

SOME LESSONS LEARNED FROM COMMISSIONING SUBSTATION AND MEDIUM VOLTAGE SWITCHGEAR EQUIPMENT

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Andrew R. Leoni
Member, IEEE
NEI Electric Power Engineering, Inc.
P.O. Box 1265
Arvada, CO 80001

John P. Nelson
Fellow, IEEE
NEI Electric Power Engineering, Inc.
P.O. Box 1265
Arvada, CO 80001

Abstract - This paper presents some general procedures for the proper inspection, testing, and start-up of critical, but often overlooked, electrical items in substations and medium voltage switchgear commonly found in petro-chemical facilities. The paper emphasizes procedures for protective relay and circuit breaker control circuit testing. Practical methods for testing current and potential circuits, which are the critical sensing inputs for most protective relaying, are discussed. Recommendations are made for confirming control circuits to ensure that protective equipment operates as intended. Finally, examples of common commissioning oversights are presented to emphasize the thoroughness needed to avoid potentially damaging consequences.

Index Terms – Commissioning, Start-up, Medium Voltage Switchgear, Protection Circuits

I. INTRODUCTION

Over the course of an average day, somewhere in the world a major electrical failure occurs at a petro-chemical plant. For many outages due to corrosion, heat build-up, insulation failures (some accelerated by contamination or humidity), animals, improperly prepared terminations, or mis-operation, the cause is quickly identified and corrected, and the equipment is placed back in service. With properly designed, installed, and maintained protection systems, damage is usually limited in scope. However, in cases with extensive and possibly collateral damage, the cause may not be found until a thorough analysis and investigation is complete. Unfortunately, the conclusion is never appealing. Often, the equipment or system:

- was designed incorrectly,
- was installed incorrectly, or
- did not perform as designed.

Furthermore, the cause of many failures is either inconclusive or misdiagnosed. For those instances when the system did not perform as designed, there are two common causes:

- Lack of maintenance
- Improper commissioning

Commissioning a substation or medium voltage switchgear line-up both safely and on schedule requires significant planning, documentation, and effort, as discussed by Bowen in [1]. Most new switchgear is assembled and tested in the factory.

However, some equipment suppliers may claim to test the switchgear but in fact may not truly perform comprehensive testing. The switchgear is disassembled for shipment, and then reassembled at the job site. The result may be the creation of many mechanical and electrical problems. Start-up lists and test procedures, including IEEE standards [2] [3] [5] [6], testing organization procedures, electric utility procedures, and equipment manufacturer guidelines, exist to help discover these problems. However, many times the electric system was designed correctly, constructed with the best intentions, but not thoroughly inspected and tested by qualified personnel before being placed in service.

This paper is not a complete treatise on the subject of testing and inspection required prior to or after energizing medium voltage switchgear and substation equipment. It does, however, discuss many important aspects of ensuring the protection systems for substation or medium voltage switchgear are, from an electrical standpoint, ready to be placed in service. The following sections discuss:

- Important items to be considered in the commissioning planning stage
- Practical methods for checking protective device circuits
- Common commissioning oversights and avoiding them

II. COMMISSIONING AND START-UP

Commissioning planning begins in the design stage. It should form a part of the specifications for the equipment purchased and installed, and must address the electrical and mechanical aspects of the installation. During procurement, careful review of submitted drawings and bills of material will help avoid conflicts in the field. The start-up process provides one of the final opportunities to review compliance with specifications and drawings. The test results form a baseline on the initial condition of the equipment. The process should ensure the equipment:

- is assembled and connected correctly,
- has the proper ratings,
- has devices which are calibrated, and
- the overall system will perform as designed.

Due to the complexity of modern protective relay systems, as discussed in [4], and the number of parties involved, the potential for errors and omissions must be accounted for in the planning stage.

For any given job, the equipment supplier, a separate testing group, the receiving organization, the design engineer, and/or end customer may provide start-up services. In all cases, a competent authority should review the test results, conduct a final inspection, and perform system tests. This review ensures that the individual systems, proven by others to be correctly installed, will in fact work together as intended. Some of these tests and inspections occur before energization and others after load has been placed on the new equipment. Improper testing and start-up may jeopardize the reliability of the equipment, the process, and the safety of personnel. The following section discusses tests that should be completed for protective device circuits.

III. PROTECTIVE DEVICE CIRCUIT TESTS

A. DC Control Circuits

DC control circuits are tested to verify that switching devices, such as circuit breakers, respond correctly to all control signals, and indicating devices, such as panel-mounted lights or remote control room monitor graphics, operate correctly within the designed logic. Control devices and operations to be verified with functional testing include:

- Control switch trip and close functions and associated indicating lights
- Protective relay tripping
- Automatic transfer schemes
- Lock-out relays and electrical interlocks
- Local, remote, and supervisory (SCADA) control and indication

Functional tests insure errors within DC control circuits are detected. These functional tests begin with checking wiring accuracy and end when the last string of logic, or more appropriately, the last contact in the last control device, is proven functional. When faced with a complicated DC schematic for a circuit breaker, this may appear to be an intimidating and time-consuming task. However, the inspection and testing must be thorough, safe and performed without damaging any equipment. In order to accomplish this, the following items should be considered:

- the source of the equipment
- the possibility of damaging relays
- undesirable circuit breaker operation

If equipment is new and thoroughly factory tested, less attention may be needed on the internal wiring. Not all suppliers have adequate quality controls in place to warrant the assumption that the equipment, if properly assembled in the field, is ready for service. If factory tests were witnessed or the equipment is from a "trusted" source, focus can be placed on confirming connections made during the field installation. If equipment was existing and significantly modified, or used equipment was purchased without being tested, extra care must be exercised and all internal connections should be reviewed before applying control power.

In order to avoid protective relay damage or accidental breaker operation, remove and/or open all test paddles and plugs, test switches, fuses, and DC power supply connections to

the relays before applying power. Removing power supply connections, whether they are made directly to the relay or through test plugs or switches, allows control voltage polarity to be checked before being applied to the relays. Assuming a typical ungrounded DC system, confirm there are no unintentional grounds in the control circuit or battery system. With grounds or shorts in the control circuit, closing the DC breaker or installing the fuses may trip (or close) a system breaker. In addition, verify that contacts are not wired so their operation results in short circuiting the control bus. After determining that correct polarity for power supplies has been applied and no trip or close paths exist, the sequential functional testing of the devices can begin. The major functional testing steps, along with examples, are discussed below. (Reference Fig. 1, a simplified trip circuit for a circuit breaker)

- Analyze the scheme to plan the test procedures.
- Work sequentially through the scheme. Each step should be structured as an action and an expected result. For example:
 - If the DC panel breaker (not shown) is open, then the control bus voltage is zero.
 - If the fuses are removed and the DC panel breaker is closed, then polarity and magnitude of the control voltage should be correct at the fuse block.
 - If DC is applied to the control bus, then the polarity and magnitude of the control voltage should be correct at the connections for the protective relay power supply.
 - After the relay power supply is connected and the DC control bus energized, the relay turns on.
 - If this breaker is closed, then (1) the red light should be illuminated and (2) input one (IN1) of the protective relay should be asserted.
 - If the control switch (52CS) is moved to the TRIP position, (1) the breaker opens, (2) the red light should be off, and (3) IN1 should be de-asserted.

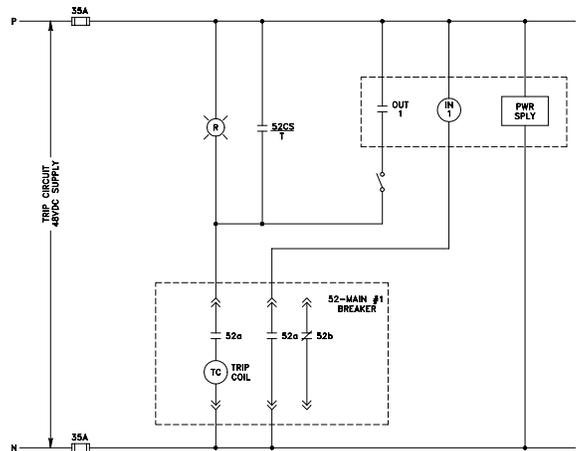


Fig. 1. Simplified DC trip circuit schematic.

- Document the results. Using a highlighter to mark those portions of the control circuit that have been successfully tested is an effective means of documenting the results and forces organization and thoroughness. *The cause of failures and unexpected, or confusing results should be*

determined and corrected before moving on to the next test to avoid compounding problems. Using Fig. 1 as an example, if the breaker is closed and IN1 is not asserted, the problem could be a number of things. Only investigation will reveal whether the wiring is correct, control voltage is present, the relay is damaged, the relay input voltage rating is appropriate, or the breaker auxiliary contact is operating.

By analyzing the scheme to plan the tests, working sequentially through the scheme, and accurately documenting the results, most control logic sequences can be simulated and proper operation verified.

As mentioned in [4], the control and protection flexibility provided by programmable relays and the use of PLC's has made some aspects of start-up and periodic testing more complex. The use of advanced communication systems, control philosophies, multi-function programmable relays, and increased automation and integration, has caused the number of items and systems to be verified to grow immensely. The logic implemented via programmable devices is not visible on the drawings. However, similar procedures, as outlined above, can be adopted to ensure the execution of the programmed logic results in proper operation.

B. Current Circuits

The following items should be verified for current circuits:

- Current transformers (CT's) accuracy class
- CT ratio and polarity (whether marked or not)
- Correct shorting screw removal
- Circuit wiring connections and terminations
- Protective device settings and displays
- Grounding

Many of these items should be tested individually. Accuracy class should be verified during construction and compared against the specifications and drawings. Ratio and Polarity can be tested with a CT test set, or other methods as described in ANSI/IEEE C57.13.1-1981 [2]. The circuit wiring could be "rung-out" to confirm the wiring connections are per the drawings and only one ground exists in the circuit. Device settings and displays, based on the coordination study for the project, are confirmed when testing the protective relays with secondary current injection at the relay panel test plug or switch. However, even though all of these tests are completed, there may still be wiring errors in the CT circuit that can damage equipment or defeat protection. Therefore, the entire current circuit must be checked and settings for CT ratios confirmed before energizing the equipment. After the substation or switchgear is energized, the current circuits, especially differential current circuits, should be rechecked to verify proper phase relationships and connections.

An effective means for testing ratio and polarity for CT's is the voltage method using an oscilloscope, as described in [2] and shown in Fig. 2. An AC voltage, set low enough to not saturate the CT, is applied to the CT secondary and monitored on channel 1 (CH1). The voltage induced on the primary is monitored on channel 2 (CH2). The two signals can then be compared for phase displacement and magnitude. For the connections shown in Fig. 2 the signals should be in phase,

confirming polarity, and differ in magnitude by approximately the CT turns ratio. Since inexpensive, dual channel, field duty oscilloscopes are readily available, this method can prove to be more cost effective than using a separate ratio and polarity test set. Note that CT's are typically stamped with the ratio and a polarity mark and have been known to be incorrect.

In order to confirm that the circuit wiring is accurate and programmable device settings in meters and relays are correct, pre-energization tests of the CT circuit wiring should be completed using the procedures for secondary or primary injection from [6]. For the secondary injection test shown in Fig. 3, the variable current source is connected to the first CT terminal block in the circuit. The source is then adjusted until a stable, measurable current is flowing in the circuit. The current is then measured with a clamp-on ammeter at different points in the circuit until reaching the relay or meter case. At that point, it can be confirmed that the wiring is correct for the phase under test. Once the wiring is confirmed, the local and/or remote displays, if equipped, can be checked and the CT ratio setting for the relay or meter confirmed. Note that the connected burden can be calculated with the recorded voltage and current.

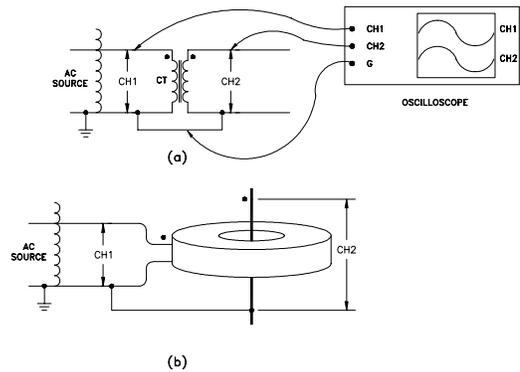


Fig. 2. CT ratio and polarity test. (a) Schematic representation. (b) Physical sketch.

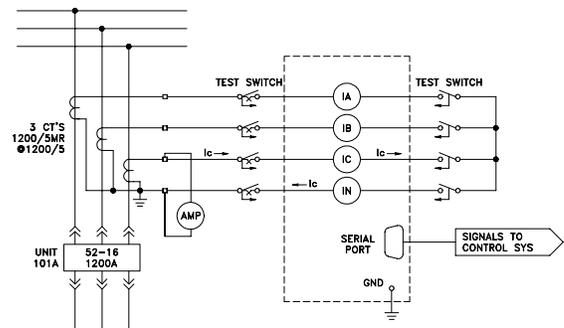


Fig. 3. Secondary current injection test.

C. Potential Circuits

Potential circuits' ratios, polarity, circuit wiring, device settings and displays, and grounding must be checked similarly to current circuits. The potential transformer (PT) connections should be compared to the drawings. Only after completely isolating the PT, use a variac to apply a secondary voltage. Proper phase connections to relays and meters as well as any PT ratio settings in programmable devices can then be checked.

The potential transformer secondary fuses must be disconnected to prevent a dangerous high voltage back-feed. Several fatalities have been caused by failing to do this on PT and CPT circuits during testing.

By following the procedures outlined above, start-up personnel can be confident the DC control circuits and sensing circuits for the protection scheme are ready for service. Certain items that, in the authors' experience, seem to be overlooked are discussed below.

IV. EXAMPLES OF COMMON OVERSIGHTS

A. Assuming Factory Wiring is Correct

Often field personnel are forced to assume the factory wiring is correct since verification of all wiring in the field would be too time consuming. Backed by a certified factory test report, the assumption may be valid. In the authors' experience some equipment suppliers are willing to provide certified test reports even though the switchgear has not, in fact, been completely checked.

A major, reputable, switchgear supplier supplied a certified test report for some new equipment. After a number of accessory equipment failures occurred when the authorized factory field service representative began commissioning, the following was discovered:

- A protective relay was damaged due to incorrect wiring in the resistance grounding current circuit.
- Pairs of 120V UPS's for a PLC were destroyed because an auto-transfer scheme was incorrectly wired at the factory.
- One circuit breaker would not charge because the wiring in the cell was incomplete.

According to the factory field service representative, four days were spent trouble-shooting and attempting to determine the cause for the failures. Had factory testing been witnessed to force the supplier to thoroughly test the equipment and provide an honest test report, this time could have been saved and the equipment supplier's reputation with their customer left intact.

B. DC Control Circuits

Common oversights involving DC control circuits include:

- Improper polarity
- Inaccurate wiring
- Improper/Unintentional grounds
- Short circuits
- Assuming all breakers controls are the same

In one facility, the sync-check relay output contact was destroyed twice because incorrect wiring to the relay set up a short circuit of the DC control bus when the output contact closed. The one-week delay for the second replacement relay could have been avoided had a short amount of time been spent to trouble-shoot and correct the circuit.

C. Current Circuits

Common oversights and problems involving current circuits include:

- Shorting screws left in terminal blocks
- Auxiliary CT's installed (wired) "backwards"
- Delta connections in differential circuits
- Protection provided by zero sequence CT's defeated by wiring errors
- Multiple grounds

1) *Shorting Screws*: Shorting type terminal blocks are normally recommended and supplied for current circuits in order to safely short circuit CT's. All CT circuits typically have shorting screws installed when the equipment is shipped and installed. These screws are not normally removed until the appropriate devices are connected in the circuit, and they must be left installed for any spare CT's. However, it is a common mistake for shorting screws to be left in terminal blocks in protective device current circuits, defeating the protection.

For example, a petro-chemical plant in Southwestern Wyoming placed a substation in service without removing the shorting screws from the CT terminal blocks for the 13.8kV switchgear when the substation was commissioned. Approximately one year later, a severe snowstorm, accompanied by high winds, forced snow into the tie section of the switchgear. The bus faulted, the switchgear relays did not operate since the CT's were shorted, and finally the 138kV transformer backup relays operated. This fault, finally cleared by the backup protection, caused major damage to the switchgear.

Based on the authors' experience, the most common current circuits that have shorting screws left in the terminal blocks are:

- Capacitor bank balance CT's (three occurrences)
- Neutral CT's in low resistance grounded systems (at least eight occurrences)
- Bus differential CT's (at least six occurrences)

Properly proving out every CT circuit individually, as described above, and documenting the test results on the drawings with a highlighter will prevent this from occurring.

2) *Auxiliary Current Transformer Connections*: In some instances it may be necessary to use an auxiliary current transformer to either step up or down a current signal. Special care must be exercised to ensure the auxiliary CT is connected correctly, since these CT's are usually installed to increase sensitivity of a protective device. If they are installed incorrectly they can also defeat the scheme. By analyzing the design, comparing the actual wiring to the drawings and testing the current circuits, proper operation of the protection can be assured.

3) *Current Transformer Connections for Transformer Differential Relays*: CT connections for differential relay protection of power transformers require consideration of (a) the transformer windings connection – e.g. wye-delta, delta-wye, wye-delta-wye and (b) the differential CT's circuitry to ensure the CT's are connected correctly based on the power transformer connections.

In power transformers, due to the ratio of transformation, the amount of current entering the transformer will differ from that leaving the transformer. If a transformer is connected delta-wye, there will also be a phase displacement between the currents. Historically for delta-wye connected transformers, the CT secondary currents are brought into phase by connecting the

CT's in wye on the delta side of the power transformer and in delta on the wye side to correct the phase shift, as shown in Fig. 4. The connection shown also helps to avoid zero sequence current problems since a transformer can be a source for zero sequence currents. More recently, some solid-state differential relays possess the means to avoid this problem and the CT's may be connected delta or wye.

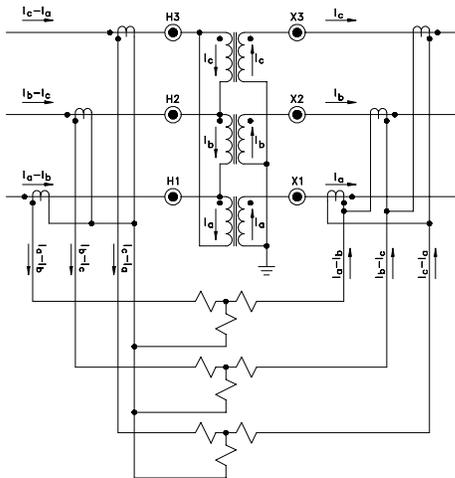


Fig. 4. Differential CT connections for delta-wye transformer.

In many petro-chemical plants, power transformers are delta-wye units. The delta connected CT's on the secondary are sometimes incorrectly wired. The result is the transformer is placed in service with incorrect wiring of the differential relay, and false tripping can occur. The false tripping may not occur until a large motor is started or the load in the substation increases to a point sufficient for the relay to falsely operate. The connections can be verified and this avoided by conducting pre-energization tests per [6] and described in Section III-B *Current Circuits*. After the drawings have been reviewed and the circuit verified, the primary and secondary differential circuits need to be verified by checking the phase angles and magnitudes of the currents entering the relay with the post-energization load test.

The post-energization load test is the final check that the CT's are connected correctly. The test results are valid only if load current is significantly greater than excitation current when conducting the procedure described below. If the phase angle between the primary voltage and current approaches ninety degrees and the primary to secondary current ratio does not closely match the turns ratio of the power transformer, load must be increased to perform the test. With adequate load on the transformer, the proper phase angle and magnitude of the CT secondary current should be observed at the transformer differential relay connections. A dual channel oscilloscope or an ammeter and phase angle meter can be used for this test. For example, as shown in Fig. 4, the H1 bushing on the power transformer enters a delta winding and consists of the currents ($I_a - I_b$). In other words, the H1 current has two components, the positive current in winding "a" and the negative current in winding "b." The delta CT's on the secondary of the transformer require this same relationship in making up the delta.

At a petro-chemical plant the authors noticed a discrepancy between the settings on a transformer differential relay and the design engineers request. While investigating the cause, it was discovered the history involved two potentially minor mistakes and one major mistake. The first minor mistake was a drafting error on the AC schematic, which the electricians used to connect the transformer CT's to the differential relay. The second minor mistake occurred when start-up personnel used the same drawing for verification and did not perform pre-energization tests on the CT connections. When the transformer was loaded, the differential relay tripped the unit off-line. Suspecting an incorrect setting, start-up personnel increased the slope setting until the relay quit tripping, thereby committing the major mistake: *The cause of the nuisance trip was not determined and corrected.*

4) *Core-Balance (Zero Sequence) CT's and Cable*: Many installations use a zero sequence CT on their medium voltage feeders for ground fault detection. However, many times the cable routing and especially the shield or ground wire routing is incorrect. This leads to defeating ground fault sensing or nuisance tripping for faults on other feeders. A properly installed zero sequence CT senses imbalances being carried by the phase conductors, as shown in Fig. 5. If the zero sequence current has a path back through the CT through the cable shields, it will be cancelled out unless the shield wires are passed back through the CT as shown in Fig. 6. (Note: Cable shield carrying capacity should be compared to available fault current magnitudes when using this type of cable.) This type of error occurs since drawings or connection diagrams rarely show electricians or cable installers how to route cable shields or ground wires. References [7] and [5] provide adequate information for designers, installers, and testing personnel to install these correctly.

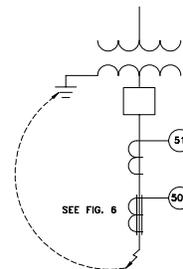


Fig. 5. Ground fault return path outside of core-balance CT.

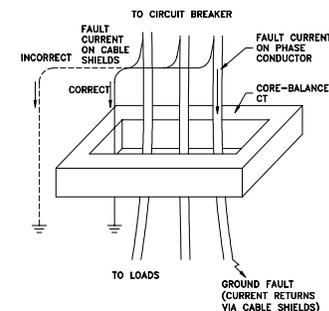


Fig. 6. Cable and shield routing through core-balance CT.

Dudor and Padden described one of their experiences in [7] which nuisance tripping led them to find incorrectly installed

core-balance CT's. The authors of this paper discovered improperly installed zero sequence CT's at a natural gas plant in Kansas. The facility included 115-13.8kV and 13.8-4.16kV substations, along with 13.8kV and 4.16kV switchgear. The new equipment had been in operation for approximately six months, after being commissioned and started up by the design engineer, equipment manufacturers, and the owner. In two 13.8kV and one 4.16kV feeders for critical equipment, the cable and associated shields were routed through the zero sequence CT's incorrectly. Had a ground fault occurred on these "commissioned" feeders, the fault would have to grow in magnitude or involve other phases before the protection would operate. This plant was fortunate to discover these errors before equipment was destroyed and production time lost.

D. Sensing Circuit Grounding

Associated with CT circuits are the grounds. With rare exceptions, only one ground per current circuit should exist. In accordance with [3], the location of this ground ". . ." should be located electrically at one end of the secondary winding of each instrument transformer and physically at the first point of application." The first point of application is typically the relay panel. Often, different personnel will wire different portions of a current circuit and each may elect to place a ground in the circuit. A simple megger test, executed after lifting what should be the only ground, will exclude multiple grounds, avoiding the possibility of circulating currents during fault conditions.

Besides having too many grounds some tests may require the ground to be lifted from such things as a PT secondary terminal block. When the test is completed, all appropriate connections must be restored. Without the ground connection meters and relays may not have a ground reference, resulting in inaccurate measurements and a safety hazard. This was the case at a Nevada mill. After using new equipment for over a year the cause for inaccurate power and voltage readings was traced back to a missing connection between the potential transformers and ground. A testing organization had removed this connection. Fortunately for these operating personnel, the PT's involved were only used for indication and metering so no nuisance trips resulted.

E. Surge Arrester Ratings

Surge arrester ratings should be verified and compared to the requirements based on the system grounding and all possible operating scenarios that affect grounding. Installation of surge arresters with inadequate Maximum Continuous Operating Voltage (MCOV) ratings on resistance grounded systems seems to occur frequently. Common causes include poor design, being overlooked during the submittal review process, or contractor mistakes. Operating conditions can affect system grounding and therefore change surge arrester rating requirements. For instance, the MCOV rating may be correct for normal system operating conditions, but not for emergencies. Fig. 7 shows a system in which the switchgear can be energized via an ungrounded source. If the emergency generator energizes the switchgear, the delta side of transformer #2 is not grounded. For such a system or for resistance grounded systems, surge arrester MCOV ratings should be based on the line-to-line voltage. If arrester ratings are based on the line to neutral

voltage and a ground fault occurs, the surge arresters may fail, typically catastrophically on the unfaulted phases.

V. CONCLUSION

Use of lists and procedures outlined in this paper as a starting point for commissioning plans will help avoid having to answer, "How could that have happened?" after an electrical failure. Qualified people must execute a comprehensive and thorough commissioning plan. The plan should require the correct tests and procedures to save time, verify functionality, and confirm protection will operate as intended, when required.

In particular, qualified personnel should check the following items:

- DC Control Circuits
- Current Circuits
- Potential Circuits
- Equipment Ratings

Start-up and testing services are extremely important. Test results provide a benchmark for future reference while the tests provide verification that the equipment will operate properly. Failing to properly and thoroughly commission facilities can result in serious and catastrophic consequences with potential for serious injury or death to operating personnel and long down time due to failure of equipment.

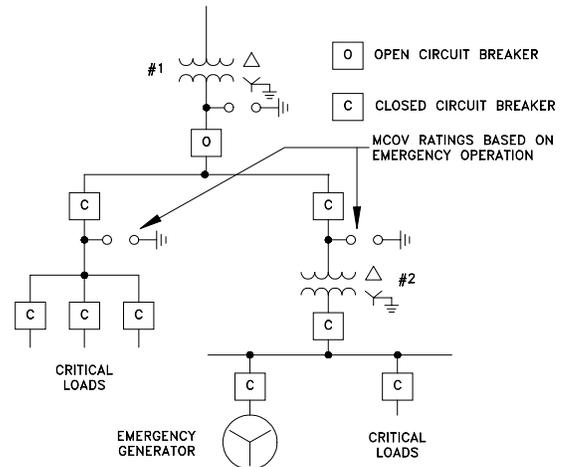


Fig. 7. Operating scenario that dictates surge arrester ratings.

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VII. VITA

Andrew R. Leoni graduated from the U.S. Merchant Marine Academy in 1990 and received his Master's degree from the University of Colorado in 1996. He has been a design and field start-up engineer with NEI since 1996. He is a registered professional engineer in the state of Colorado.

John P. Nelson received his BSEE from the University of Illinois at Urbana-Champaign in 1970 and his MSEE from the University of Colorado at Boulder in 1975. He founded NEI Electric Power Engineering in 1982. He is a registered professional engineer in the states of Arizona, California, Colorado, Louisiana, New Mexico, Utah, Wisconsin, and Wyoming.