to do so.
4. Voltmeters for all 480 volt buses should indicate a notable unbalance with one phase reduced 10% or more from the other two phases.
5. Voltmeters located in the 13.8KV SWGR, Rm 224 for the incoming 13.8 KV distribution lines can be expected to show a very notable unbalance.
6. The vital MG sets vital buses may separate from commercial power automatically, however, this is not assured. Hence if symptoms 1 thru 5, in total or in part, are noted circuit breakers CV-A-V and CV-B-V should be opened. The performance of the vital power system should then be checked for normality, ie; lights, motors and balanced AC voltage.

Paragraph 2.7.1.3, "Unbalance Protection and Phase Failure". Extracted from ANSI C37.96-1975, IEEE Std. 588-1976, "Guide for AC Motor Protection".

B. SINGLE PHASE ON THREE PHASE CIRCUITS WITHIN LOFT

1. The previous symptoms 1 thru 5 will be observed to a limited extent and only on the circuits affected.
2. As in A-6 the vital circuit breakers CB-A-V and CB-B-V should be opened by the operator. This may assist in isolating the problem to either the commercial or vital power system.
3. If an open phase occurs within the LOFT system the 13.8KV voltmeters will not show an unbalance and indication of the location of the fault within LOFT may be found by checking the voltmeters of the various 480 volt commercial and vital buses.

AC MOTOR PROTECTION

perature. Therefore, overcurrent devices with their distinct current pickup level will permit a higher winding temperature to occur on overvoltage than at rated voltage. Only a device that senses winding temperature can adequately protect against such an abnormal operating condition.

When starting with overvoltage, the locked-rotor current will be higher than rated starting current in somewhat greater than direct proportion to the increase in voltage. The locked rotor relay will protect the motor against thermal damage if the voltage is not more than 10 percent above rated voltage at the time of start.

2.7.1.3 Unbalance Protection and Phase Failure. Unbalanced voltage and phase failure are similar phenomena, differing only in degree of unbalance. While unbalanced phase voltages or currents are readily identified, it is the negative sequence component (refer to Section 5.7, Ref [15]) which actually jeopardizes the motor. Hence simple unbalance measurements may not provide the degree of motor protection required.

When the voltages supplied to an operating motor become unbalanced, the positive-sequence current will remain substantially unchanged, and a negative sequence current will flow due to the unbalance. If, for instance, the nature of the unbalance is an open circuit in any phase, a negative-sequence current will flow that is equal and opposite to the previous load current in that phase. The combination of positive- and negative-sequence currents produces theoretical phase currents of approximately 1.7 times the previous load in each sound phase and zero current in the open phase. This is illustrated in Figs 20, 21, and 22.

Due to additional motor losses, the actual value of motor phase current in each sound phase is closer to 2.0 times the previous load current. Three-phase voltages will still be observed at the motor terminals with one supply phase open. The actual magnitudes will depend on the motor shaft load and on whether any other loads or capacitors are connected in parallel.

If a synchronous motor is running at rated load and then one supply phase is lost, the motor will probably pull out of step and have to be removed from service. However, if the motor is lightly loaded and continues running

Fig 20
Current in Motor Windings With One Phase Open Circuited; Wye-Connected Motor

Fig 21
Connection of Sequence Networks for Open-Phase Condition

Fig 22
Sequence Currents for Open-Phase Supply to Motor

synchronously, there will be extra losses as a result of the asymmetry in line current, and destruction of the damper winding may result.

When an induction motor loses one phase, its slip will increase, but it usually will not stall unless the resulting single-phase supply voltage is below normal or the shaft load is more than 80 percent of full load. The losses will increase significantly when loaded near or above its rating. With either type motor, single phasing is a hazardous condition, and steps should be taken (preferably by relay action) to de-energize the motor.

A small-voltage unbalance produces a large negative-sequence current flow in either a synchronous or induction motor. The per-unit negative-sequence impedance of either is approximately equal to the reciprocal of the rated voltage per-unit locked-rotor current. If, for example, a motor has a locked-rotor current of 6 times rated, it has a negative-sequence impedance of approximately 0.167 on the motor rated input kilovolt-ampere base. If voltages having 0.05 per-unit negative-sequence component are applied to the motor, negative-sequence currents of 0.30 per unit will flow in the windings. Thus, a 5 percent voltage unbalance produces a stator negative-sequence current of 30 percent of full-load current. The severity of this condition is indicated by the fact that with this extra current, the motor may experience a 40 to 50 percent increase in temperature rise.

The increase in loss is largely in the rotor. Negative-sequence phase currents produce a flux that rotates in a direction opposite to the rotor rotation. This flux cuts the rotor bars at a very high speed and generates a pronounced voltage resulting in a large rotor current. In addition, the 120 Hz nature of the induced current produces a marked skin effect in the rotor bars, greatly increasing rotor resistance. Rotor heating is substantial for minor voltage unbalance. Excessive heating may occur with phase current less than the rated current of the motor.

When a three-phase induction or synchronous motor is energized and one supply phase is open, the motor will not start. Under these conditions, it will overheat rapidly and will be destroyed unless corrective action is taken to de-energize it. The heating under these circumstances is similar to that in a three-phase

failure to start, except that the line current is slightly lower (about 0.9 times the normal three-phase locked rotor current).

Unbalance protection must sense damaging conditions without responding to conditions for which the protective equipment is not intended to operate. Several classes of relays are used to provide unbalance protection.

Phase-balance relays compare the relative magnitudes of the phase currents. When the magnitudes differ by a given amount, the relay operates. When an open circuit occurs on the load or source side of the current transformers supplying the relay, sufficient unbalance should exist to make it operate. Phase balance relays are available with 1.0 A sensitivity and will operate if one phase of the supply to the motor opens with the load on the motor prior to the open in excess of approximately 0.6 A in the relay. Caution must be exercised in current transformer selection to ascertain with older phase-balance relays that the thermal capability of the relay is not exceeded at maximum load.

Phase-balance relays without additional time delay beyond what the available relays inherently provide may cause unnecessary tripping of large motors during phase-to-ground or phase-to-phase disturbances remotely located on the power system. Inasmuch as the clearing time of the relays on a power system are generally quite short in comparison with the required clearing time of phase-balance relays on the motor, a timing relay can be used without degrading the protection of the motor. Relay coordination is usually easier to attain with inverse time relay characteristics than with separate fixed time delays.

Negative-sequence current relays respond to the negative sequence component of the phase currents. The instantaneous version of this relay provides excellent sensitivity. Because of this, it will operate undesirably on the motor contribution to unbalanced faults on the supply system and therefore must trip through a timer or be directionally supervised.

The application of phase-balance and negative-sequence overcurrent relays (and neutral overcurrent relays) should consider current transformer characteristics under high-current conditions. Excessive current transformer burdens will result in current transformers saturating during fault conditions.

AC MOTOR PROTECTION

Heavy motor starting currents can also cause current transformer saturation, especially when the starting current has a large asymmetrical dc component. This dc resulting from motor inrush may last for a significant period of time compared to an asymmetrical fault current condition. This is because of the much greater Inductance Resistance (I/R) of the total circuit when starting a motor.

These current transformer saturations usually will occur unevenly between phases and result in false negative- or zero-sequence currents. Hence this needs to be considered when applying these types of relays. Unequal saturation is also encouraged by unequal burdens on the three current transformers. Phase unbalance relays usually have considerable variation in the burden between the three phases, and any unsymmetrical conditions such as single-phase ammeters and ammeter selector switches can cause relay misoperation due to unequal saturation.

Current transformer saturation is minimized by keeping burdens low (especially the dc resistive component), by using high ratio current transformers, and by selecting current transformers with a high knee point (saturation) voltage. Even these may be insufficient for the sustained dc in some motor inrush currents. In such cases desensitizing the relay with respect to current or increasing operating time or both may be necessary.

Negative-sequence voltage or reverse-phase relays respond to single phasing, to unbalanced voltage, or to reversed phase sequence. For motor protection these relays must sense the same voltage supplying the motor. They are particularly applicable to a bus with substantial static load along with the motor load. For an all-motor load, the negative-sequence voltage relay may not, depending on the motor characteristics, operate for single phasing at light load. Where motors constitute only a small proportion of the total load, single phasing of the total load will be recognized by this relay even with no shaft load irrespective of motor characteristics. In general, only the motor loads should be tripped when source single phasing or excessive unbalance is recognized.

2.7.2 Abnormal Frequency. Frequency in excess of rated frequency but not in excess of 5 percent over the rated frequency without a corresponding voltage rise is not considered to

be a hazardous condition for synchronous or induction motors, provided the driven equipment does not overload the motors at the higher frequency.

At decreased frequency without a corresponding voltage reduction, the flux requirements of a motor are increased, thus increasing the hysteresis and eddy-current losses and heating. Sustained operation at reduced frequency and rated or overvoltage is not permissible if the effect of the voltage and frequency exceeds the standard tolerances (see Section 2.2.6). Protection against this type of operation is usually allocated to the thermal protective equipment, but more refined protection is possible using a frequency-sensitive relay or a volt per hertz relay which measures the actual abnormality.

2.8 Abnormal Operating Conditions

2.8.1 Incomplete-Starting-Sequence Protection. An incomplete-sequence relay is a relay that returns the equipment to the normal or off position and locks it out if the normal starting, operating, or stopping sequence is not properly completed within a predetermined time.

Incomplete-starting-sequence protection can be provided by an adjustable definite-time relay furnished on electrically operated reduced-voltage, and some full-voltage, motor starters to protect the machine and starting reactor, autotransformer, or resistance against prolonged operation at subnormal speed. The stator overload relays do not provide such protection.

2.8.2 Out-of-Phase Re-energization Protection. Motors designed for across-the-line starting have the ability to withstand the mechanical forces developed by normal currents during starting at rated voltage. Abnormally high inrush currents can be produced in a motor when it is re-energized soon after a power interruption, and the possibility of damage should be assessed.

Inrush currents under such conditions can be as much as 2.5 times the magnitude of the normal locked rotor currents for which the motor is designed, depending on the degree of saturation of the motor magnetic paths, the system impedance, and the resultant voltage at the instant of re-energization.

High-speed automatic reclosure of a single feeder to an industrial plant can theoretically