Rev. 1

ROOT CAUSE REPORT FOR THE

EXIDE UPS 1A, B, C, D, G

TRIP EVENT OF AUGUST 13, 1991

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PURPOSE/SCOPE

This report has been generated to document the analysis of the root cause for the tripping of Uninterruptable Power Supplies (UPS) 2VBB-UPS 1A, B, C, D and G and the failure to transfer their loads to the maintenance supply.

This analysis was performed in accordance with NDP-16.01 by reviewing plant operator and damage control team observations and actions, performance of troubleshooting activities on in-plant equipment, review of various drawings, performance of laboratory diagnostic testing, consultation with the UPS manufacturer, review of data recorded during the event, and consultation with other industry experts.

ABSTRACT

On August 13, 1991 at 5:48 AM an electrical fault on the B phase main step-up transformer occurred. At that same time five (5) Exide Uninterruptable Power Supplies (UPS) tripped simultaneously. Transfer of the UPS's loads to the maintenance power supplies did not occur. The system conditions as documented by operators that were dispatched to restore the units immediately after the incident as well as observations by the System Engineer and other damage control team members indicated that the UPS's logic had tripped their input and output breakers. Post event review of equipment drawings with the vendor revealed that the DC power supply which powers the system control logic normally draws its power from the maintenance power supply. The inverter output is utilized as a backup source. This scheme of connection allows transients on the AC power line to be transmitted to the DC logic power supply. Tests performed by the System Engineer support this conclusion. The bypass breaker CB-4 did not close and transfer the UPS loads to the maintenance supply. This functioned per design since permissives for CB-4 closure were not satisfied due to the degraded voltage conditions present on the maintenance supply.

The initial inspection of the units revealed that alarm indications on the five units were not identical. The inverter logic alarm light was not lit on UPS1G but was lit on A, B, and C. The voltage difference alarm indication did not clear on 2 out of 5 units (Alarm should clear in 10-15 seconds after condition clears). The over-voltage/undervoltage (OV/UV) alarm was present on 3 out of 5 units although all units should have displayed this alarm. In addition, none of the 10 LEDs that indicate the initiating signals for a logic trip were lit on any of the UPS units.

DISCUSSION

On August 13, 1991 at 5:48 AM a ground fault occurred on the B phase main transformer. This event was detected and recorded on the Scriba Substation oscillograph. Five Exide UPSs (2VBD-UPS 1A,B,C,D, and G) tripped during this event resulting in a loss of power to all their loads.

The results of observations by plant operators and damage control team personnel are summarized on Attachment 1. All five UPS loads were initially restored to their maintenance supplies by plant operators after initially attempting (unsuccessfully) to restart the D unit. The damage control team was able to restart the C, D, and G units. The A and B units were left on the maintenance supply because the damage control team was not successful in restarting those units.

As a result of these observations, it has been concluded that all five units shut down as a result of a logic initiated trip. This conclusion is based on the as found positions of breakers CB-1,2,3 on all five units and the presence of the module trip alarm on all the units except D which was reset by a plant operator while attempting to restart that unit. It is noted however, that none of the 10 LEDs on the A13A21 card which should indicate what condition caused the logic to trip were lit. In addition, two units (UPS1D, UPS1G) displayed voltage difference alarms. This alarm indication should have cleared in 10-15 seconds after the plant operators manually restored the UPS loads to the maintenance supply. The OV/UV alarm indication was present on three units only, (UPS1C, UPS1D, UPS1G), although all units would be expected to display that alarm indication. The inverter logic alarm light was not lit on UPS1G although it was lit on the other units that were not initially reset (UPS1A, 1B, and 1C).

Breaker CB-4 was found open on all five units. A review of the oscillograph recording indicates that for the duration of the transformer fault (i.e., approx. 100 msec.) the B phase voltage of the station's normal AC distribution system decreased to approximately 50% of its normal level. It has been concluded that this condition prevented the automatic transfer of the UPS's loads to their maintenance supplies. This is due to a logic feature which prevents static switch transfer to the maintenance supply under conditions that could cause damage to the connected loads.

The following potential causes for the simultaneous tripping of the five UPSs were evaluated:

(1) Voltage transient on the B phase of the normal AC distribution system

(2) Propagation of high frequency noise from the main transformer fault

(3) Voltage transient on the station ground system

Transmission of high frequency noise from the transformer fault through the atmosphere to the UPS units could not have caused the UPS trips. Preoperational testing demonstrated that the units are not sensitive to radio frequency (RF) transmissions unless the panel doors are open and an RF source is in close proximity. The report provided as Attachment 2 indicates that it is unlikely that high frequency noise could have been transmitted through the station's normal AC distribution system to the UPSs due to intervening transformers that would filter such a signal. As a result, potential cause (2) is not considered credible.

Potential Cause (3) is considered unlikely due to the fact that one of the five UPSs is located in an area substantially away from the other four units yet exhibited similar behavior. In addition, no other station equipment (including other UPSs) appears to have been affected by a ground transient. Initial laboratory testing indicates that a significant ground transient would have caused the destruction of numerous logic circuit components which has not been observed in the field. Further laboratory tests are being conducted in an attempt to identify the mechanism by which inconsistent alarm light indications were received. Potential Cause (1) was investigated as the most probable cause.

Troubleshooting performed following the event to evaluate and demonstrate the validity of potential cause (1) indicated the following:

1) The DC logic power supply for UPSs 1A, B, C, D, G is normally fed from the B phase of the maintenance supply with the inverter output supply as a backup.

2) The trip point of the DC logic is at 17.3 VDC for UPS1D corresponding to 84.5 VAC on its input; and 16.9 VDC for UPS1C corresponding to 84.59 VAC on its input.* New control batteries (fully charged) only provide approximately 18 VDC.

3) Transfer to alternate power is accomplished via a K-5 relay. K-5 relay drop out voltage is 45 VAC for UPS1C and pick up voltage is 52 VAC.
K-5 relay drop out voltage is 42 VAC for UPS1D and pick up voltage is 55 VAC.*

4) Voltage transients generated during troubleshooting on the normal AC input power line feeding UPS1C did not trip the UPS.

*These measurements were not repeated on the other units since the results were essentially the same for the C and D units and should not be any different for the A, B, and G units.

5) The internal logic batteries on all five units were in a degraded condition and were not capable of sustaining proper logic voltage when all other sources were disconnected. There is no way to determine that the batteries are in a degraded condition with the current UPS design during normal operation.

6) Voltage transients injected (i.e., dropping AC input voltage to near zero for 100-200 msec.) on the maintenance power line in combination with the degraded batteries affected the DC logic such that it tripped the units without allowing the K-5 relay to change state. This was demonstrated on UPS1C and UPS1D.

7) A sudden complete loss of the maintenance supply voltage with both new and degraded batteries installed did not cause the unit to trip. In this case, the logic power supply properly transferred to the inverter output and therefore prevented a trip.

8) Voltage transients injected on the maintenance power line (i.e., similar to those utilized in 6) above) with good batteries installed did not produce any unit trips, although some voltage perturbations on the logic power supply were observed. This was demonstrated on UPS1C and UPS1D.

9) Fully charged batteries are required for successful K-5 relay transfer under some degraded voltage conditions on the maintenance line since other-wise the unit may trip on logic power supply failure < 16.9 VDC (84.5 VAC) before the K-5 relay will transfer the logic power supply to the inverter output.

Laboratory testing is being conducted to more fully evaluate the condition of critical components and to investigate why none of the 10 LEDs were lit on the A13A21 board even though the logic was tripped. The pertinent results of this testing to date indicate the following:

1) Significant ground voltage transients applied to certain circuit components causes their destruction.

2) Injection of noise into the boards has not caused a trip signal to be generated.

Laboratory testing will continue to further investigate the inconsistent alarm light indications. The outcome of this work is not expected to affect this root cause determination or the functionality of the UPSs. Results of in-plant troubleshooting and laboratory testing to date indicate proper function of the various alarms.

A review of the UPS vendor manual resulted in the identification of the following deficiencies:

- The vendor manual implies that the function of the batteries is to allow logic testing with no other input power available to the logic. This contributed to the system engineer not knowing that fully charged batteries could prevent a trip. The following statement is from the vendor manual:

  "A redundant logic supply, powered by the inverter output, a separate 120 VAC bypass source, and/or internal rechargeable sealed batteries, allows logic testing with no input power applied and keeps alarms indicating for as long as any source of AC control power is available."

- The section of the vendor manual which describes preventive maintenance does not mention the logic batteries, In addition, the general description section of the manual states,

  "(The batteries should be replaced at 4-year intervals)".

  The 4-year replacement frequency is not satisfactory for service over the acceptable ambient temperature range specified for the UPSs.

- The description of the logic power supply in the manual (shown below) is incorrect.

  "These power supplies are powered through relay A27K1, which selects inverter output (preferred) or bypass (alternate) source."

As a result of discussions with the UPS vendor it has been determined that the logic backup batteries are not designed to mitigate a degraded voltage condition. Additionally, the UPS design does not provide a battery test feature or allow for safe replacement of the batteries without removing the entire unit from service. Removing the unit from service would result in de-energizing the connected loads.

CONCLUSIONS

1) The main transformer fault caused a voltage drop on the maintenance supply to all five UPS units.

2) The degraded voltage on the maintenance supply caused the voltage on the UPS logic power supply to decrease below its trip setpoint causing the units to trip.

3) Automatic load transfer to the maintenance supply was prevented by design due to the degraded voltage conditions on the maintenance supply.

4) The <u>root cause</u> for the simultaneous tripping of the UPSs is <u>improper design</u>. The UPS is not designed to accomodate a degraded voltage condition. The following design deficiencies allowed the UPS logic power supply voltage to decrease below its trip setpoint as a result of the main step up transformer fault.

- The logic power supply is normally energized from the maintenance supply with the inverter output as a backup instead of visa versa.

- Under degraded voltage conditions the logic power supply switching circuit does not actuate until the supply voltage has decreased to well below the level that will cause the logic to trip.

5) Fully charged batteries probably would have prevented the tripping of the UPSs even though that is not part of their design.

CORRECTIVE ACTIONS

1) Modify the UPS logic power supply for units 1A,B,C,D, and G to be inverter preferred with maintenance backup prior to plant restart.

2) Replace all UPS logic backup batteries prior to restart.

3) Prior to restart review other plant hardware which utilizes backup batteries and verify that appropriate replacement schedules exist for those applications. Ensure any control functions dependent on batteries are identified prior to restart.

4) Process appropriate changes to the UPS vendor manual to address the identified deficiencies.

RECOMMENDATIONS

1) Evaluate (post restart) further logic power supply modifications to rectify the K-5 relay drop out characteristic problem and to provide easy access to the logic batteries for testing and replacement.

2) Develop an appropriate replacement schedule for the logic batteries based on supplier recommendations, actual service conditions, and purpose of batteries.

8/13/91, UPS FAILURE TO TRANSFER ON TRANSIENT ON AC INPUT:

A.) Operators responded to 2VBB-UPS1A, 1B, 1C, 1D, 1G and found the following:

1.) UPS1A:
   a.) CB-1 tripped
   b.) CB-2 tripped
   c.) CB-3 OPEN
   d.) CB-4 OPEN
   e.) AUTO restart
   f.) CB-3 switch closed
   g.) Module TRIP
   h.) Inverter Logic Alarm

2.) UPS1B:
   a.) CB-1 tripped
   b.) CB-2 tripped
   c.) CB-3 OPEN
   d.) CB-4 OPEN
   e.) AUTO restart
   f.) CB-3 switch closed
   g.) Module TRIP
   h.) Inverter Logic Alarm

3.) UPS1C:
   a.) CB-1 tripped
   b.) CB-2 tripped
   c.) CB-3 OPEN
   d.) CB-4 OPEN
   e.) AUTO restart
   f.) CB-3 switch closed
   g.) Module TRIP
   h.) Inverter Logic Alarm
   i.) OV/UV

4.) UPS1D:
   a.) CB-1 tripped
   b.) CB-2 tripped
   c.) CB-3 OPEN
   d.) CB-4 OPEN
   e.) AUTO restart
   f.) CB-3 switch closed
   g.) No module TRIP
   h.) No Logic TRIP
   i.) OV/UV
   j.) OV/UV Transfer
   k.) Voltage Difference

5.) UPS1G:
- a.) CB-1 tripped
- b.) CB-2 tripped
- c.) CB-3 OPEN
- d.) CB-4 OPEN
- e.) AUTO restart
- f.) CB-3 switch closed
- g.) Module TRIP
- h.) Voltage Difference
- i.) OV/UV

B.) The operators did the following manipulations in attempting to restore the UPS':

1.) UPS1A:

- a.) Placed restart switch to MANUAL
- b.) Placed the CB-3 toggle switch to OPEN position.
- c.) Reset the alarms
- d.) LIFTED CB-4 MOTOR OPERATOR AND MANUALLY CLOSED CB-4. * see note

2.) UPS1B:

- a.) Closed CB-1
- b.) Closed CB-2
- c.) Reset the alarms
- d.) LIFTED CB-4 MOTOR OPERATOR AND MANUALLY CLOSED CB-4. * see note

3.) UPS1C:

- a.) Placed restart switch to MANUAL
- b.) Placed CB-3 toggle switch to OPEN position
- c.) LIFTED CB-4 MOTOR OPERATOR AND MANUALLY CLOSED CB-4. * see note

4.) UPS1D:

- a.) Closed CB-1
- b.) Closed CB-2
- c.) Reset the alarms
- d.) LIFTED CB-4 MOTOR OPERATOR AND MANUALLY CLOSED CB-4. * see note

5.) UPS1G:

a.) Placed CB-3 toggle switch to OPEN position.
b.) LIFTED CB-4 MOTOR OPERATOR AND MANUALLY CLOSED CB-4. * see note

* NOTE: When the operators tried to restart UPS1D the procedure called out verifying that CB-4 was closed but it was open. The operators made a decision to energize the UPS loads by manually closing CB-4 by first lifting the motor operator off of the breaker. They restored each UPS in that same manner.

C.) At approximately 0830 the system engineer went down with damage control team #3 (operators, electricians and I/C technician) to restore each UPS.

UPS1C: Found CB-1, CB-2 tripped and CB-3 was open. CB-4 was closed and the CB-4 motor operator (in the OFF position) was lifted off breaker. Removed P6 plug from the CB-4 motor operator and aligned the motor operator to the ON position. Reset all alarms. Closed CB-1 and restarted the unit. It started up and "synced" to the maintenance supply. Closed CB-2, restored P6 plug and reinstalled the motor operator for CB-4 back on the breaker. Transferred the load to UPS power and put transfer switch in AUTO position.

UPS1D: Found CB-1, CB-2 closed and CB-3 was open. CB-4 was closed and the CB-4 motor operator (in OFF position) was lifted off the breaker. Removed P6 plug from the CB-4 motor operator and aligned the motor operator to the ON position. Opened CB-1 and CB-2. Closed CB-1 and restarted the unit. It started up and "synced" to the maintenance supply. Closed CB-2, restored P6 plug and reinstalled motor operator for CB-4 back on breaker. Attempted to transfer load to UPS power but CB-3 would not close. It was found in tripped position. CB-3 was reset, the motor operator was restored and the unit transferred to UPS power. Put the transfer switch in AUTO position.

UPS1A: Found CB-1 and CB-2 tripped and CB-3 was open. CB-4 was closed and the CB-4 motor operator (in OFF position) was lifted off the breaker. Removed the P6 plug from the CB-4 motor operator and aligned the motor operator to the ON position. Closed CB-1 and attempted to restart the unit. Closing CB-1 caused an inrush to the UPS and tripped the upstream breaker, 2VBB-PNL301, breaker #1. Reset breaker in 2VBB-PNL301 and reclosed CB-1 on UPS1A. Upstream breaker tripped again. Wrote WR (WR # 162319) and Deficiency tag to repair Rectifier section of UPS1A. Unit left with CB-4 closed.

UPS1B: Found CB-1, CB-2 closed and CB-3 open. CB-4 was closed and the CB-4 motor operator (in OFF position) was lifted off breaker. Removed P6 plug from the motor operator and aligned motor operator to ON position. Opened CB-1 and CB-2. Closed CB-1 and restarted unit. It started up and "synced" to the maintenance supply. Closed CB-2, restored P6 plug and reinstalled motor operator for CB-4 back on breaker. Attempted to transfer load to UPS power but CB-3 would not close. It was found in the tripped position. CB-3 was reset, the motor operator was restored and attempted to transfer load to UPS power but CB-3 again would not close. CB-3 cannot be reset due to a previously identified problem. Unit left with CB-4 closed - on Maintenance supply power.
Note: WR# 138173 exists to replace CB-3.

UPS1G: Found CB-1, CB-2 tripped and CB-3 open. CB-4 was closed and the CB-4 motor operator (in OFF position) was lifted off breaker. Removed P6 plug from motor operator and aligned motor operator to ON position. Reset all alarms. Noted 575vac input to UPS. Closed CB-1. When CB-1 was closed it tripped its upstream breaker in 2VBB-PNL301. Breaker #7 in 2VBB-PNL301 was reset and CB-1 reclosed (successfully). The unit was restarted. It started up and "synced" to the maintenance supply. Closed CB-2, restored P6 plug. When restoring the P6 block the CB-4 motor operator went to the OFF position. Opened CB-2 and CB-1 and removed logic power from unit to reset all logic. Reset motor operator on CB-4 to ON position. Reclosed logic power, closed CB-1 and restarted UPS. Unit started up and "synced" to the maintenance supply. Closed CB-2, restored P6 plug and reinstalled the motor operator for CB-4 back on the breaker. Transferred load to UPS power and put transfer switch in the AUTO position.

NOTE: When a trip signal is generated within the UPS it sends a shunt trip signal to both CB-1 and CB-2. It also sends an OFF signal to CB-3 and an ON signal to CB-4. A voltage difference alarm will inhibit a closure of CB-4.

UPS ALIGNMENT AT TIME OF EVENT:

		2NPS-SWG001	2NPS-SWG003
UPS1A Normal AC	(US3-B)		X
UPS1A Maint. Supply	(US5)	X	
UPS1B Normal AC	(US3-B)		X
UPS1B Maint. Supply	(US6)		X
UPS1C Normal AC	(US3-B)		X
UPS1C Maint. Supply	(US5)	X	
UPS1D Normal AC	(US3-A)	X	
UPS1D Maint. Supply	(US6)		X
UPS1G Normal AC	(US3-B)		X
UPS1G Maint. Supply	(US6)		X

Niagara Mohawk

Nine Mile Point Unit 2

Event of 13 August 1991

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5 September 1991

Niagara Mohawk Nine Mile Point Unit 2 Event of 13 August 1991 05:48

Introduction

On August 13, 1991, at 5:48 AM the Unit 2 phase B generator step-up transformer failed. Oscillographic records of the event are available from a digital data recorder at the Scriba Substation. They show various 345 kV and 115 kV system voltages and currents. Figure A with notations is attached.

The four cycles preceding the fault show no signs of a gradual degradation or a developing disturbance. The oscillographic traces and station protective relay targets reported, indicate a ground fault occurred on the high voltage winding. Depression of the 345 kV phase B bus voltage to about 39% of the prior value was observed from the oscillographic trace. This suggests the involvement of only a portion of the entire winding. The 345 kV line currents and voltages show rapid development of the ground fault beginning at point 1 with the ground current reaching a constant value of 1,300 amperes in 1 1/2 cycles at point 4. The flashover in the faulted transformer occurs just preceding a maximum in phase 2 to neutral voltage (as would have been expected) at point 2. The 345 kV line current in an unfaulted phase increases in step function manner to 350% of the prefault value at point 3.

No high speed recordings of voltages or currents within the plant were available. No sequence of event recordings were available to correlate relay operation times. Due to the large amount of magnetic energy coupling the generator rotor and stator, and known electrical parameters, the decay of fault current contributed by the generator to the solidly connected transformer would have spanned a number of seconds as the field decayed.

Relay operation targets reported were:

1. Transformer Differential Relay (Type BDD) on Transformer 2MTX-XM1B.

2. Transformer Neutral Current Relay (Type IAC).

3. Overall Unit Differential Relays (Type BDD) in phases 2 and 3.

4. Generator Phase Overcurrent Relays (Type PJC) in phases 2 and 3.

Postulated Event Scenario

Following isolation of the generator and failed transformer from the power grid, marked 5 on Figure A, only a single 345 kV phase to ground voltage record is available. The magnitude of this voltage on an unfaulted phase is 74% of the pre-fault value. Since generator neutral current is limited to less than 8 amperes, it is known that the faulted transformer appears as a line to line fault with some impedance to the generator. By trial and error calculation, generator line currents are found to be 0, 1.9 and 1.9, multiples of the rated value of 31,140 amperes. The line-to-line voltages have magnitudes 74% 74%, and 25% of the rated value of 25,000 volts. The decay of this voltage for 0.25 seconds of the recording has a measured time constant of 2.7 seconds. The calculated value of the impedance of the faulted transformer as seen by the generator is 0.23 per unit.

Conditions prevailing during the six cycle time period following the fault, marked 2 on Figure A, cannot be determined with certainty. The exact nature of the fault within the transformer is not known and the physical evidence will be strongly affected by the continued flow of energy from the generator due to the inherent time constant. The flashover of only a portion of the HV winding is evident since the 345 line voltages to neutral remain at 39%, 86% and 86% of the pre-fault values. The presence of "residual" in the measured 345 kV line currents provides the evidence of transformer neutral to ground current. This requires that the fault involves a path for current to ground from the high voltage winding. Recorded voltages and currents show a step change to new values and no dramatic change during the time period of the record, which totals somewhat less than 1/2 second. It could be said they are "cleaner" and less distorted than commonly seen oscillograph recordings of faults.

Given these observations and since both the generator and the system were supplying fault current into the faulted transformer, generator line-to-line voltages preceding isolation would be expected to be greater than those immediately following isolation.

High Frequency Voltage Transfer

It has been speculated that very high frequency energy (mHz region) may have caused malfunction of logic and control circuitry in the UPS equipment. A broad range of frequencies would be expected in any arcing phenomenon such as occurred in this failure. Nothing in the available data or design parameters of the plant equipment would suggest an extraordinary generation or propagation of higher frequency components. The failure of a transformer and internal arcing is not a rare occurrence. Comparison of oscillographic charts

from similar events in other plants show nothing unexpected or unusual in this particular failure. It must be borne in mind that the sampling rate of the recorder is listed as 5.814 kHz and frequency components in excess of perhaps 500 Hz would not be accurately portrayed.

GE experience in testing of typical power transformers (such as the Unit Auxiliaries Transformers) provides an indication of the expected coupling between windings at radio frequencies in the region of 1 megahertz: The attenuation factors range from 1,000: 1 to 10's of thousands: 1. Direct measurements could be made in this plant to determine attenuation factors for individual transformers over a range of frequencies. These tests would be made on non-energized transformers using an RF signal generator and a sensitive, calibrated detector.

Attached recent articles on electro-magnetic interference. Reference 1 discusses IEC 801.4 and the characteristics of electrically fast transients. Reference 2 discusses testing of ground connections.

Station Ground Elevation

The possibility of elevation of the station grounding system as a result of this disturbance was postulated. The relatively high level of ground fault current, estimated at 1,300 amperes from the available recording, would not have been conducted into the plant. This current can only flow in from the 345 kV system for the 6 cycle period required for relay and circuit breaker operation to achieve isolation. The generator ground current would have been limited to less than 8 amperes by the neutral grounding equipment. Elevation or differences in ground potential within the plant would therefore not have been expected during this event.

Reference 1 discusses the problem of achieving a "super" ground and concludes that a stable ground reference for interconnected equipment is of greater significance. Since normally circulating ground currents are not expected, testing with very low voltages and currents is recommended. Note especially the recommendation to test with a frequency non-harmonically related to the power line frequency.

Design Review of Nine Mile Point Auxiliaries Power Distribution System

The transformers stepping the voltage down to successively lower voltage levels are connected in a manner to minimize coupling of power frequency and higher frequency components between the various busses. Specific configurations are:

1. Normal Station Service Transformer -
   delta 25 kV to wye 13.8 kV with 400 ampere resistive grounding on the 13.8 kV side.

2. Load Center Transformers -
   delta 13.8 kV to wye 4.16 kV with 400 ampere resistive grounding on the 4.16 kV side.

3. Load Center Transformers -
   delta 13.8 kV or 4.16 kV to wye 600 volts with neutral solidly grounded on the 600 volt side.

4. Reserve Station Service Transformers -
   wye 115 kV, delta 4.16 kV, wye 13.8 kV. The 13.8 kV neutral is 400 ampere resistive grounded. The 4.16 kV circuit is connected to a zig-zag grounding transformer with a resistor in the neutral connection, presumably for 400 amperes.

These configurations provide "effectively grounded" distribution busses as defined in IEEE Standard 142 and will serve to limit transient over voltages. This is in accordance with design practices deemed prudent and conservative within the power industry.

Transformer Failures

The industry continues to review the effects of geomagnetic disturbances on power transformers.

While no evidence is seen of voltage distortion in the four cycles preceeding the failure, excessive duty could have occurred if these transformers had been subjected to low level direct current previously. References 3 and 4 are attached for perusal.

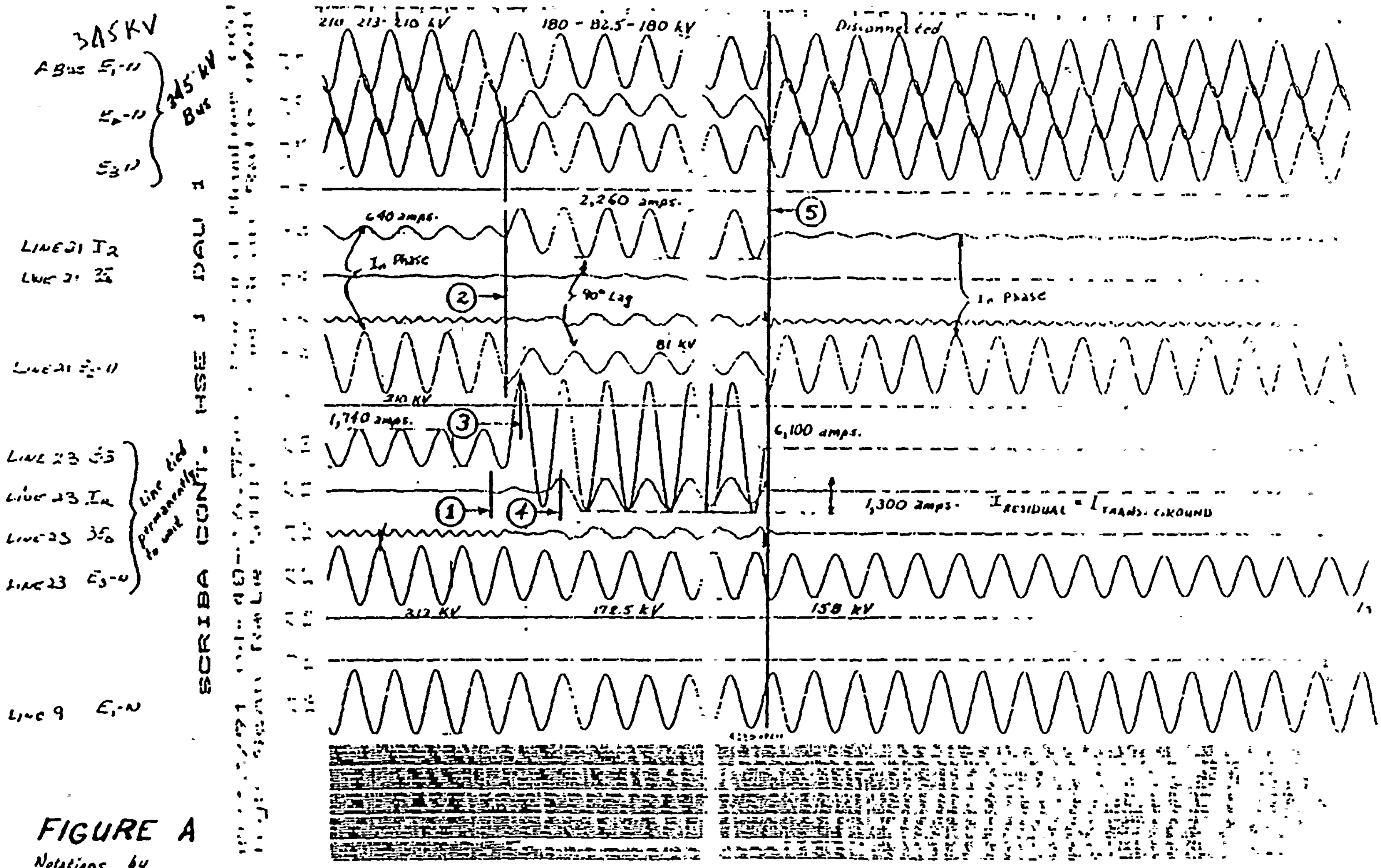

FIGURE A

Notations by M.L. Crenshaw

Electronics in Industrial Applications

A Discussion of Fundamental EMC Principles for Electronic Controllers in an Industrial Environment

By William D. Kimmel, PE
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EMC problems with industrial controls are aggravated by harsh environments, mixed technologies and a lack of uniform EMC guidelines. This article will concentrate on the common aspects of electronic controls in an industrial environment, which is generally much harsher than the office environment.

What is the industrial environment and what can be done about it? The environment includes the entire gamut of the basic threats, power disturbances, RFI, and ESD. RFI and power disturbances may be locally generated or not. Mixed technologies compound the problem. Digital circuits are used to switch line voltages via relays. Analog sensors are input devices to digital controls.

Increasingly, there is a need for a cooperative effort between the designers, manufacturers and installers to come up with a rock-solid system. A common complaint is that the installers or maintenance people won't follow the installation requirements. This may be true, but it must change, since there are problems which cannot be solved at the board level. It is also true that manufacturers often specify installation requirements which are not practical to implement, and there are documented cases where the prescribed installation procedures will cause rather than cure a problem.

The lack of uniform guidelines has hampered EMC progress in the industrial arena. Fortunately, the European Community is working to adopt the IEC 801.x specifications, and domestic companies would be wise to adopt them, even if there is no intention to export.

The Basic Threats

The three basic threats to industrial electronics are power disturbances, radio frequency interference, and ESD.

Power Disturbances. Power disturbances are a well known industrial problem. In fact, when a problem occurs, the first thought is to blame the power company. Often power quality is a problem (especially if grounding issues are included), but the problem is almost always generated by adjacent equipment.

Traditional problems with power include spikes and transients, sags and surges, and outages, which threaten the electronics via the power supply. These problems are fairly well documented and are often solved using power conditioners or UPS.

The most common power problems confronting electronics today is the sag which typically occurs during turn on and the spikes which typically occur during turn off of heavy inductive loads. The sags simply starve the electronics. The high frequency transients barrel right through the supposedly filtered power supply to attack the electronics inside.

Digital circuits are most vulnerable to spikes which cause data errors or worse. Analog circuits are most vulnerable to continuous RF riding on top of the power.

FIPS PUB 94 provides guidelines on electrical power for commercial computers. This is good information, but beware that factory power is much noisier than commercial power.

The guidelines of IEC 801.4 specifies an electrically fast transient (EFT) that simulates arcing and other high speed noise. EFTs are quite short ranged — they diminish rapidly with distance due to inductance in the line. But at short range, they are devastating.

Unfortunately, attention is placed on the front end of the electronics, the power supply. With industrial controls, the problem is the controlled elements. If the electronics is controlling line power, the disturbances sneak in the back end where little or no protection exists.

System ground, while not being specifically a power disturbance problem, is the carrier of residual effects of po[wer] disturbances. Any industrial or commer[cial] structure has significant low freque[ncy] currents circulating through the gro[und] system, sometimes because the energy [is] intentionally dumped onto the ground (s[uch] as with an arc welder) and sometim[es] because of unintentional coupling or e[ven] an inadvertent connection between neu[tral] and ground somewhere in the facility.

Radio Frequency Interference. R[a]dio frequency interference affects b[oth] analog and digital circuits, with ana[log] circuits being generally more suscepti[ble]. Surprising to many, the principle threat [is] not the TV or FM station down the ro[ad] but rather it is the hand held transmit[ters] carried around by facilities personnel. A o[ne] watt radio will result in an electric field [of] five volts/meter at a one meter distanc[e], enough to upset many electronics system[s].

IEC 801.3 specifies immunity to elect[ric] fields of one to ten volts per met[er], depending on the equipment, with thr[ee] volts per meter being the level for typic[al] equipment. As can be seen from the abov[e] approximation, three volts per meter is n[ot] an excessive requirement, and even te[n] volts per meter is fairly modest.

Electrostatic Discharges. Electr[o]static discharge is an intense short duratio[n] pulse, having a risetime of about on[e] nanosecond. This is equivalent to a burs[t] of 300 MHz interference. Static buildup of 15 kV are not uncommon.

Dry climates, including northern climate

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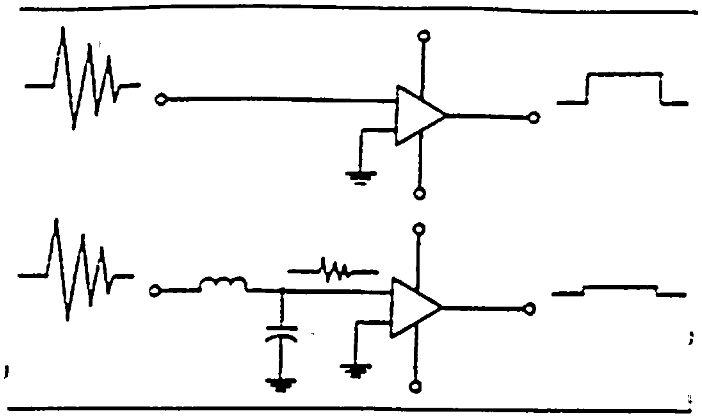

Figure 1. Amplifier demodulation.

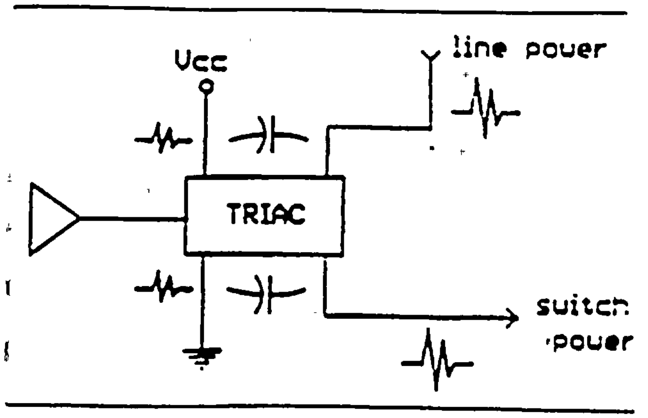

Figure 2. Transient feedback path.

in winter, offer opportunity for ESD. Industrial environments, with their moving equipment, are loaded with potential ESD sources: rubber rollers, belts, and production output such as plastic and paper rolls, all add up to a real ESD threat, and this threat is more likely to occur even in relatively moist environments. Look to IEC 801.2 for ESD standards.

Electronics Design

Electronics is generally the ultimate victim of interference. The interference finds its way through various paths to the electronics equipment itself. Let's concentrate on what can happen to your electronics from the back door, that is, by direct radiation into the electronics and by conducted interference through the signal and control lines.

Sensors. Low level sensors, such as thermocouples, pressure sensors, etc., are characterized by very low bandwidths and low signal levels. A major threat to these sensors is radio frequency interference, either from nearby hand held transmitters or more distance land mobile or fixed transmitters.

But these are high frequency, much above the bandpass of your amplifier, right? Wrong! Low frequency amplifiers are plagued by two phenomena: out of band response and audio rectification. These combine to provide false information on levels to the system.

All amplifiers have a normal bandpass, typified by a 20 dB/decade rolloff or more at the high end. But resonances due to stray inductance and capacitance will give rise to amplifier response five orders of magnitude or more above the nominal bandpass of the amplifier. This means an audio amplifier will respond to signals in the hundreds of MHz.

The second aspect occurs when RF encounters a nonlinearity such as a semiconductor device. All such devices give rise to a DC level shift when confronted with RF. In a radio receiver they are called detectors. Nonlinearities are minimized in linear devices, but there is always enough to cause problems. The upshot is that the amplifier demodulates the RF, generates an erroneous signal, and passes this error on. This effect is shown in Figure 1. Output lines are similarly affected, with capacitive coupling back to the input.

The solution is to prevent the RF from getting to the amplifier, either by shielding or filtering. The most common path to the amplifier is via an external signal line from the sensor, but if the electronics is not shielded, direct radiation to the circuit board may also present a problem.

Assuming filtering is the selected method, use a high frequency filter, designed to block signals up to 1 GHz or even more. Use ferrites and high frequency capacitors. Do not rely on your low frequency filter to take out RF.

At the op amp, you should also decouple your plus and minus power to ground at the chip. If your ground is carrying RF, you can anticipate the same problem mentioned above, since it will corrupt the reference level.

Data Lines. Digital data lines will be upset by the RF problem as in analog, but the levels necessary to upset are higher. Instead, digital data lines are much more susceptible to transient glitches. All signal lines should be filtered to pass only the frequencies necessary for operation. If the threat lies in the bandpass of the signal, then shielding or optical links will be needed.

Switched Power Lines. This refers specifically to the power being controlled by the controller device. Industrial controllers are commonly tasked to control power to heavy equipment, which is character by heavy starting loads and inductive at turn off. Typically the electronic con switch line power using relays or tr This exposes the back end of the contr to substantial line transients, which co back to the circuit power and ground disrupt the digital circuitry as show Figure 2.

It is mandatory that the transient rents be diverted or blocked, since digital system cannot withstand the ma tudes likely to occur with an inductive k unless special steps are taken.

Self jamming can be limited by contro when you switch the line, using z crossing devices. Of particular importa is the turn off, since that is when inductive kick occurs.

If all power switching used zero cross devices, the transient levels in the fact would be dramatically reduced. Unfor nately, that goal is well off in the futu Until then, expect that high voltage pov transients will occur, and they must be de with.

Optical couplers and relays do not prov sufficient isolation by themselves. Th high capacitance provides an excellent hi frequency path, and if they are stacked in an array, the capacitance will add up pass surprisingly low frequencies. The capacitances can't be eliminated, but y can design your control circuits to minimi coupling paths and to maximize low impe ance alternate paths.

Transient suppressors should be install at the load, which is the source of the spik but they can be installed at the controll as well.

An interesting effect occurs when co bining zero crossing SCR regulators w low level sensors which use line frequen noise canceling techniques. Very sensitiv sensors sometimes are sampled for

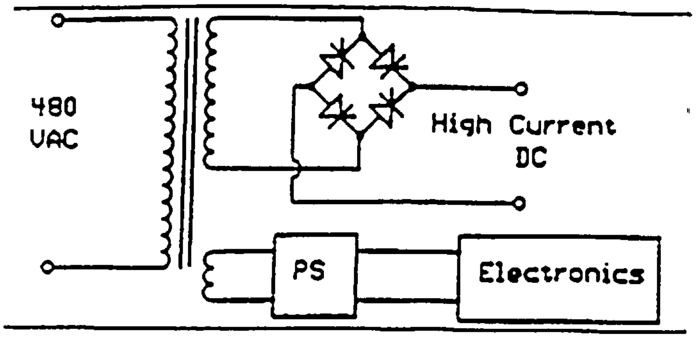

Figure 3. Common industrial power supply.

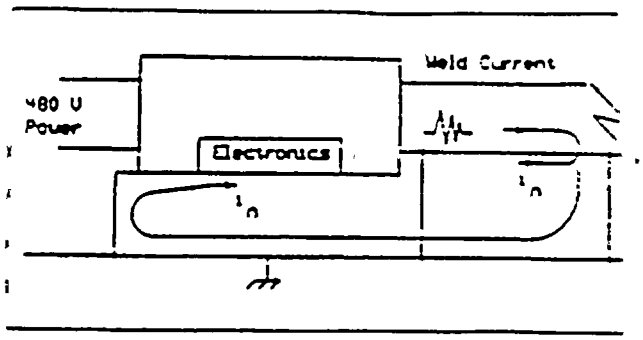

Figure 4. Multiple ground paths.

entire power cycle to cancel the line frequency component. If the sample occurs concurrently with the power switching on or off, the average to the sensor will be upset, and an error will be recorded.

System Design and Installation

Once the electronics is designed, it becomes a problem of the system integrator and installer to ensure that the electronics is provided with the environment for which it was designed. Most of the time, this work is performed by power experts and electricians, and they are not always aware of the interference problem. Often, on site, the power quality is blamed for the equipment anomalies. But the problem can often be avoided by following a few basic principles.

The industrial control device is either integrated into a system at the factory or installed separately on site. Controllers handle a variety of devices such as motor speed controls, positioning devices, welders, etc. Interference presented to the electronics can be significantly reduced by appropriate measures outside of the electronics box.

There is no way to accurately assess the threat without test data. But regardless of the information available, much can be accomplished by correct installation, and it doesn't cost much if done at the start. Retrofits become costly, especially if accompanied with factory down time.

Let's consider the same problems from a system standpoint. Your goal is to limit the interference which must be handled by the electronics.

Direct radiation to the electronics is not often a problem in an industrial environment, but it does occur, and most often with a plastic enclosure. The NEMA type enclosures provide enough shielding for most industrial needs. If you don't want to use a metal enclosure, be sure to get electronics which will withstand the RF which will occur.

More often the problem is conducted, either via power or ground. The problem occurs due to power and ground disturbances caused by the equipment. It is an all too common practice to draw controller power from the same source as feeds the power equipment. This power may provide the necessary energy to drive the equipment, but it is not suitable to power the electronics (Figure 3).

Hopefully, all industrial equipment will have electronics powered from a separate low power 120 volt circuit. It solves several problems. First, it separates the electronics power from the probably very noisy industrial grade power, preventing the switching transients and startup sags from getting to the electronics. Second, if it is necessary to condition the electronics power from an external problem, it is far cheaper to condition the watts needed for electronics power than it is to condition the kilowatts required by the system.

If power cannot be separated, then it is necessary to provide a bulletproof power supply, preferably including an isolation transformer, to separate the entire power supply from the electrical equipment.

Ground Noise. Ground noise, inevitable in industrial environments, must be diverted from the electronics module. Multiple grounds in a system will often result in ground currents circulating through the equipment, and ground noise circulating through the electronics path will cause malfunction. Figure 4 shows some typical ground loop situations.

A common approach is to demand a super earth ground. This is good, but it is not a cure all, and often a super ground cannot be achieved, no matter how you try. How do you get a super ground from the third floor? The real need is to get a stable ground reference to all interconnected equipments. If this equipment is closely located, then a very low impedance interconnect is feasible.

Power conditioners are often tasked to eliminate RF or ground noise. Tha[t] work, but these problems can be s[olved] with an isolation transformer to elim[inate] neutral to ground noise and with EMI p[ower] line filters. So you may want to try [the] inexpensive approach first.

Data Links. Data links are strun[g] over the entire facility, exposing the[m to] two principle effects, ground noise an[d RF] pickup. Ground noise will cause data er[rors] unless the electronics has been designe[d to] accommodate potential differences of [sev]eral volts or more. This is accompli[shed] with differential drivers and receivers if [they] must be direct coupled. Optical links [will] eventually take over these links.

The other aspect is RF pickup. Inex[pen]sive shielded cable is suitable for [this] purpose. Ground both ends! Do not a[pply] single point ground techniques to RF. [If] low frequency ground loop problem [is a] threat, then one end can be capaciti[vely] grounded.

Summary

Industrial electronics are subjected t[o a] harsh environment. Good design and ins[tal]lation techniques will minimize problem[s in] the field. Adherence to the Europ[ean] standards, IEC 801.x is a good start, e[ven] if you are only marketing in the USA.

Bibliography

FIPS PUB 94, Guideline on Electr[ical] Power for ADP Installations, Septemb[er] 1983.

IEC 801-2, Electromagnetic compatibi[lity] for industrial-process measurement a[nd] control equipment, Electrostatic dischar[ge] requirements, 1984.

IEC 801-3, Electromagnetic compatibi[lity] for industrial-process measurement a[nd] control equipment, Radiated electrom[ag]netic field requirements, 1984.

IEC 801-4, Electromagnetic compatibi[lity] for industrial-process measurement a[nd] control equipment, Electrical fast transie[nt] burst requirements, 1984.

Equipment Ground Bonding — Designing for Performance and Life

A Discussion of Ground Connection Fundamentals to Control EMI

By D.B.L. Durham
Dytecna Ltd. UK

The problem of achieving satisfactory earth bonds or ground connections has plagued EMC engineers for many years, not only because the bonds are often vital for the achievement of satisfactory equipment performance but because they affect the long term performance of equipment after it has been introduced into service.

Recommendations on bonding have existed in the form of military specifications, such as Mil Std 1310, Mil 188-124A and Mil-B-5087 (ASG) for some years and these have generally proved satisfactory for most new builds. However, these specifications have certain limitations in that they generally do not specify consistently low levels of bond impedance, nor a suitable test method. The introduction of new EMC specifications in Europe with the EEC Directive on EMC and the requirements for long term stability in EMC characteristics has directed the UK military to review existing specifications and introduce a new Defence Standard to tighten up performance requirements for military equipment. Def Stan 58-6 (Part 1)/1 has been introduced to address this area as far as mobile and transportable communications installations are concerned, but the requirements should have implications in industrial applications and over the whole electronics market if long term product performance is to be guaranteed.

Bond Degradation

Earth or ground bonds are generally considered essential not only for safety reasons, but as a means of diverting EMI currents, "locking" circuit boards and equipment to a stable ground point, achieving adequate levels of cable shielding and for many other reasons. Many designers understand the requirement for short, fat bond leads to minimize ground inductance but few appreciate that a critical aspect is the connection resistance with which the bond strap is attached to the equipment ground point. The basic requirement of any bond is that it should have as low an impedance as possible (unless it is a deliberate inductive bond to limit ground currents). The impedance is a combination of the resistive and the inductive components. The resistive element is a function of the bond strap resistivity, cross sectional area and length, see Equation 1, whilst the inductive component is a more complex function of the bond strap characteristics as shown in Equation 2.

$$R = \frac{\varrho \ell}{A} \tag{1}$$

$$L = \frac{\mu_o \mu_r}{2\pi}\left[\ln \frac{2\ell}{b+c} + 0.5 + 0.2235\,\frac{b+c}{2\ell}\right] \tag{2}$$

where R = resistance, ϱ = resistivity, ℓ = length, A = area, μ_o = permeability of free space, L = inductance, μ_r = relative permeability, b = strap width, and c = strap thickness.

The frequency at which the inductive element dominates the impedance expression when calculating the total inductance is, from Equation 3, typically 1 kHz. It will be seen therefore that to all intents and purposes the bond except at DC and power frequencies, may be assumed to be an inductance. At very high frequencies stray capacitance across the strap dominate. This means that the volt dr across a bond is generally a function inductance and frequency. Based on Ohm Law this volt drop is shown in Equation For transients the voltage drop is given Equation 5.

$$Z = \sqrt{R^2 + \omega^2 L^2}$$

$$V = IZ = j\omega LI$$

$$V = -L\,\frac{dI}{dt}$$

where Z = strap impedance, ω = radi frequency, V = voltage, and I = current.

From this, the higher the inductance th more isolated the circuit or box become from ground. This can have significan effects on equipment, including enhancement of noise injection onto circuits, reduction of filter performance, and loss c communication range. From a TEMPEST standpoint it may result in more radiation from equipment. It would seem from this that the criteria for any bond is the inductance and hence the choice of short fat

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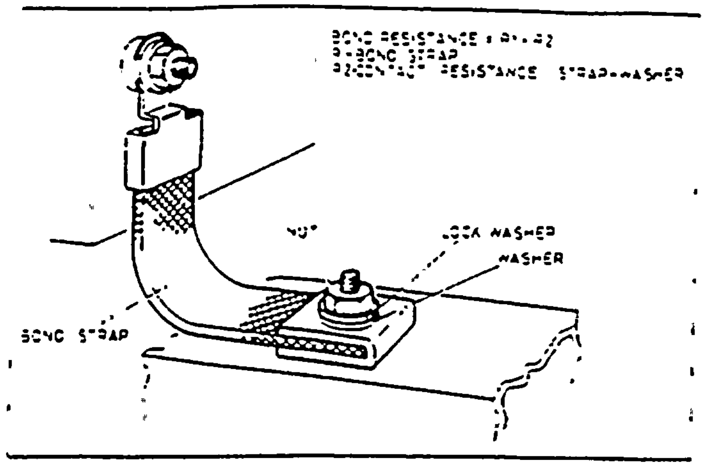

Figure 1. Bond resistance.

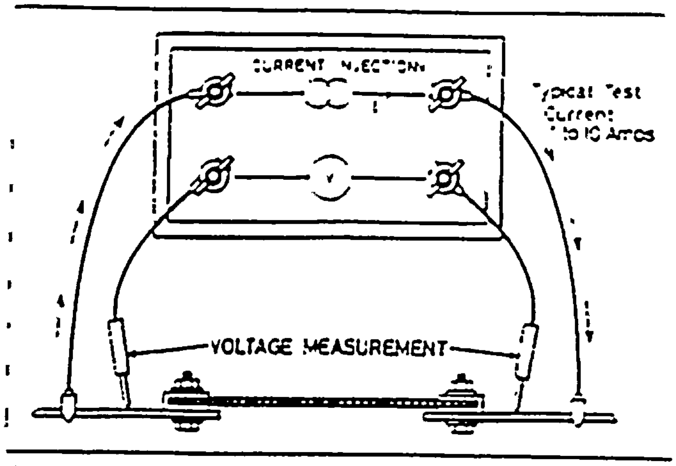

Figure 2. Four wire bridge method.

bond straps. However, an analysis of the bond inductance shows that for a bond strap of 100 mm long, 15 mm wide and 2 mm thick the impedance at 1 MHz will be 3.8 Ohms. It sounds extremely simple, but work performed in the USA and UK shows that if an error is made in the way the strap is terminated then a progressive increase in the resistance of the bond strap to box junction can occur as the equipment ages. Eventually the resistance will begin to exceed hundreds of ohms and may eventually go open circuit. This can negate the effect of the bond strap completely as part of the EMI protection.

What happens with bonds to cause this change? Essentially a ground connection is a series of impedances from the strap through to the ground material, as shown in Figure 1. Each point of contact contributes to the total bond performance. As a result, a change in any contact condition can result in a change in the total bond resistance. As is well appreciated, the contact resistance between two metal surfaces is a function of the pressure. The pressure exerted by the tip of a drawing pin is vastly greater than that from the thumb pressing by itself. Thus the contact from a sharp point gives a much higher pressure than a flat point and therefore lower contact resistance. Measurements have shown that sharp points enable contact resistance of a few microohm to be achieved whilst similar pressures on flat surfaces result in milliohms of contact resistance. It might be felt that there is little or no difference between these values, but in reality there is. An essential aspect of a good bond is that it should remain so after the equipment has entered use. High pressures also have the effect of squeezing out corrosive materials and insulating films. The former causes progressive degradation of bonds, whilst the latter can reduce the efficiency of the bond from the moment it is installed. It is particularly important in communications systems, where filters are installed and shielded cable terminations are made that the bonds are of low resistance and retain their performance.

Bond Performance and Measurement

Experience has shown over a number of years that for long term consistent bond performance a low value of resistance must be achieved. This is typically 1-5 milliohms. In Def Stan 58-6 (Part 1)/1 the value has been set at a maximum of 2 milliohms. This level is measured through the individual bonds. The logic behind this level is twofold. Firstly, experience has shown that with communications equipment in particular this value of bond resistance is required if consistent performance is to be achieved in terms of reception efficiency and transmission characteristics. This is particularly so for TEMPEST protected equipments. The second point is that if the bond has a higher resistance then there is a significant likelihood that progressive degradation will occur and the bond resistance will increase in value. There will then be a progressive loss in performance.

The main problem with measuring bond resistances is that it should be measured using a low voltage/current technique. Most techniques to date for assessing safety involves driving a large current through the bond. This checks the bond's ability to carry current but does not necessarily check its EMI protection performance. The reason is that many bonds may when in normal use have a high resistance due to oxide and greasy films, but when subjected to a high current the layers heat up and are vaporised. After the current is removed the film can return. Thus high current techniques are not recommended for testing EMI bonds. The new Defence Standard in the UK specifies a maximum probe voltage of 100 microvolts. This represents typically a probe current of 50 milliamps under short circuit (< 1 mΩ) conditions. This is insufficient to destroy surface films. The classic method for measuring low resistance has been to use a four terminal bridge as shown in Figure 2. In this case the current is driven between two points and the voltage across the sample is measured with a high resistance probe. This removes the effects of the probe contact resistance and lead resistance. This is generally considered to be a laboratory method as the use of four contacts can be awkward. If the lead resistance can be removed by a calibration technique then the four terminals may be replaced with a two terminal system.

A further possible refinement to the technique is to use a frequency that is not DC or 50/60/400Hz. In this case 10.4 Hz has been chosen. If an active filter is used to filter out all other electrical noise, then it is possible to use the bond resistance meter on powered up systems. It is worth noting that at this frequency the impedance is still largely represented by resistance rather than inductance. The two terminal method is shown in Figure 3.

The introduction of new EMC/EMI specifications in Europe has made it more important that once made the bonds have consistent long term performance. This means measuring on periodic inspection and after maintenance. It is an essential aspect of insuring consistent performance. It has been shown that within months apparently good bonds can deteriorate to high resis-

tance. Therefore all types of bonds subject to testing and examination as a maintenance task.

UK Military Experience

There have been two major pro caused by poor bonds experienced by military equipment users. The first degradation in performance already tioned in this article. The loss of com cation range, poor EMI performance other effects all contribute to a consider reduction in equipment efficiency and ability. The second effect which is difficult to identify is that of No Fault Fo (NFF) problems. An analysis of repo. failures from military reliability data shown that NFF incidents can be extrem high, particularly in humid climates. has been partially confirmed by reports f the Gulf War when all forces reported increase in availability of equipment in drier climate. Many faults are due to electrical contacts in connectors, but a la number have been identified as excess EMI induced through poor ground bon This may be caused by either a loose grou strap or connector termination to the A significant improvement in equipme availability and performance is expec when more recent statistics are analysed

The introduction into the British Air service of the Dytecna Bond Resistan Test Set — DT 109 has enabled the U military to measure bond resistances installed equipment and reduce the curances of NFF errors. The UK milita measurement procedure uses a two term nal bridge method and an accurate milliohm calibration standard. This mea urement procedure and equipment is als in use by other NATO nations and else where by military and naval forces who hav recognized the same problem.

Conclusions

The problems with ground bonds hav become significant with the development o sensitive and secure communications equip ment. This coupled with an increasing need to achieve higher and higher levels of EM protection has lead to an increased emphasis being placed on the effectiveness of all types of system grounds. These, further combined with a requirement to ensure the long life of systems once in service, have resulted in the assessment that bonds and terminations are one of the primary causes of EMI failures in systems. The requirement to test these is clear, however the means to do so have not always been available to engineers.

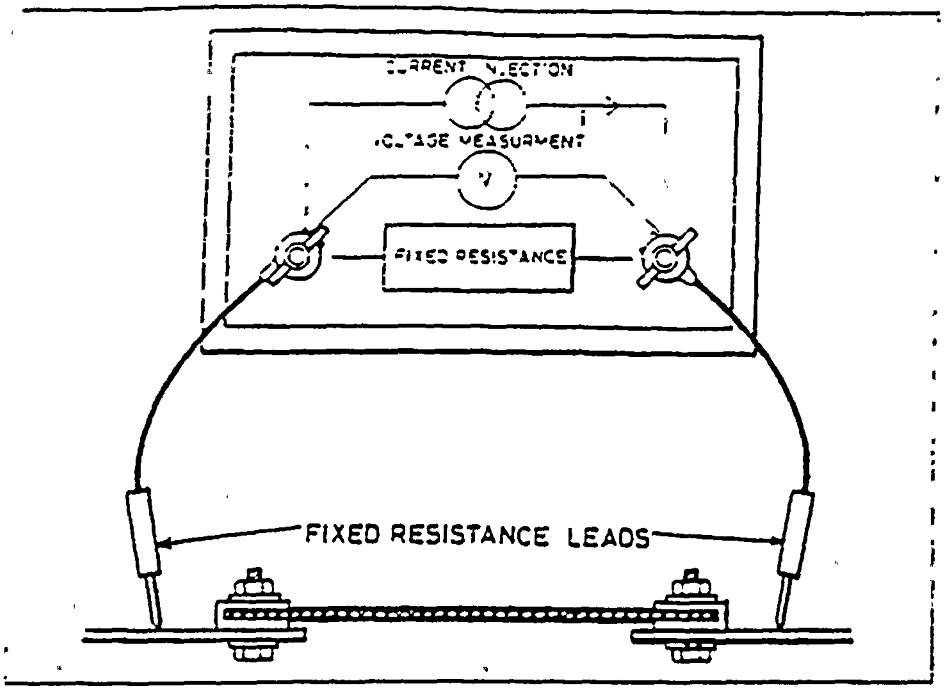

Figure 3. Two terminal bridge method.

Effects Of Geomagnetic Disturbances On Power Systems

Panel Session

PES Summer Meeting, July 12, 1989
Long Beach, California
John G. Kappenman, Chairman

Power System Susceptibility To Geomagnetic Disturbances: Present And Future Concerns

John G. Kappenman, Minnesota Power

The effects of Solar-Geomagnetic Disturbances have been observed for decades on power systems. However, the profound impact of the March 13, 1989 geomagnetic disturbance has created a much greater level of concern about the phenomena in the power industry.

Several man-made systems have suffered disruptions to their normal operation due to the occurrence of geomagnetic phenomena. Most of the man-made systems, such as communications, have been made less susceptible to the phenomena through technological evolution (microwave and fiber-optic have replaced metallic wire systems). However, the bulk transmission system, if anything, is more susceptible *today than ever before* to geomagnetic disturbance events. And if the present trends continue, it is likely the bulk transmission network will become more susceptible in the future. Some of the most concerning trends are: 1) The transmission systems of today span greater distances of earth-surface-potential which result in the flow of larger geomagnetically-induced-currents in the system, 2) the interconnected systems tend to be more stressed by large *region-to-region* transfers, combined with GIC which will simultaneously turn every transformer in the bulk system into a large reactive power consumer and harmonic current generator and 3) in general, large EHV transformers, static var compensators and relay systems are more susceptible to adverse influence and microperation due to GIC.

TRANSFORMER OPERATION

The primary concern with Geomagnetically-Induced Currents is the effect that they have upon the operation of large power transformers. The three major effects produced by GIC in transformers is 1) the increased var consumption of the affected transformer, 2) the increased even and odd harmonics generated by the half-cycle saturation, and 3) the possibilities of equipment damaging stray flux heating. As is well documented, the presence of even a small amount of GIC (20 amps or less) will cause a *large power transformer* to half-cycle saturate. The half-cycle saturation distorted exciting current is rich in even and odd harmonics which become introduced to the power system. The distortion of the exciting current also determines the real and reactive power requirements of the transformer. The saturation of the core steel, under half-cycle saturation, can cause stray flux to enter structural tank members or current windings which has the potential to produce severe transformer heating.

[illegible] results indicate that single phase transformers half-cycle saturate much more easily and to a much greater degree than comparable three-phase units. These transformers produce higher magnitudes of harmonics and consume larger amounts of reactive power when compared with three phase designs.

RELAY AND PROTECTIVE SYSTEMS

There are three basic failure modes of relay and protective systems that can be attributed to ggeomagnetic disturbances:

- False Operation of the protection system, such as having occurred for SVC, capacitor and line relay operations where the flow of harmonic currents are misinterpreted by the relay as a fault or overload condition. This is the most common failure mode.
- Failure to Operate when an operation is desirable, this has shown to be a problem for transformer differential protection schemes and for situations in which the output of the current transformer is distorted.
- Slower than Desired Operation, the presence of GIC can easily build-up high levels of offset or remanent flux in a current transformer. The high GIC induced offset can significantly reduce the CT time-to-saturation for offset fault currents.

Most of the relay and protective system misoperations that are attributed to GIC are directly caused by some malfunction due to the harsh harmonic environment resulting from large power transformer half-cycle saturation. Current transformer response errors are more difficult to directly associate with the GIC event. For example in the case of CT remanence, the CT response error may not occur until several days after the GIC event that produced the remanence. Therefore, these types of failures are more difficult to substantiate.

CONCLUSIONS

As evident by the March 13th blackout in the Hydro Quebec system and transformer heating failures in the eastern US, the power industry is facing an immediate and serious challenge. The power industry is more susceptible than ever to the influence of geomagnetic disturbances. And the industry will continue to become more susceptible to this phenomenon unless concerted efforts are made to develop mitigation techniques.

Geomagnetic Disturbance Causes And Power System Effects

Vernon D. Albertson
University of Minnesota

SOLAR ORIGINS OF GEOMAGNETIC STORMS

The solar wind is a rarified plasma of protons and electrons emitted from the sun. The solar wind is affected by solar flares, coronal holes, and disappearing filaments, and the solar wind particles interact with the earth's magnetic field to produce auroral currents, or auroral electrojets, that follow generally circular paths around the geomagnetic poles at altitudes of 100 kilometers or more (1). The aurora borealis is visual evidence of the auroral electrojets in the northern geomagnetic storms when they are of sufficient severity.

SUNSPOT CYCLES AND GEOMAGNETIC DISTURBANCE CYCLES

On the average, solar activity, as measured by the number of monthly sunspots, follows an 11-year cycle. The present sunspot cycle 22 had its minimum in September 1986, and is expected to peak in 1990–1991. Geomagnetic field disturbance cycles do not have the same shape as the sunspot number cycles, even though they are cyclical. Figure 1 shows the nature of the sunspot numbers and geomagnetic activity

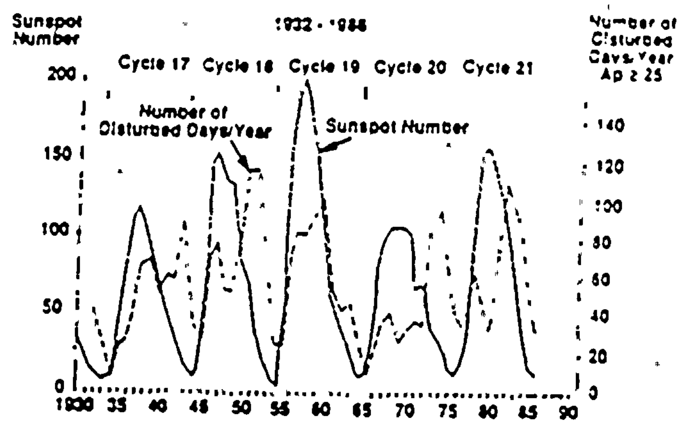

Figure 1. Variations of the Yearly-Averaged Sunspot Number and Geomagnetically Disturbed Days from 1932–1986.

cycles from 1932 to 1986 (2, 3). Note that the geomagnetic disturbance cycles can have a double peak, one of which can lag the sunspot cycle peak. While geomagnetic activity in the present cycle is expected to maximize in approximately 1993–1994, severe geomagnetic storms can occur at any time during the cycle; the K-9 storm of March 13, 1989 was a striking example.

EARTH-SURFACE-POTENTIAL AND GEOMAGNETICALLY-INDUCED-CURRENTS

The auroral electrojets produce transient fluctuations in the earth's magnetic field during magnetic storms. The earth is a conducting sphere and portions of it experience this time-varying magnetic field, resulting in an induced earth-surface-potential (ESP) that can have values of 1.2 to 6 volts/km (2 to 10 volts/mile) during severe geomagnetic storms in regions of low earth conductivity (4).

Electric power systems become exposed to the ESP through the grounded neutrals of wye-connected transformers at the opposite ends of long transmission lines, as shown in Figure 2. The ESP acts as an ideal voltage source impressed between the grounded neutrals and has a frequency of one to a few millihertz. The geomagnetically-induced-currents (GIC) are then determined by dividing the ESP by the equivalent dc resistance of the paralleled transformer windings and line conductors. The GIC is a quasi-direct current, and values in excess of 100 amperes have been measured in transformer neutrals.

POWER SYSTEM EFFECTS OF GIC

The per-phase GIC in power transformer windings can be

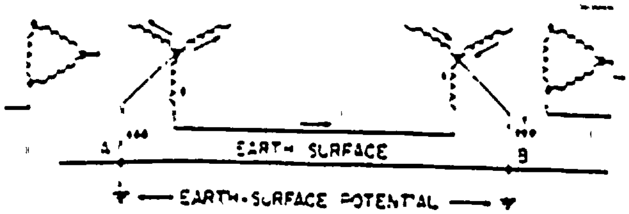

Figure 2. Induced Earth-Surface-Potential (ESP) Producing Geomagnetically-Induced-Currents (GIC) in Power Systems.

many times larger than the RMS ac magnetizing current, resulting in a dc bias of transformer core flux, as in Figure 3.

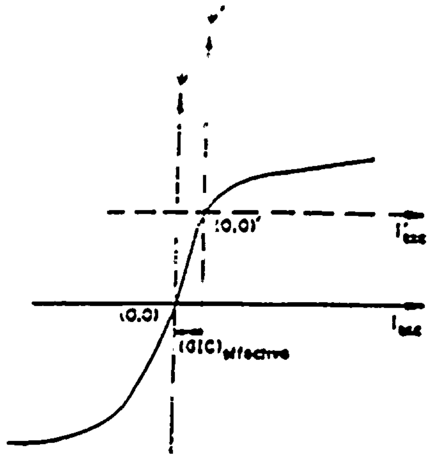

Figure 3. DC Bias of Transformer Core Flux Due to GIC.

The half-cycle saturation of transformers on a power system is the source of nearly all operating and equipment problems caused by GIC's during magnetic storms. The direct consequences of the half-cycle transformer saturation are:

- The transformer becomes a rich source of even and odd harmonics
- A great increase in inductive vars drawn by the transformer
- Possible drastic stray leakage flux effects in the transformer with resulting excessive localized heating.

There are a number of effects due to the generation of high levels of harmonics by system power transformers, including,

- Overloading of capacitor bands
- Possible misoperation of relays
- Sustained overvoltages on long-line energization
- Higher secondary arc currents during single-pole switching
- Higher circuit breaker recovery voltage
- Overloading of harmonic filters of HVDC converter terminals, and distortion in the ac voltage wave shape that may result in loss of dc power transmission.

The increased inductive vars drawn by system transformers during half-cycle saturation are sufficient to cause intolerable system voltage depression, unusual swings in MW and MVAR flow on transmission lines, and problems with generator var limits in some instances.

In addition to the half-cycle saturation of power transformers, high levels of GIC can produce a distorted response [...] transformers [...] cause relay misoperation (5).

REFERENCES

1. Akasofu, S.-I., "The Dynamic Aurora," Scientific American Magazine, May 1989, pp. 90–97.
2. Joselyn, J. A., "Real-Time Prediction of Global Geomagnetic Activity," Solar Wind-Magnetosphere Coupling, pp. 127–141, Terra Scientific Publishing Company, Tokyo, 1986.
3. Thompson, R. J., "The Amplitude of Solar Cycle 22," Radio and Space Services Technical Report TR-87-03, October 1987.
4. V. D. Albertson and J. A. Van Baelen, "Electric and Magnetic Fields at the Earth's Surface due to Auroral Currents," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, No. 2, April 1970, pp. 578–584.
5. J. G. Kappenman, V. D. Albertson, N. Mohan, "Current Transformer and Relay Performance in the Presence of Geomagnetically-Induced-Currents," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 3, pp. 1078–1088, March 1981.

The Hydro-Quebec System Blackout Of March 31, 1989

Daniel Soulier,
Hydro-Quebec

On March 13, 1989, an exceptionally intense magnetic storm caused seven Static Var Compensators (SVC) on the 735-kV network to trip or shut down. These compensators are essential for voltage control and system stability. With their loss, voltage dropped and frequency increased. This led to system instability and the tripping of all the La Grande transmission lines thereby depriving the HQ system of 9500 MW of generation. The remaining power system collapsed within seconds of the loss of the La Grande network. The system blackout affected all but a few substations isolated onto local generating stations.

Power was gradually restored over a nine hours period. Delays in restoring power were encountered because of damaged equipment on the La Grande network and problems with cold load pickup.

SYSTEM CONDITION PRIOR TO THE EVENTS

Total system generation prior to the events was 21500 MW, most of it coming from remote power-generating stations at La Grande, Manicouagan and Churchill Falls. Exports to neighboring Systems totalled 1949 MW of which 1352 MW were on DC interconnections. The 735-kV transmission network was loded at 90% of its stability limit.

SEQUENCE OF EVENTS

At 2:45 a.m. on March 13, a very intense magnetic storm led to the consequential trip or shut down of seven SVC's. Containing the impact of the event through operator intervention was impossible all SVC's having tripped or ceased to function within a one minute period.

A few seconds (8–9 s.) after the loss of the last SVC, all five 735-kV lines of the La Grande transmission network tripped due to an out of step condition. These line trips deprived the system of 9500 MW of generation and subsequently led to a complete system collapse.

tection while remaining four SVC's shut down by capacitor voltage unbalance protection. Analysis of voltage and current oscillograms taken at the Chibougamau site before the SVC trips showed the following harmonic contents.

Harmonic Order	AC Voltage at 735 kV	AC Current at 16 kV	
		TCR Branche	TSC Branche
1	100%	100%	100%
2	7%	3%	38%
3	2%	12%	24%
4	3%	1%	16%
5	2%	5%	5%
6	1%	1%	16%
7	3%	3%	4%

Quasi-DC currents generated by the magnetic disturbance, saturating in the SVC coupling transformers are thought to be the cause for such a large second harmonic component of current in the TSC branch.

GENERAL OBSERVATIONS ON THE SYSTEM BEHAVIOR

The system blackout was caused by loss of all SVC on La Grande Network. Seven SVC tripped or stopped functioning. Prior to and during the event all the DC interconnections behaved properly. No relay false trips or misoperation of special protection systems were observed. Telecommunications were not affected. No equipment damage was directly attributable to GIC but once the system split, some equipment was damaged due to load rejection overvoltages.

REMEDIAL ACTIONS TAKEN

Since the event, the following actions were implemented:

- SVC protection circuits have been readjusted on four SVC's so as to render their operation reliable during magnetic storms similar work is being performed on the four remaining SVC's.
- Energy, Mines and Resource Canada now provides Hydro-Québec with updated forecasts on the probability of magnetic disturbances. These forecasts are used by the System Control Center dispatcher to position the transmission system within secure limits.
- A.C. voltage asymmetry is monitored at four key locations on the system (Boucherville, Arnaud, LG2, Châtgeaguay). Upon detection of a 3% voltage asymmetry at any one location, the system control center dispatcher is alarmed and will immediately take action to position system transfer levels within secure limits if this hasn't already been done because of forecasted magnetic activity.

OPERATING LIMITS DURING MAGNETIC DISTURBANCES (AND ALERT SITUATIONS)

The following operating limits are now being applied:

- 10% safety margin shall be applied on maximum transfer limits.
- Maximum transfer limits shall not take into account the availability of static compensators deemed unreliable.
- Adjust the loading on HVDC circuits to be within the 40% to 90%, or less, of the normal full load rating.

Disturbances On Power Transformers

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James R. Stewart
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This discussion addresses the effects of geomagnetic disturbances on power transformers. The primary effect is due to core saturation resulting from geomagnetically induced currents, GICs. Core saturation can impose severe temperature problems in windings, leads, tank plate and structural members of transformers and place heavy var and harmonic burdens on the power system and voltage support equipment. GIC's of 10 to 100 amperes are more than mere nuisances in the operation of power transformers, the manner of flow can result in saturation of the core and consequent changes in system var requirements, increases in harmonic current magnitudes, increased transformer stray and eddy losses, and problems with system voltage control.

GIC EFFECTS VERSUS CORE AND WINDING CONFIGURATIONS

Principal concerns in this discussion are for EHV systems with grounded Y transformer banks providing conducting paths for GIC and zero sequence currents. Core and winding configurations respond differently to zero sequence open-circuit currents and to GICs. Note: as used here, the term "open circuit" refers to tests performed with all delta connections opened or "broken." For example, the three-phase three leg core form transformers are less prone to GIC induced saturation than three-phase shell form transformers. But, both core form and shell form single phase transformers are susceptible to GIC induced saturation.

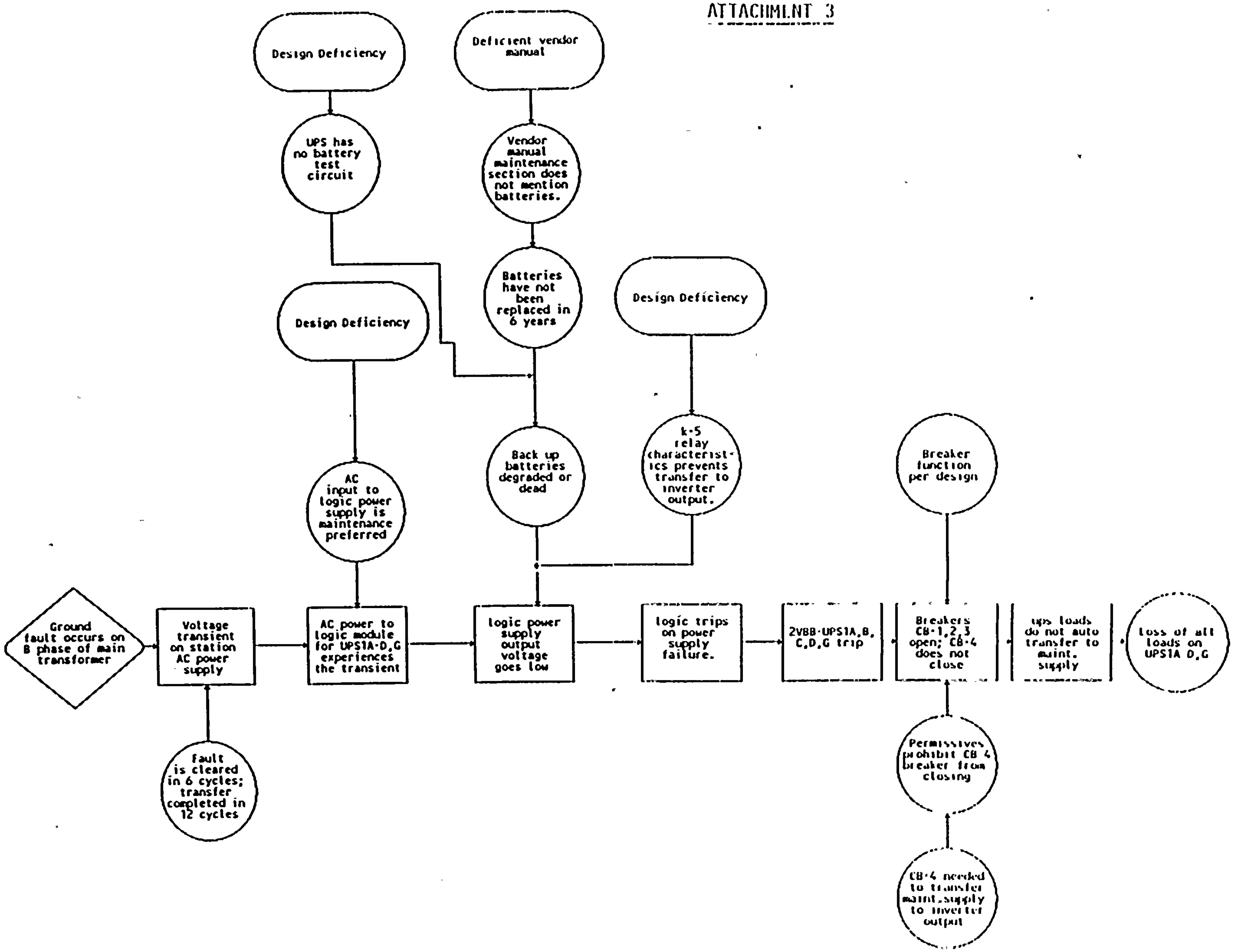
Winding and lead arrangements respond differently to GIC induced core saturation as well. For example, the current distribution within parallel winding paths and within low voltage leads depends upon the leakage flux paths and mutual coupling. Losses within windings and leads may change significantly under GIC-induced saturation owing to the change in magnetic field intensity, H, and the resultant changes in the boundary conditions for the leakage field path.

EDDY LOSSES IN STEEL MEMBERS

The changes in the magnetic intensity, H, and the magnetic boundary conditions resulting from the GIC excitation bias can increase the losses in steel plate, the losses for fields parallel to the plane of the plate increase nearly as the square of H. Note also that the level of losses increase approximately as the square root of the frequency of H, owing to the effect of depth of penetration. The magnetic field along yoke clamps and leg plates in core form transformers and in Tee beams and tank plate in shell form transformers closely matches the magnetic gradient in the core. Areas of the tank and core clamps are subjected to the winding leakage field. If the core saturates, the magnetic field impressed upon the steel members may rise ten to one hundred times normal due to the saturation and the effects of the leakage field. The losses in the steel members will rise hundreds of times normal, even under half-cycle saturation. On the steel surfaces, eddy loss density may rise ten to thirty watts per square inch, approaching the thermal flux density of an electric range element.

Surface temperatures rise rapidly with this thermal flux and can result in degradation of insulation touching the steel

ATTACHMENT 3



07 602-92
Rev. 1

ROOT CAUSE REPORT FOR THE

EXIDE UPS 1A, B, C, D, G

TRIP EVENT OF AUGUST 13, 1991

SEPTEMBER 9, 1991

FILE CODE: NMP77748

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91-09-11-0276

PURPOSE/SCOPE

This report has been generated to document the analysis of the root cause for the tripping of Uninterruptable Power Supplies (UPS) 2VBB-UPS 1A, B, C, D and G and the failure to transfer their loads to the maintenance supply.

This analysis was performed in accordance with NDP-16.01 by reviewing plant operator and damage control team observations and actions, performance of troubleshooting activities on in-plant equipment, review of various drawings, performance of laboratory diagnostic testing, consultation with the UPS manufacturer, review of data recorded during the event, and consultation with other industry experts.

ABSTRACT

On August 13, 1991 at 5:48 AM an electrical fault on the B phase main step-up transformer occurred. At that same time five (5) Exide Uninterruptable Power Supplies (UPS) tripped simultaneously. Transfer of the UPS's loads to the maintenance power supplies did not occur. The system conditions as documented by operators that were dispatched to restore the units immediately after the incident as well as observations by the System Engineer and other damage control team members indicated that the UPS's logic had tripped their input and output breakers. Post event review of equipment drawings with the vendor revealed that the DC power supply which powers the system control logic normally draws its power from the maintenance power supply. The inverter output is utilized as a backup source. This scheme of connection allows transients on the AC power line to be transmitted to the DC logic power supply. Tests performed by the System Engineer support this conclusion. The bypass breaker CB-4 did not close and transfer the UPS loads to the maintenance supply. This functioned per design since permissives for CB-4 closure were not satisfied due to the degraded voltage conditions present on the maintenance supply.

The initial inspection of the units revealed that alarm indications on the five units were not identical. The inverter logic alarm light was not lit on UPS1G but was lit on A, B, and C. The voltage difference alarm indication did not clear on 2 out of 5 units (Alarm should clear in 10-15 seconds after condition clears). The over-voltage/undervoltage (OV/UV) alarm was present on 3 out of 5 units although all units should have displayed this alarm. In addition, none of the 10 LEDs that indicate the initiating signals for a logic trip were lit on any of the UPS units.

DISCUSSION

On August 13, 1991 at 5:48 AM a ground fault occurred on the B phase main transformer. This event was detected and recorded on the Scriba Substation oscillograph. Five Exide UPSs (2VBD-UPS 1A,B,C,D, and G) tripped during this event resulting in a loss of power to all their loads.

The results of observations by plant operators and damage control team personnel are summarized on Attachment 1. All five UPS loads were initially restored to their maintenance supplies by plant operators after initially attempting (unsuccessfully) to restart the D unit. The damage control team was able to restart the C, D, and G units. The A and B units were left on the maintenance supply because the damage control team was not successful in restarting those units.

As a result of these observations, it has been concluded that all five units shut down as a result of a logic initiated trip. This conclusion is based on the as found positions of breakers CB-1,2,3 on all five units and the presence of the module trip alarm on all the units except D which was reset by a plant operator while attempting to restart that unit. It is noted however, that none of the 10 LEDs on the A13A21 card which should indicate what condition caused the logic to trip were lit. In addition, two units (UPS1D, UPS1G) displayed voltage difference alarms. This alarm indication should have cleared in 10-15 seconds after the plant operators manually restored the UPS loads to the maintenance supply. The OV/UV alarm indication was present on three units only, (UPS1C, UPS1D, UPS1G), although all units would be expected to display that alarm indication. The inverter logic alarm light was not lit on UPS1G although it was lit on the other units that were not initially reset (UPS1A, 1B, and 1C).

Breaker CB-4 was found open on all five units. A review of the oscillograph recording indicates that for the duration of the transformer fault (i.e., approx. 100 msec.) the B phase voltage of the station's normal AC distribution system decreased to approximately 50% of its normal level. It has been concluded that this condition prevented the automatic transfer of the UPS's loads to their maintenance supplies. This is due to a logic feature which prevents static switch transfer to the maintenance supply under conditions that could cause damage to the connected loads.

The following potential causes for the simultaneous tripping of the five UPSs were evaluated:

(1) Voltage transient on the B phase of the normal AC distribution system

(2) Propagation of high frequency noise from the main transformer fault

(3) Voltage transient on the station ground system

Transmission of high frequency noise from the transformer fault through the atmosphere to the UPS units could not have caused the UPS trips. Preoperational testing demonstrated that the units are not sensitive to radio frequency (RF) transmissions unless the panel doors are open and an RF source is in close proximity. The report provided as Attachment 2 indicates that it is unlikely that high frequency noise could have been transmitted through the station's normal AC distribution system to the UPSs due to intervening transformers that would filter such a signal. As a result, potential cause (2) is not considered credible.

Potential Cause (3) is considered unlikely due to the fact that one of the five UPSs is located in an area substantially away from the other four units yet exhibited similar behavior. In addition, no other station equipment (including other UPSs) appears to have been affected by a ground transient. Initial laboratory testing indicates that a significant ground transient would have caused the destruction of numerous logic circuit components which has not been observed in the field. Further laboratory tests are being conducted in an attempt to identify the mechanism by which inconsistent alarm light indications were received. Potential Cause (1) was investigated as the most probable cause.

Troubleshooting performed following the event to evaluate and demonstrate the validity of potential cause (1) indicated the following:

1) The DC logic power supply for UPSs 1A, B, C, D, G is normally fed from the B phase of the maintenance supply with the inverter output supply as a backup.

2) The trip point of the DC logic is at 17.3 VDC for UPS1D corresponding to 84.5 VAC on its input; and 16.9 VDC for UPS1C corresponding to 84.59 VAC on its input.* New control batteries (fully charged) only provide approximately 18 VDC.

3) Transfer to alternate power is accomplished via a K-5 relay. K-5 relay drop out voltage is 45 VAC for UPS1C and pick up voltage is 52 VAC.
K-5 relay drop out voltage is 42 VAC for UPS1D and pick up voltage is 55 VAC.*

4) Voltage transients generated during troubleshooting on the normal AC input power line feeding UPS1C did not trip the UPS.

*These measurements were not repeated on the other units since the results were essentially the same for the C and D units and should not be any different for the A, B, and G units.

5) The internal logic batteries on all five units were in a degraded condition and were not capable of sustaining proper logic voltage when all other sources were disconnected. There is no way to determine that the batteries are in a degraded condition with the current UPS design during normal operation.

6) Voltage transients injected (i.e., dropping AC input voltage to near zero for 100-200 msec.) on the maintenance power line in combination with the degraded batteries affected the DC logic such that it tripped the units without allowing the K-5 relay to change state. This was demonstrated on UPS1C and UPS1D.

7) A sudden complete loss of the maintenance supply voltage with both new and degraded batteries installed did not cause the unit to trip. In this case, the logic power supply properly transferred to the inverter output and therefore prevented a trip.

8) Voltage transients injected on the maintenance power line (i.e., similar to those utilized in 6) above) with good batteries installed did not produce any unit trips, although some voltage perturbations on the logic power supply were observed. This was demonstrated on UPS1C and UPS1D.

9) Fully charged batteries are required for successful K-5 relay transfer under some degraded voltage conditions on the maintenance line since other-wise the unit may trip on logic power supply failure < 16.9 VDC (84.5 VAC) before the K-5 relay will transfer the logic power supply to the inverter output.

Laboratory testing is being conducted to more fully evaluate the condition of critical components and to investigate why none of the 10 LEDs were lit on the A13A21 board even though the logic was tripped. The pertinent results of this testing to date indicate the following:

1) Significant ground voltage transients applied to certain circuit components causes their destruction.

2) Injection of noise into the boards has not caused a trip signal to be generated.

Laboratory testing will continue to further investigate the inconsistent alarm light indications. The outcome of this work is not expected to affect this root cause determination or the functionality of the UPSs. Results of in-plant troubleshooting and laboratory testing to date indicate proper function of the various alarms.

A review of the UPS vendor manual resulted in the identification of the following deficiencies:

- The vendor manual implies that the function of the batteries is to allow logic testing with no other input power available to the logic. This contributed to the system engineer not knowing that fully charged batteries could prevent a trip. The following statement is from the vendor manual:

  "A redundant logic supply, powered by the inverter output, a separate 120 VAC bypass source, and/or internal rechargeable sealed batteries, allows logic testing with no input power applied and keeps alarms indicating for as long as any source of AC control power is available."

- The section of the vendor manual which describes preventive maintenance does not mention the logic batteries, In addition, the general description section of the manual states,

  "(The batteries should be replaced at 4-year intervals)".

  The 4-year replacement frequency is not satisfactory for service over the acceptable ambient temperature range specified for the UPSs.

- The description of the logic power supply in the manual (shown below) is incorrect.

  "These power supplies are powered through relay A27K1, which selects inverter output (preferred) or bypass (alternate) source."

As a result of discussions with the UPS vendor it has been determined that the logic backup batteries are not designed to mitigate a degraded voltage condition. Additionally, the UPS design does not provide a battery test feature or allow for safe replacement of the batteries without removing the entire unit from service. Removing the unit from service would result in de-energizing the connected loads.

CONCLUSIONS

1) The main transformer fault caused a voltage drop on the maintenance supply to all five UPS units.

2) The degraded voltage on the maintenance supply caused the voltage on the UPS logic power supply to decrease below its trip setpoint causing the units to trip.

3) Automatic load transfer to the maintenance supply was prevented by design due to the degraded voltage conditions on the maintenance supply.

4) The root cause for the simultaneous tripping of the UPSs is **improper design**. The UPS is not designed to accomodate a degraded voltage condition. The following design deficiencies allowed the UPS logic power supply voltage to decrease below its trip setpoint as a result of the main step up transformer fault.

   - The logic power supply is normally energized from the maintenance supply with the inverter output as a backup instead of visa versa.

   - Under degraded voltage conditions the logic power supply switching circuit does not actuate until the supply voltage has decreased to well below the level that will cause the logic to trip.

5) Fully charged batteries probably would have prevented the tripping of the UPSs even though that is not part of their design.

CORRECTIVE ACTIONS

1) Modify the UPS logic power supply for units 1A,B,C,D, and G to be inverter preferred with maintenance backup prior to plant restart.

2) Replace all UPS logic backup batteries prior to restart.

3) Prior to restart review other plant hardware which utilizes backup batteries and verify that appropriate replacement schedules exist for those applications. Ensure any control functions dependent on batteries are identified prior to restart.

4) Process appropriate changes to the UPS vendor manual to address the identified deficiencies.

RECOMMENDATIONS

1) Evaluate (post restart) further logic power supply modifications to rectify the K-5 relay drop out characteristic problem and to provide easy access to the logic batteries for testing and replacement.

2) Develop an appropriate replacement schedule for the logic batteries based on supplier recommendations, actual service conditions, and purpose of batteries.

8/13/91, UPS FAILURE TO TRANSFER ON TRANSIENT ON AC INPUT:

A.) Operators responded to 2VBB-UPS1A, 1B, 1C, 1D, 1G and found the following:

1.) UPS1A:
   a.) CB-1 tripped
   b.) CB-2 tripped
   c.) CB-3 OPEN
   d.) CB-4 OPEN
   e.) AUTO restart
   f.) CB-3 switch closed
   g.) Module TRIP
   h.) Inverter Logic Alarm

2.) UPS1B:
   a.) CB-1 tripped
   b.) CB-2 tripped
   c.) CB-3 OPEN
   d.) CB-4 OPEN
   e.) AUTO restart
   f.) CB-3 switch closed
   g.) Module TRIP
   h.) Inverter Logic Alarm

3.) UPS1C:
   a.) CB-1 tripped
   b.) CB-2 tripped
   c.) CB-3 OPEN
   d.) CB-4 OPEN
   e.) AUTO restart
   f.) CB-3 switch closed
   g.) Module TRIP
   h.) Inverter Logic Alarm
   i.) OV/UV

4.) UPS1D:
   a.) CB-1 tripped
   b.) CB-2 tripped
   c.) CB-3 OPEN
   d.) CB-4 OPEN
   e.) AUTO restart
   f.) CB-3 switch closed
   g.) No module TRIP
   h.) No Logic TRIP
   i.) OV/UV
   j.) OV/UV Transfer
   k.) Voltage Difference

5.) UPS1G:
a.) CB-1 tripped
b.) CB-2 tripped
c.) CB-3 OPEN
d.) CB-4 OPEN
e.) AUTO restart
f.) CB-3 switch closed
g.) Module TRIP
h.) Voltage Difference
i.) OV/UV

B.) The operators did the following manipulations in attempting to restore the UPS':

1.) UPS1A:

a.) Placed restart switch to MANUAL
b.) Placed the CB-3 toggle switch to OPEN position.
c.) Reset the alarms
d.) LIFTED CB-4 MOTOR OPERATOR AND MANUALLY CLOSED CB-4. * see note

2.) UPS1B:

a.) Closed CB-1
b.) Closed CB-2
c.) Reset the alarms
d.) LIFTED CB-4 MOTOR OPERATOR AND MANUALLY CLOSED CB-4. * see note

3.) UPS1C:

a.) Placed restart switch to MANUAL
b.) Placed CB-3 toggle switch to OPEN position
c.) LIFTED CB-4 MOTOR OPERATOR AND MANUALLY CLOSED CB-4. * see note

4.) UPS1D:

a.) Closed CB-1
b.) Closed CB-2
c.) Reset the alarms
d.) LIFTED CB-4 MOTOR OPERATOR AND MANUALLY CLOSED CB-4. * see note

5.) UPS1G:

a.) Placed CB-3 toggle switch to OPEN position.
b.) LIFTED CB-4 MOTOR OPERATOR AND MANUALLY CLOSED CB-4. * see note

* NOTE: When the operators tried to restart UPS1D the procedure called out verifying that CB-4 was closed but it was open. The operators made a decision to energize the UPS loads by manually closing CB-4 by first lifting the motor operator off of the breaker. They restored each UPS in that same manner.

C.) At approximately 0830 the system engineer went down with damage control team #3 (operators, electricians and I/C technician) to restore each UPS.

UPS1C: Found CB-1, CB-2 tripped and CB-3 was open. CB-4 was closed and the CB-4 motor operator (in the OFF position) was lifted off breaker. Removed P6 plug from the CB-4 motor operator and aligned the motor operator to the ON position. Reset all alarms. Closed CB-1 and restarted the unit. It started up and "synced" to the maintenance supply. Closed CB-2, restored P6 plug and reinstalled the motor operator for CB-4 back on the breaker. Transferred the load to UPS power and put transfer switch in AUTO position.

UPS1D: Found CB-1, CB-2 closed and CB-3 was open. CB-4 was closed and the CB-4 motor operator (in OFF position) was lifted off the breaker. Removed P6 plug from the CB-4 motor operator and aligned the motor operator to the ON position. Opened CB-1 and CB-2. Closed CB-1 and restarted the unit. It started up and "synced" to the maintenance supply. Closed CB-2, restored P6 plug and reinstalled motor operator for CB-4 back on breaker. Attempted to transfer load to UPS power but CB-3 would not close. It was found in tripped position. CB-3 was reset, the motor operator was restored and the unit transferred to UPS power. Put the transfer switch in AUTO position.

UPS1A: Found CB-1 and CB-2 tripped and CB-3 was open. CB-4 was closed and the CB-4 motor operator (in OFF position) was lifted off the breaker. Removed the P6 plug from the CB-4 motor operator and aligned the motor operator to the ON position. Closed CB-1 and attempted to restart the unit. Closing CB-1 caused an inrush to the UPS and tripped the upstream breaker, 2VBB-PNL301, breaker #1. Reset breaker in 2VBB-PNL301 and reclosed CB-1 on UPS1A. Upstream breaker tripped again. Wrote WR (WR # 162319) and Deficiency tag to repair Rectifier section of UPS1A. Unit left with CB-4 closed.

UPS1B: Found CB-1, CB-2 closed and CB-3 open. CB-4 was closed and the CB-4 motor operator (in OFF position) was lifted off breaker. Removed P6 plug from the motor operator and aligned motor operator to ON position. Opened CB-1 and CB-2. Closed CB-1 and restarted unit. It started up and "synced" to the maintenance supply. Closed CB-2, restored P6 plug and reinstalled motor operator for CB-4 back on breaker. Attempted to transfer load to UPS power but CB-3 would not close. It was found in the tripped position. CB-3 was reset, the motor operator was restored and attempted to transfer load to UPS power but CB-3 again would not close. CB-3 cannot be reset due to a previously identified problem. Unit left with CB-4 closed - on Maintenance supply power.
Note: WR# 138173 exists to replace CB-3.

UPS1G: Found CB-1, CB-2 tripped and CB-3 open. CB-4 was closed and the CB-4 motor operator (in OFF position) was lifted off breaker. Removed P6 plug from motor operator and aligned motor operator to ON position. Reset all alarms. Noted 575vac input to UPS. Closed CB-1. When CB-1 was closed it tripped its upstream breaker in 2VBB-PNL301. Breaker #7 in 2VBB-PNL301 was reset and CB-1 reclosed (successfully). The unit was restarted. It started up and "synced" to the maintenance supply. Closed CB-2, restored P6 plug. When restoring the P6 block the CB-4 motor operator went to the OFF position. Opened CB-2 and CB-1 and removed logic power from unit to reset all logic. Reset motor operator on CB-4 to ON position. Reclosed logic power, closed CB-1 and restarted UPS. Unit started up and "synced" to the maintenance supply. Closed CB-2, restored P6 plug and reinstalled the motor operator for CB-4 back on the breaker. Transferred load to UPS power and put transfer switch in the AUTO position.

NOTE: When a trip signal is generated within the UPS it sends a shunt trip signal to both CB-1 and CB-2. It also sends an OFF signal to CB-3 and an ON signal to CB-4. A voltage difference alarm will inhibit a closure of CB-4.

UPS ALIGNMENT AT TIME OF EVENT:

		2NPS-SWG001	2NPS-SWG003
UPS1A Normal AC	(US3-B)		X
UPS1A Maint. Supply	(US5)	X	
UPS1B Normal AC	(US3-B)		X
UPS1B Maint. Supply	(US6)		X
UPS1C Normal AC	(US3-B)		X
UPS1C Maint. Supply	(US5)	X	
UPS1D Normal AC	(US3-A)	X	
UPS1D Maint. Supply	(US6)		X
UPS1G Normal AC	(US3-B)		X
UPS1G Maint. Supply	(US6)		X

Niagara Mohawk

Nine Mile Point Unit 2

Event of 13 August 1991

Report by: Melvin L. Crenshaw
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5 September 1991

Niagara Mohawk Nine Mile Point Unit 2 Event of 13 August 1991 05:48

Introduction

On August 13, 1991, at 5:48 AM the Unit 2 phase B generator step-up transformer failed. Oscillographic records of the event are available from a digital data recorder at the Scriba Substation. They show various 345 kV and 115 kV system voltages and currents. Figure A with notations is attached.

The four cycles preceding the fault show no signs of a gradual degradation or a developing disturbance. The oscillographic traces and station protective relay targets reported, indicate a ground fault occurred on the high voltage winding. Depression of the 345 kV phase B bus voltage to about 39% of the prior value was observed from the oscillographic trace. This suggests the involvement of only a portion of the entire winding. The 345 kV line currents and voltages show rapid development of the ground fault beginning at point 1 with the ground current reaching a constant value of 1,300 amperes in 1 1/2 cycles at point 4. The flashover in the faulted transformer occurs just preceding a maximum in phase 2 to neutral voltage (as would have been expected) at point 2. The 345 kV line current in an unfaulted phase increases in step function manner to 350% of the prefault value at point 3.

No high speed recordings of voltages or currents within the plant were available. No sequence of event recordings were available to correlate relay operation times. Due to the large amount of magnetic energy coupling the generator rotor and stator, and known electrical parameters, the decay of fault current contributed by the generator to the solidly connected transformer would have spanned a number of seconds as the field decayed.

Relay operation targets reported were:

1. Transformer Differential Relay (Type BDD) on Transformer 2MTX-XM1B.

2. Transformer Neutral Current Relay (Type IAC).

3. Overall Unit Differential Relays (Type BDD) in phases 2 and 3.

4. Generator Phase Overcurrent Relays (Type PJC) in phases 2 and 3.

Postulated Event Scenario

Following isolation of the generator and failed transformer from the power grid, marked 5 on Figure A, only a single 345 kV phase to ground voltage record is available. The magnitude of this voltage on an unfaulted phase is 74% of the pre-fault value. Since generator neutral current is limited to less than 8 amperes, it is known that the faulted transformer appears as a line to line fault with some impedance to the generator. By trial and error calculation, generator line currents are found to be 0, 1.9 and 1.9, multiples of the rated value of 31,140 amperes. The line-to-line voltages have magnitudes 74% 74%, and 25% of the rated value of 25,000 volts. The decay of this voltage for 0.25 seconds of the recording has a measured time constant of 2.7 seconds. The calculated value of the impedance of the faulted transformer as seen by the generator is 0.23 per unit.

Conditions prevailing during the six cycle time period following the fault, marked 2 on Figure A, cannot be determined with certainty. The exact nature of the fault within the transformer is not known and the physical evidence will be strongly affected by the continued flow of energy from the generator due to the inherent time constant. The flashover of only a portion of the HV winding is evident since the 345 line voltages to neutral remain at 39%, 86% and 86% of the pre-fault values. The presence of "residual" in the measured 345 kV line currents provides the evidence of transformer neutral to ground current. This requires that the fault involves a path for current to ground from the high voltage winding. Recorded voltages and currents show a step change to new values and no dramatic change during the time period of the record, which totals somewhat less than 1/2 second. It could be said they are "cleaner" and less distorted than commonly seen oscillograph recordings of faults.

Given these observations and since both the generator and the system were supplying fault current into the faulted transformer, generator line-to-line voltages preceding isolation would be expected to be greater than those immediately following isolation.

High Frequency Voltage Transfer

It has been speculated that very high frequency energy (mHz region) may have caused malfunction of logic and control circuitry in the UPS equipment. A broad range of frequencies would be expected in any arcing phenomenon such as occurred in this failure. Nothing in the available data or design parameters of the plant equipment would suggest an extraordinary generation or propagation of higher frequency components. The failure of a transformer and internal arcing is not a rare occurrence. Comparison of oscillographic charts

from similar events in other plants show nothing unexpected or unusual in this particular failure. It must be borne in mind that the sampling rate of the recorder is listed as 5.814 kHz and frequency components in excess of perhaps 500 Hz would not be accurately portrayed.

GE experience in testing of typical power transformers (such as the Unit Auxiliaries Transformers) provides an indication of the expected coupling between windings at radio frequencies in the region of 1 megahertz: The attenuation factors range from 1,000: 1 to 10's of thousands: 1. Direct measurements could be made in this plant to determine attenuation factors for individual transformers over a range of frequencies. These tests would be made on non-energized transformers using an RF signal generator and a sensitive, calibrated detector.

Attached recent articles on electro-magnetic interference. Reference 1 discusses IEC 801.4 and the characteristics of electrically fast transients. Reference 2 discusses testing of ground connections.

Station Ground Elevation

The possibility of elevation of the station grounding system as a result of this disturbance was postulated. The relatively high level of ground fault current, estimated at 1,300 amperes from the available recording, would not have been conducted into the plant. This current can only flow in from the 345 kV system for the 6 cycle period required for relay and circuit breaker operation to achieve isolation. The generator ground current would have been limited to less than 8 amperes by the neutral grounding equipment. Elevation or differences in ground potential within the plant would therefore not have been expected during this event.

Reference 1 discusses the problem of achieving a "super" ground and concludes that a stable ground reference for interconnected equipment is of greater significance. Since normally circulating ground currents are not expected, testing with very low voltages and currents is recommended. Note especially the recommendation to test with a frequency non-harmonically related to the power line frequency.

Design Review of Nine Mile Point Auxiliaries Power Distribution System

The transformers stepping the voltage down to successively lower voltage levels are connected in a manner to minimize coupling of power frequency and higher frequency components between the various busses. Specific configurations are:

1. Normal Station Service Transformer -
   delta 25 kV to wye 13.8 kV with 400 ampere resistive grounding on the 13.8 kV side.

2. Load Center Transformers -
   delta 13.8 kV to wye 4.16 kV with 400 ampere resistive grounding on the 4.16 kV side.

3. Load Center Transformers -
   delta 13.8 kV or 4.16 kV to wye 600 volts with neutral solidly grounded on the 600 volt side.

4. Reserve Station Service Transformers -
   wye 115 kV, delta 4.16 kV, wye 13.8 kV. The 13.8 kV neutral is 400 ampere resistive grounded. The 4.16 kV circuit is connected to a zig-zag grounding transformer with a resistor in the neutral connection, presumably for 400 amperes.

These configurations provide "effectively grounded" distribution busses as defined in IEEE Standard 142 and will serve to limit transient over voltages. This is in accordance with design practices deemed prudent and conservative within the power industry.

Transformer Failures

The industry continues to review the effects of geomagnetic disturbances on power transformers.

While no evidence is seen of voltage distortion in the four cycles preceeding the failure, excessive duty could have occurred if these transformers had been subjected to low level direct current previously. References 3 and 4 are attached for perusal.

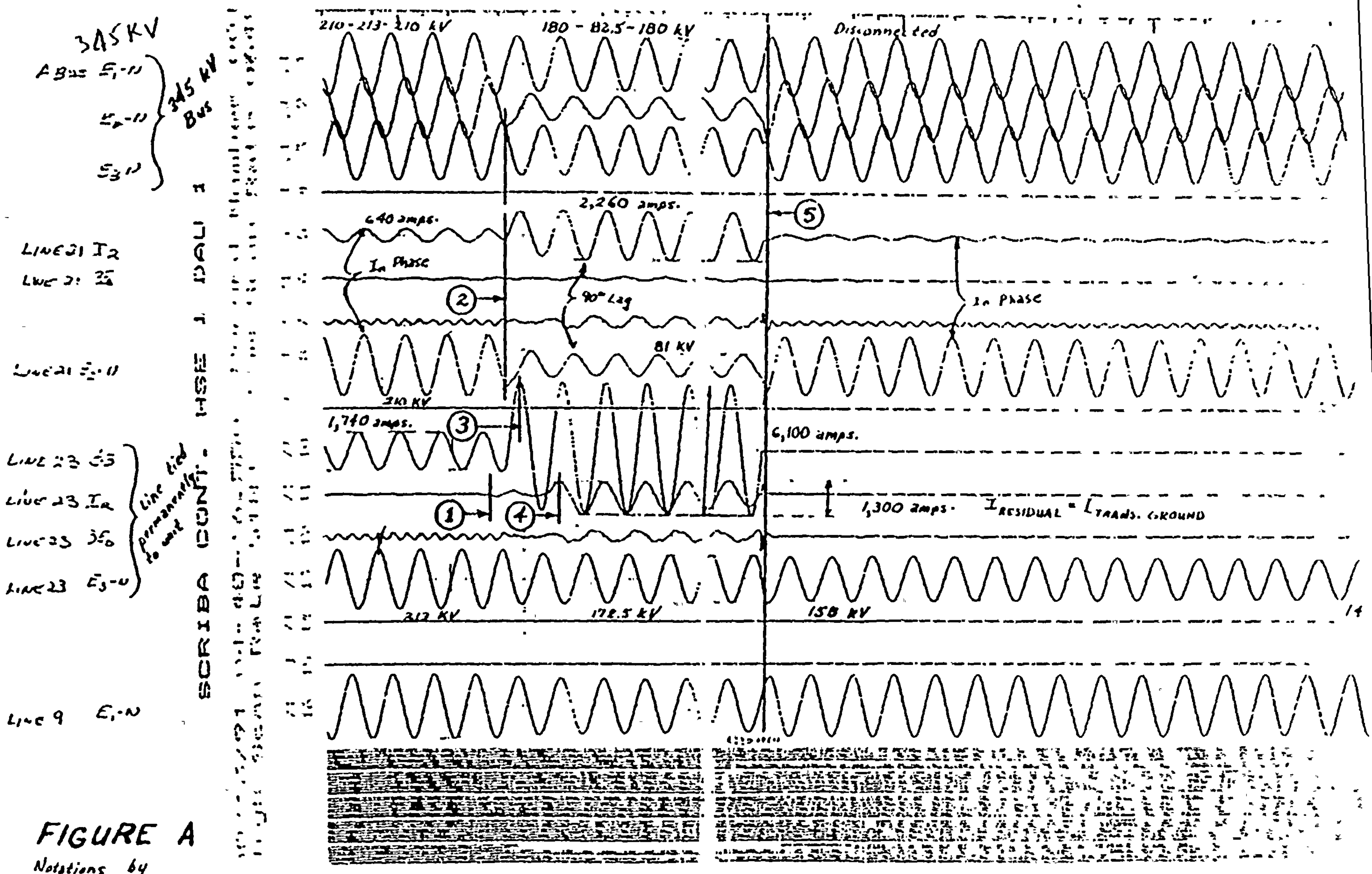

FIGURE A

Notations by
M.L. Crenshaw

Electronics in Industrial Applications

A Discussion of Fundamental EMC Principles for Electronic Controllers in an Industrial Environment

By William D. Kimmel, PE
Kimmel Gerke Associates, Ltd

EMC problems with industrial controls are aggravated by harsh environments, mixed technologies and a lack of uniform EMC guidelines. This article will concentrate on the common aspects of electronic controls in an industrial environment, which is generally much harsher than the office environment.

What is the industrial environment and what can be done about it? The environment includes the entire gamut of the basic threats, power disturbances, RFI, and ESD. RFI and power disturbances may be locally generated or not. Mixed technologies compound the problem. Digital circuits are used to switch line voltages via relays. Analog sensors are input devices to digital controls.

Increasingly, there is a need for a cooperative effort between the designers, manufacturers and installers to come up with a rock-solid system. A common complaint is that the installers or maintenance people won't follow the installation requirements. This may be true, but it must change, since there are problems which cannot be solved at the board level. It is also true that manufacturers often specify installation requirements which are not practical to implement, and there are documented cases where the prescribed installation procedures will cause rather than cure a problem.

The lack of uniform guidelines has hampered EMC progress in the industrial arena. Fortunately, the European Community is working to adopt the IEC 801.x specifications, and domestic companies would be wise to adopt them, even if there is no intention to export.

The Basic Threats

The three basic threats to industrial electronics are power disturbances, radio frequency interference, and ESD.

Power Disturbances. Power disturbances are a well known industrial problem. In fact, when a problem occurs, the first thought is to blame the power company. Often power quality is a problem (especially if grounding issues are included), but the problem is almost always generated by adjacent equipment.

Traditional problems with power include spikes and transients, sags and surges, and outages, which threaten the electronics via the power supply. These problems are fairly well documented and are often solved using power conditioners or UPS.

The most common power problems confronting electronics today is the sag which typically occurs during turn on and the spikes which typically occur during turn off of heavy inductive loads. The sags simply starve the electronics. The high frequency transients barrel right through the supposedly filtered power supply to attack the electronics inside.

Digital circuits are most vulnerable to spikes which cause data errors or worse. Analog circuits are most vulnerable to continuous RF riding on top of the power.

FIPS PUB 94 provides guidelines on electrical power for commercial computers. This is good information, but beware that factory power is much noisier than commercial power.

The guidelines of IEC 801.4 specifies an electrically fast transient (EFT) that simulates arcing and other high speed noise. EFTs are quite short ranged — they diminish rapidly with distance due to inductance in the line. But at short range, they are devastating.

Unfortunately, attention is placed on the front end of the electronics, the power supply. With industrial controls, the problem is the controlled elements. If the electronics is controlling line power, the disturbances sneak in the back end where little or no protection exists.

System ground, while not being specifically a power disturbance problem, is oft the carrier of residual effects of pow disturbances. Any industrial or commerc structure has significant low frequen currents circulating through the grou system, sometimes because the energy intentionally dumped onto the ground (su as with an arc welder) and sometime because of unintentional coupling or eve an inadvertent connection between neutr and ground somewhere in the facility.

Radio Frequency Interference. Radio frequency interference affects bot analog and digital circuits, with analo circuits being generally more susceptibl Surprising to many, the principle threat not the TV or FM station down the road but rather it is the hand held transmitte carried around by facilities personnel. A on watt radio will result in an electric field c five volts/meter at a one meter distance enough to upset many electronics systems

IEC 801.3 specifies immunity to electr fields of one to ten volts per mete depending on the equipment, with thre volts per meter being the level for typic equipment. As can be seen from the abov approximation, three volts per meter is nc an excessive requirement, and even te volts per meter is fairly modest.

Electrostatic Discharges. Electrostatic discharge is an intense short duration pulse, having a risetime of about one nanosecond. This is equivalent to a burst of 300 MHz interference. Static buildups of 15 kV are not uncommon.

Dry climates, including northern climates

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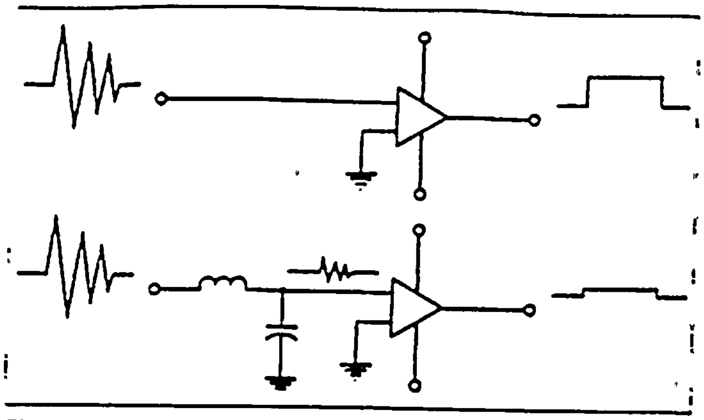

Figure 1. Amplifier demodulation.

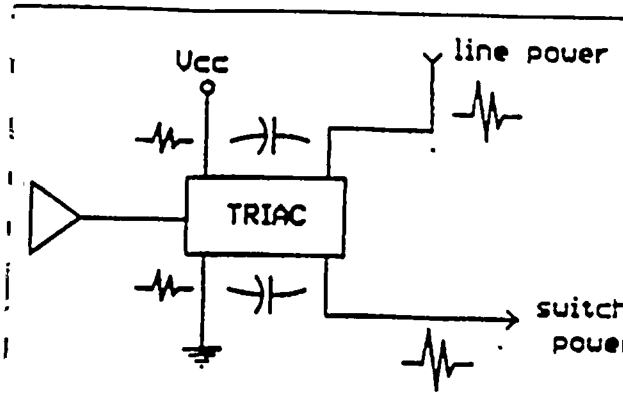

Figure 2. Transient feedback path.

in winter, offer opportunity for ESD. Industrial environments, with their moving equipment, are loaded with potential ESD sources: rubber rollers, belts, and production output such as plastic and paper rolls, all add up to a real ESD threat, and this threat is more likely to occur even in relatively moist environments. Look to IEC 801.2 for ESD standards.

Electronics Design

Electronics is generally the ultimate victim of interference. The interference finds its way through various paths to the electronics equipment itself. Let's concentrate on what can happen to your electronics from the back door, that is, by direct radiation into the electronics and by conducted interference through the signal and control lines.

Sensors. Low level sensors, such as thermocouples, pressure sensors, etc., are characterized by very low bandwidths and low signal levels. A major threat to these sensors is radio frequency interference, either from nearby hand held transmitters or more distance land mobile or fixed transmitters.

But these are high frequency, much above the bandpass of your amplifier, right? Wrong! Low frequency amplifiers are plagued by two phenomena: out of band response and audio rectification. These combine to provide false information on levels to the system.

All amplifiers have a normal bandpass, typified by a 20 dB/decade rolloff or more at the high end. But resonances due to stray inductance and capacitance will give rise to amplifier response five orders of magnitude or more above the nominal bandpass of the amplifier. This means an audio amplifier will respond to signals in the hundreds of MHz.

The second aspect occurs when RF encounters a nonlinearity such as a semiconductor device. All such devices give rise to a DC level shift when confronted with RF. In a radio receiver they are called detectors. Nonlinearities are minimized in linear devices, but there is always enough to cause problems. The upshot is that the amplifier demodulates the RF, generates an erroneous signal, and passes this error on. This effect is shown in Figure 1. Output lines are similarly affected, with capacitive coupling back to the input.

The solution is to prevent the RF from getting to the amplifier, either by shielding or filtering. The most common path to the amplifier is via an external signal line from the sensor, but if the electronics is not shielded, direct radiation to the circuit board may also present a problem.

Assuming filtering is the selected method, use a high frequency filter, designed to block signals up to 1 GHz or even more. Use ferrites and high frequency capacitors. Do not rely on your low frequency filter to take out RF.

At the op amp, you should also decouple your plus and minus power to ground at the chip. If your ground is carrying RF, you can anticipate the same problem mentioned above, since it will corrupt the reference level.

Data Lines. Digital data lines will be upset by the RF problem as in analog, but the levels necessary to upset are higher. Instead, digital data lines are much more susceptible to transient glitches. All signal lines should be filtered to pass only the frequencies necessary for operation. If the threat lies in the bandpass of the signal, then shielding or optical links will be needed.

Switched Power Lines. This refers specifically to the power being controlled by the controller device. Industrial controllers are commonly tasked to control power to heavy equipment, which is characteri by heavy starting loads and inductive at turn off. Typically the electronic contr switch line power using relays or tria This exposes the back end of the contro to substantial line transients, which cou back to the circuit power and ground a disrupt the digital circuitry as shown Figure 2.

It is mandatory that the transient cu rents be diverted or blocked, since digital system cannot withstand the magn tudes likely to occur with an inductive kic unless special steps are taken.

Self jamming can be limited by controlli when you switch the line, using ze crossing devices. Of particular importanc is the turn off, since that is when t inductive kick occurs.

If all power switching used zero crossir devices, the transient levels in the factor would be dramatically reduced. Unfort nately, that goal is well off in the futu Until then, expect that high voltage pow transients will occur, and they must be de with.

Optical couplers and relays do not provi sufficient isolation by themselves. The high capacitance provides an excellent hi frequency path, and if they are stacked u in an array, the capacitance will add up t pass surprisingly low frequencies. Thes capacitances can't be eliminated, but yo can design your control circuits to minimiz coupling paths and to maximize low imped ance alternate paths.

Transient suppressors should be installe at the load, which is the source of the spike but they can be installed at the controlle as well.

An interesting effect occurs when com bining zero crossing SCR regulators wit low level sensors which use line frequenc noise canceling techniques. Very sensitiv sensors sometimes are sampled for a

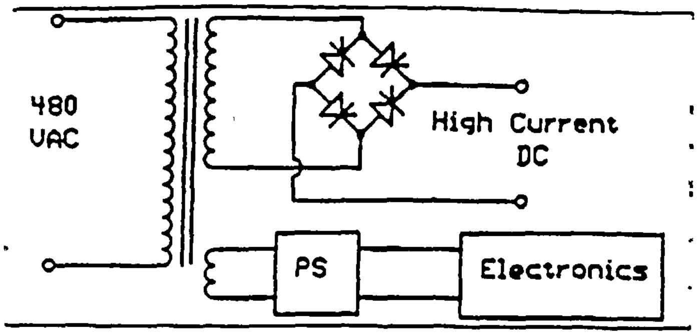

Figure 3. Common industrial power supply.

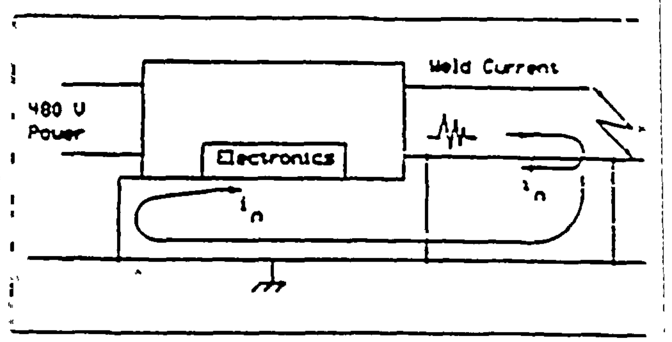

Figure 4. Multiple ground paths.

entire power cycle to cancel the line frequency component. If the sample occurs concurrently with line power switching on or off, the average to the sensor will be upset, and an error will be recorded.

System Design and Installation

Once the electronics is designed, it becomes a problem of the system integrator and installer to ensure that the electronics is provided with the environment for which it was designed. Most of the time, this work is performed by power experts and electricians, and they are not always aware of the interference problem. Often, on site, the power quality is blamed for the equipment anomalies. But the problem can often be avoided by following a few basic principles.

The industrial control device is either integrated into a system at the factory or installed separately on site. Controllers handle a variety of devices such as motor speed controls, positioning devices, welders, etc. Interference presented to the electronics can be significantly reduced by appropriate measures outside of the electronics box.

There is no way to accurately assess the threat without test data. But regardless of the information available, much can be accomplished by correct installation, and it doesn't cost much if done at the start. Retrofits become costly, especially if accompanied with factory down time.

Let's consider the same problems from a system standpoint. Your goal is to limit the interference which must be handled by the electronics.

Direct radiation to the electronics is not often a problem in an industrial environment, but it does occur, and most often with a plastic enclosure. The NEMA type enclosures provide enough shielding for most industrial needs. If you don't want to use a metal enclosure, be sure to get electronics which will withstand the RF which will occur.

More often the problem is conducted, either via power or ground. The problem occurs due to power and ground disturbances caused by the equipment. It is an all too common practice to draw controller power from the same source as feeds the power equipment. This power may provide the necessary energy to drive the equipment, but it is not suitable to power the electronics (Figure 3).

Hopefully, all industrial equipment will have electronics powered from a separate low power 120 volt circuit. It solves several problems. First, it separates the electronics power from the probably very noisy industrial grade power, preventing the switching transients and startup sags from getting to the electronics. Second, if it is necessary to condition the electronics power from an external problem, it is far cheaper to condition the watts needed for electronics power than it is to condition the kilowatts required by the system.

If power cannot be separated, then it is necessary to provide a bulletproof power supply, preferably including an isolation transformer, to separate the entire power supply from the electrical equipment.

Ground Noise. Ground noise, inevitable in industrial environments, must be diverted from the electronics module. Multiple grounds in a system will often result in ground currents circulating through the equipment, and ground noise circulating through the electronics path will cause malfunction. Figure 4 shows some typical ground loop situations.

A common approach is to demand a super earth ground. This is good, but it is not a cure all, and often a super ground cannot be achieved, no matter how you try. How do you get a super ground from the third floor? The real need is to get a stable ground reference to all interconnected equipments. If this equipment is closely located, then a very low impedance interconnect is feasible.

Power conditioners are often tasked to eliminate RF or ground noise. That work, but these problems can be so[lved] with an isolation transformer to elimi[nate] neutral to ground noise and with EMI po[wer] line filters. So you may want to try [the] inexpensive approach first.

Data Links. Data links are strung over the entire facility, exposing them [to] two principle effects, ground noise and [RF] pickup. Ground noise will cause data err[ors] unless the electronics has been designed [to] accommodate potential differences of se[v]eral volts or more. This is accomplish[ed] with differential drivers and receivers if [they] must be direct coupled. Optical links [will] eventually take over these links.

The other aspect is RF pickup. Inexpe[n]sive shielded cable is suitable for [this] purpose. Ground both ends! Do not app[ly] single point ground techniques to RF. [If] low frequency ground loop problem is [a] threat, then one end can be capacitive[ly] grounded.

Summary

Industrial electronics are subjected to [a] harsh environment. Good design and insta[l]lation techniques will minimize problems [in] the field. Adherence to the Europe[an] standards, IEC 801.x is a good start, ev[en] if you are only marketing in the USA.

Bibliography

FIPS PUB 94, Guideline on Electric Power for ADP Installations, September 1983.

IEC 801-2, Electromagnetic compatibilit[y] for industrial-process measurement an[d] control equipment, Electrostatic discharg[e] requirements, 1984.

IEC 801-3, Electromagnetic compatibilit[y] for industrial-process measurement an[d] control equipment, Radiated electromag[n]etic field requirements, 1984.

IEC 801-4, Electromagnetic compatibility for industrial-process measurement an[d] control equipment, Electrical fast transient burst requirements, 1984.

Equipment Ground Bonding — Designing for Performance and Life

A Discussion of Ground Connection Fundamentals to Control EMI

By D.B.L. Durham
Dytecna Ltd. UK

The problem of achieving satisfactory earth bonds or ground connections has plagued EMC engineers for many years, not only because the bonds are often vital for the achievement of satisfactory equipment performance but because they affect the long term performance of equipment after it has been introduced into service.

Recommendations on bonding have existed in the form of military specifications, such as Mil Std 1310, Mil 188-124A and Mil-B-5087 (ASG) for some years and these have generally proved satisfactory for most new builds. However, these specifications have certain limitations in that they generally do not specify consistently low levels of bond impedance, nor a suitable test method. The introduction of new EMC specifications in Europe with the EEC Directive on EMC and the requirements for long term stability in EMC characteristics has directed the UK military to review existing specifications and introduce a new Defence Standard to tighten up performance requirements for military equipment. Def Stan 58-6 (Part 1)/1 has been introduced to address this area as far as mobile and transportable communications installations are concerned, but the requirements should have implications in industrial applications and over the whole electronics market if long term product performance is to be guaranteed.

Bond Degradation

Earth or ground bonds are generally considered essential not only for safety reasons, but as a means of diverting EMI currents, "locking" circuit boards and equipment to a stable ground point, achieving adequate levels of cable shielding and for many other reasons. Many designers understand the requirement for short, fat bond leads to minimize ground inductance, but few appreciate that a critical aspect is the connection resistance with which the bond strap is attached to the equipment ground point. The basic requirement of any bond is that it should have as low an impedance as possible (unless it is a deliberate inductive bond to limit ground currents). The impedance is a combination of the resistive and the inductive components. The resistive element is a function of the bond strap resistivity, cross sectional area and length, see Equation 1, whilst the inductive component is a more complex function of the bond strap characteristics as shown in Equation 2.

$$R = \frac{\varrho \ell}{A} \quad (1)$$

$$L = \frac{\mu_o \mu_r}{2\pi}\left[\ln\frac{2\ell}{b+c} + 0.5 + 0.2235\,\frac{b+c}{2\ell}\right] \quad (2)$$

where R = resistance, ϱ = resistivity, ℓ = length, A = area, μ_o = permeability of free space, L = inductance, μ_r = relative permeability, b = strap width, and c = strap thickness.

The frequency at which the inductive element dominates the impedance expression when calculating the total inductance is, from Equation 3, typically 1 kHz. It will be seen therefore that to all intents and purposes the bond except at DC and power frequencies, may be assumed to be an inductance. At very high frequencies the stray capacitance across the strap may dominate. This means that the volt drop across a bond is generally a function of inductance and frequency. Based on Ohm's Law this volt drop is shown in Equation 4. For transients the voltage drop is given by Equation 5.

$$Z = \sqrt{R^2 + \omega^2L^2} \quad (3)$$

$$V = IZ = j\omega LI \quad (4)$$

$$V = -L\,\frac{dI}{dt} \quad (5)$$

where Z = strap impedance, ω = radial frequency, V = voltage, and I = current.

From this, the higher the inductance the more isolated the circuit or box becomes from ground. This can have significant effects on equipment, including enhancement of noise injection onto circuits, reduction of filter performance, and loss of communication range. From a TEMPEST standpoint it may result in more radiation from equipment. It would seem from this that the criteria for any bond is the inductance and hence the choice of short fat

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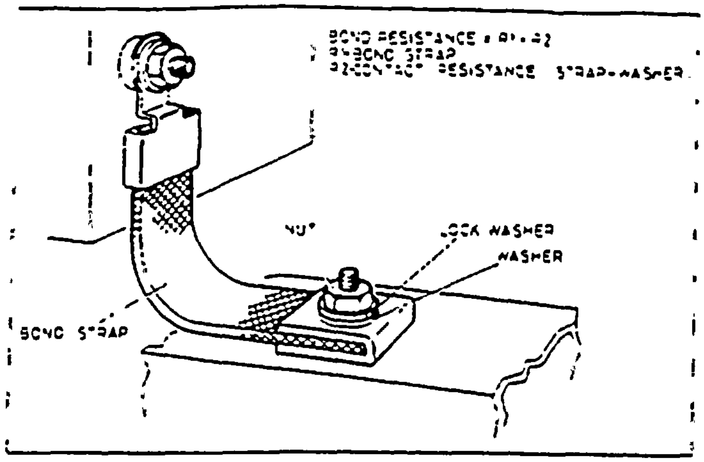


Figure 1. Bond resistance.

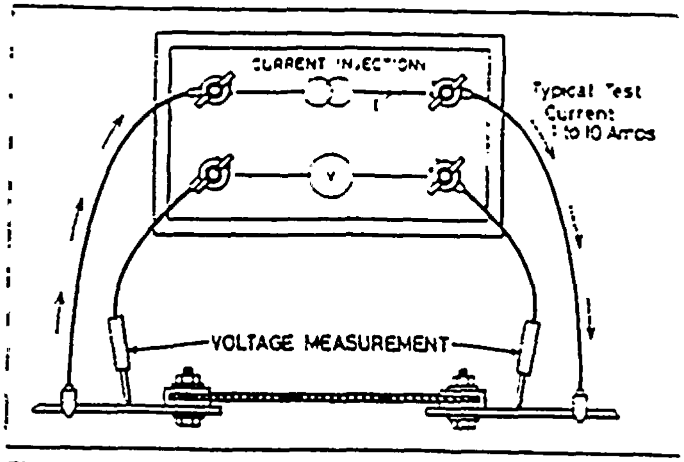


Figure 2. Four wire bridge method.

bond straps. However, an analysis of the bond inductance shows that for a bond strap of 100 mm long, 15 mm wide and 2 mm thick the impedance at 1 MHz will be 3.8 Ohms. It sounds extremely simple, but work performed in the USA and UK shows that if an error is made in the way the strap is terminated then a progressive increase in the resistance of the bond strap to box junction can occur as the equipment ages. Eventually the resistance will begin to exceed hundreds of ohms and may eventually go open circuit. This can negate the effect of the bond strap completely as part of the EMI protection.

What happens with bonds to cause this change? Essentially a ground connection is a series of impedances from the strap through to the ground material, as shown in Figure 1. Each point of contact contributes to the total bond performance. As a result, a change in any contact condition can result in a change in the total bond resistance. As is well appreciated, the contact resistance between two metal surfaces is a function of the pressure. The pressure exerted by the tip of a drawing pin is vastly greater than that from the thumb pressing by itself. Thus the contact from a sharp point gives a much higher pressure than a flat point and therefore lower contact resistance. Measurements have shown that sharp points enable contact resistance of a few microohm to be achieved whilst similar pressures on flat surfaces result in milliohms of contact resistance. It might be felt that there is little or no difference between these values, but in reality there is. An essential aspect of a good bond is that it should remain so after the equipment has entered use. High pressures also have the effect of squeezing out corrosive materials and insulating films. The former causes progressive degradation of bonds, whilst the latter can reduce the efficiency of the bond from the moment it is installed. It is particularly important in communications systems, where filters are installed and shielded cable terminations are made that the bonds are of low resistance and retain their performance.

Bond Performance and Measurement

Experience has shown over a number of years that for long term consistent bond performance a low value of resistance must be achieved. This is typically 1-5 milliohms. In Def Stan 58-6 (Part 1)/1 the value has been set at a maximum of 2 milliohms. This level is measured through the individual bonds. The logic behind this level is twofold. Firstly, experience has shown that with communications equipment in particular this value of bond resistance is required if consistent performance is to be achieved in terms of reception efficiency and transmission characteristics. This is particularly so for TEMPEST protected equipments. The second point is that if the bond has a higher resistance then there is a significant likelihood that progressive degradation will occur and the bond resistance will increase in value. There will then be a progressive loss in performance.

The main problem with measuring bond resistances is that it should be measured using a low voltage/current technique. Most techniques to date for assessing safety involves driving a large current through the bond. This checks the bond's ability to carry current but does not necessarily check its EMI protection performance. The reason is that many bonds may when in normal use have a high resistance due to oxide and greasy films, but when subjected to a high current the layers heat up and are vaporised. After the current is removed the film can return. Thus high current techniques are not recommended for testing EMI bonds. The new Defence Standard in the UK specifies a maximum probe voltage of 100 microvolts. This represents typically a probe current of 50 milliamps under short circuit (< 1 mΩ) conditions. This is insufficient to destroy surface films. The classic method for measuring low resistance has been to use a four terminal bridge as shown in Figure 2. In this case the current is driven between two points and the voltage across the sample is measured with a high resistance probe. This removes the effects of the probe contact resistance and lead resistance. This is generally considered to be a laboratory method as the use of four contacts can be awkward. If the lead resistance can be removed by a calibration technique then the four terminals may be replaced with a two terminal system.

A further possible refinement to the technique is to use a frequency that is not DC or 50/60/400Hz. In this case 10.4 Hz has been chosen. If an active filter is used to filter out all other electrical noise, then it is possible to use the bond resistance meter on powered up systems. It is worth noting that at this frequency the impedance is still largely represented by resistance rather than inductance. The two terminal method is shown in Figure 3.

The introduction of new EMC/EMI specifications in Europe has made it more important that once made the bonds have consistent long term performance. This means measuring on periodic inspection and after maintenance. It is an essential aspect of insuring consistent performance. It has been shown that within months apparently good bonds can deteriorate to high resis-

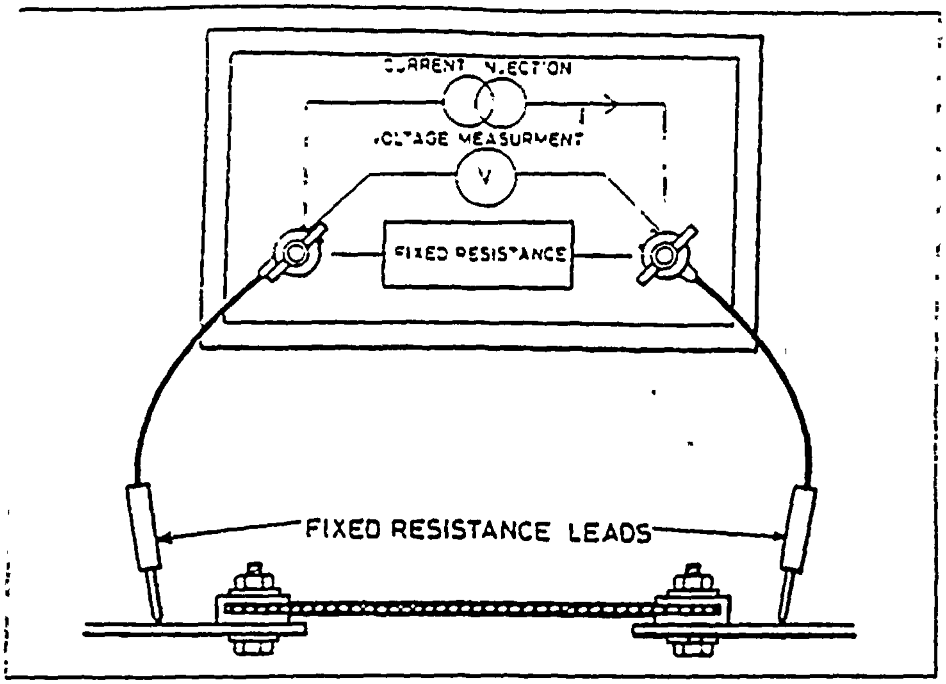
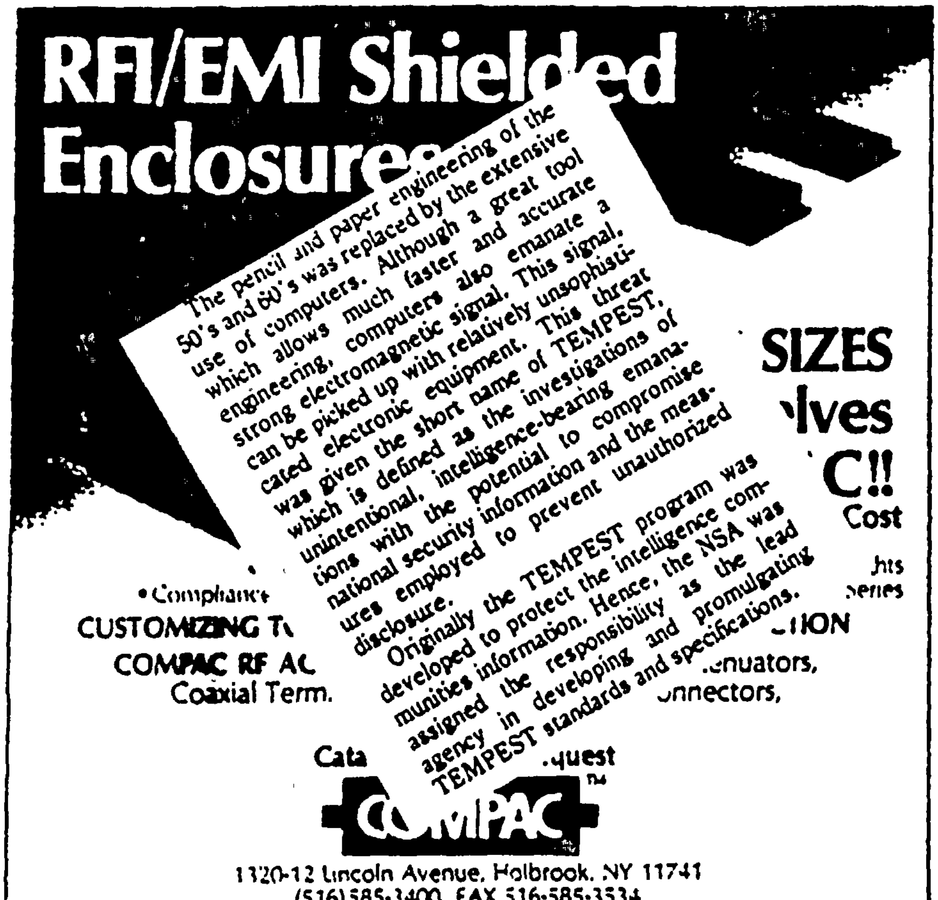


Figure 3. Two terminal bridge method.



tance. Therefore all types of bonds ... subject to testing and examination ... as a maintenance task.

UK Military Experience

There have been two major pro... caused by poor bonds experienced ... by military equipment users. The first ... degradation in performance already ... tioned in this article. The loss of com... cation range, poor EMI performance ... other effects all contribute to a consider... reduction in equipment efficiency and a... ability. The second effect which is ... difficult to identify is that of No Fault Fo... (NFF) problems. An analysis of repor... failures from military reliability data ... shown that NFF incidents can be extrem... high, particularly in humid climates. T... has been partially confirmed by reports fr... the Gulf War when all forces reported ... increase in availability of equipment in ... drier climate. Many faults are due to ... electrical contacts in connectors, but a lar... number have been identified as excessi... EMI induced through poor ground bond... This may be caused by either a loose grou... strap or connector termination to the bo... A significant improvement in equipme... availability and performance is expecte... when more recent statistics are analysed.

The introduction into the British Arm... service of the Dytecna Bond Resistanc... Test Set — DT 109 has enabled the U... military to measure bond resistances ... installed equipment and reduce the oc... curances of NFF errors. The UK military measurement procedure uses a two termi... nal bridge method and an accurate ... milliohm calibration standard. This meas... urement procedure and equipment is als... in use by other NATO nations and else... where by military and naval forces who hav... recognized the same problem.

Conclusions

The problems with ground bonds have become significant with the development of sensitive and secure communications equipment. This coupled with an increasing need to achieve higher and higher levels of EMI protection has lead to an increased emphasis being placed on the effectiveness of all types of system grounds. These, further combined with a requirement to ensure the long life of systems once in service, have resulted in the assessment that bonds and terminations are one of the primary causes of EMI failures in systems. The requirement to test these is clear, however the means to do so have not always been available to engineers.

Effects Of Geomagnetic Disturbances On Power Systems

Panel Session

PES Summer Meeting, July 12, 1989
Long Beach, California
John G. Kappenman, Chairman

Power System Susceptibility To Geomagnetic Disturbances: Present And Future Concerns

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The effects of Solar-Geomagnetic Disturbances have been observed for decades on power systems. However, the profound impact of the March 13, 1989 geomagnetic disturbance has created a much greater level of concern about the phenomena in the power industry.

Several man-made systems have suffered disruptions to their normal operation due to the occurrence of geomagnetic phenomena. Most of the man-made systems, such as communications, have been made less susceptible to the phenomena through technological evolution (microwave and fiber-optic have replaced metallic wire systems). However, the bulk transmission system, if anything, is more susceptible *today than ever before* to geomagnetic disturbance events. And if the present trends continue, it is likely the bulk transmission network will become more susceptible in the future. Some of the most concerning trends are: 1) The transmission systems of today span greater distances of earth-surface-potential which result in the flow of larger geomagnetically-induced-currents in the system, 2) the interconnected systems tend to be more stressed by large region-to-region transfers, combined with GIC which will simultaneously turn every transformer in the bulk system into a large reactive power consumer and harmonic current generator and 3) in general, large EHV transformers, static var compensators and relay systems are more susceptible to adverse influence and misoperation due to GIC.

TRANSFORMER OPERATION

The primary concern with Geomagnetically-Induced Currents is the effect that they have upon the operation of large power transformers. The three major effects produced by GIC in transformers is 1) the increased var consumption of the affected transformer, 2) the increased even and odd harmonics generated by the half-cycle saturation, and 3) the possibilities of equipment damaging stray flux heating. As is well documented, the presence of even a small amount of GIC (20 amps or less) will cause a large power transformer to half-cycle saturate. The half-cycle saturation distorted exciting current is rich in even and odd harmonics which become introduced to the power system. The distortion of the exciting current also determines the real and reactive power requirements of the transformer. The saturation of the core steel, under half-cycle saturation, can cause stray flux to enter structural tank members or current windings which has the potential to produce severe transformer heating.

[illegible] field test results indicate that single phase transformers half-cycle saturate much more easily and to a much greater degree than comparable three-phase units. These transformers produce higher magnitudes of harmonics and consume larger amounts of reactive power when compared with three phase designs.

RELAY AND PROTECTIVE SYSTEMS

There are three basic failure modes of relay and protective systems that can be attributed to ggeomagnetic disturbances:

- False Operation of the protection system, such as having occurred for SVC, capacitor and line relay operations where the flow of harmonic currents are misinterpreted by the relay as a fault or overload condition. This is the most common failure mode.
- Failure to Operate when an operation is desirable, this has shown to be a problem for transformer differential protection schemes and for situations in which the output of the current transformer is distorted.
- Slower than Desired Operation, the presence of GIC can easily build-up high levels of offset or remanent flux in a current transformer. The high GIC induced offset can significantly reduce the CT time-to-saturation for offset fault currents.

Most of the relay and protective system misoperations that are attributed to GIC are directly caused by some malfunction due to the harsh harmonic environment resulting from large power transformer half-cycle saturation. Current transformer response errors are more difficult to directly associate with the GIC event. For example in the case of CT remanence, the CT response error may not occur until several days after the GIC event that produced the remanence. Therefore, these types of failures are more difficult to substantiate.

CONCLUSIONS

As evident by the March 13th blackout in the Hydro Quebec system and transformer heating failures in the eastern US, the power industry is facing an immediate and serious challenge. The power industry is more susceptible than ever to the influence of geomagnetic disturbances. And the industry will continue to become more susceptible to this phenomenon unless concerted efforts are made to develop mitigation techniques.

Geomagnetic Disturbance Causes And Power System Effects

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SOLAR ORIGINS OF GEOMAGNETIC STORMS

The solar wind is a rarified plasma of protons and electrons emitted from the sun. The solar wind is affected by solar flares, coronal holes, and disappearing filaments, and the solar wind particles interact with the earth's magnetic field to produce auroral currents, or auroral electrojets, that follow generally circular paths around the geomagnetic poles at altitudes of 100 kilometers or more (1). The aurora borealis is visual evidence of the auroral electrojets in the northern [illegible] magnetic field that are termed geomagnetic storms when they are of sufficient severity.

SUNSPOT CYCLES AND GEOMAGNETIC DISTURBANCE CYCLES

On the average, solar activity, as measured by the number of monthly sunspots, follows an 11-year cycle. The present sunspot cycle 22 had its minimum in September 1986, and is expected to peak in 1990–1991. Geomagnetic field disturbance cycles do not have the same shape as the sunspot number cycles, even though they are cyclical. Figure 1 shows the nature of the sunspot numbers and geomagnetic activity

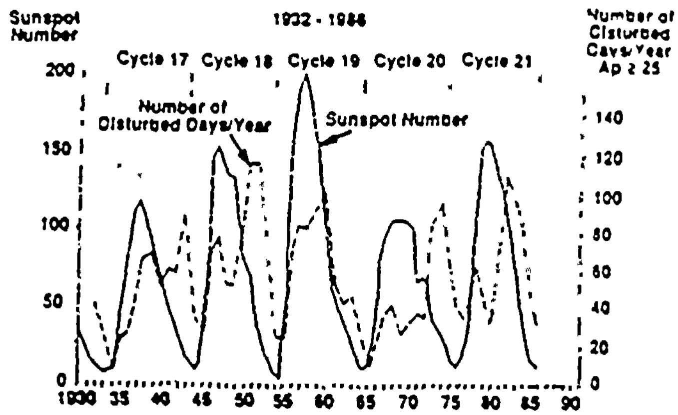

Figure 1. Variations of the Yearly-Averaged Sunspot Number and Geomagnetically Disturbed Days from 1932–1986.

cycles from 1932 to 1986 (2, 3). Note that the geomagnetic disturbance cycles can have a double peak, one of which can lag the sunspot cycle peak. While geomagnetic activity in the present cycle is expected to maximize in approximately 1993–1994, severe geomagnetic storms can occur at any time during the cycle; the K-9 storm of March 13, 1989 was a striking example.

EARTH-SURFACE-POTENTIAL AND GEOMAGNETICALLY-INDUCED-CURRENTS

The auroral electrojets produce transient fluctuations in the earth's magnetic field during magnetic storms. The earth is a conducting sphere and portions of it experience this time-varying magnetic field, resulting in an induced earth-surface-potential (ESP) that can have values of 1.2 to 6 volts/km (2 to 10 volts/mile) during severe geomagnetic storms in regions of low earth conductivity (4).

Electric power systems become exposed to the ESP through the grounded neutrals of wye-connected transformers at the opposite ends of long transmission lines, as shown in Figure 2. The ESP acts as an ideal voltage source impressed between the grounded neutrals and has a frequency of one to a few millihertz. The geomagnetically-induced-currents (GIC) are then determined by dividing the ESP by the equivalent dc resistance of the paralleled transformer windings and line conductors. The GIC is a quasi-direct current, and values in excess of 100 amperes have been measured in transformer neutrals.

POWER SYSTEM EFFECTS OF GIC

The per-phase GIC in power transformer windings can be

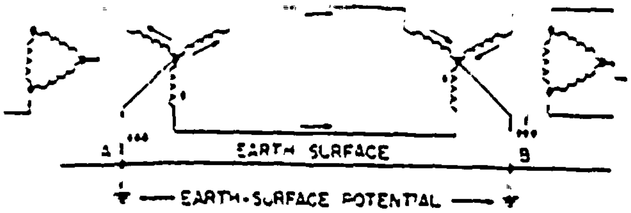

Figure 2. Induced Earth-Surface-Potential (ESP) Producing Geomagnetically-Induced-Currents (GIC) in Power Systems.

many times larger than the RMS ac magnetizing current, resulting in a dc bias of transformer core flux, as in Figure 3.

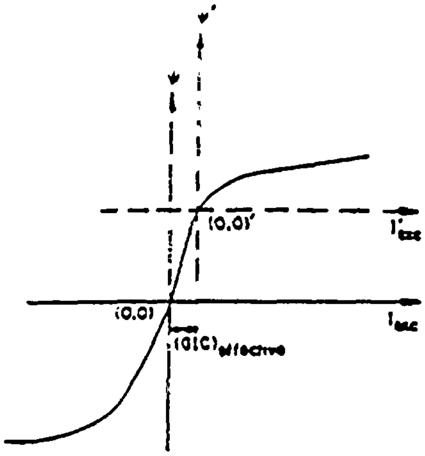

Figure 3. DC Bias of Transformer Core Flux Due to GIC.

The half-cycle saturation of transformers on a power system is the source of nearly all operating and equipment problems caused by GIC's during magnetic storms. The direct consequences of the half-cycle transformer saturation are:

- The transformer becomes a rich source of even and odd harmonics
- A great increase in inductive vars drawn by the transformer
- Possible drastic stray leakage flux effects in the transformer with resulting excessive localized heating.

There are a number of effects due to the generation of high levels of harmonics by system power transformers, including,

- Overloading of capacitor bands
- Possible misoperation of relays
- Sustained overvoltages on long-line energization
- Higher secondary arc currents during single-pole switching
- Higher circuit breaker recovery voltage
- Overloading of harmonic filters of HVDC converter terminals, and distortion in the ac voltage wave shape that may result in loss of dc power transmission.

The increased inductive vars drawn by system transformers during half-cycle saturation are sufficient to cause intolerable system voltage depression, unusual swings in MW and MVAR flow on transmission lines, and problems with generator var limits in some instances.

In addition to the half-cycle saturation of power transformers, high levels of GIC can produce a distorted response ... half-cycle saturation in current transformers, to cause relay misoperation (5).

REFERENCES

1. Akasofu, S.-I., "The Dynamic Aurora," Scientific America Magazine, May 1989, pp. 90-97.
2. Joselyn, J. A., "Real-Time Prediction of Global Geomagnetic Activity," Solar Wind-Magnetosphere Coupling, pp. 127-141, Terra Scientific Publishing Company, Tokyo, 1986.
3. Thompson, R. J., "The Amplitude of Solar Cycle 22," ... Radio and Space Services Technical Report TR-87-03, October 1987.
4. V. D. Albertson and J. A. Van Baelen, "Electric and Magnetic Fields at the Earth's Surface due to Auroral Currents," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89 No. 2, April 1970, pp. 578-584.
5. J. G. Kappenman, V. D. Albertson, N. Mohan, "Current Transformer and Relay Performance in the Presence of Geomagnetically-Induced-Currents," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 3, pp. 1078-1088, March 1981.

The Hydro-Quebec System Blackout Of March 31, 1989

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On March 13, 1989, an exceptionally intense magnetic storm caused seven Static Var Compensators (SVC) on the 735-kV network to trip or shut down. These compensators are essential for voltage control and system stability. With their loss, voltage dropped and frequency increased. This led to system instability and the tripping of all the La Grande transmission lines thereby depriving the HQ system of 9500 MW of generation. The remaining power system collapsed within seconds of the loss of the La Grande network. The system blackout affected all but a few substations isolated onto local generating stations.

Power was gradually restored over a nine hours period. Delays in restoring power were encountered because of damaged equipment on the La Grande network and problems with cold load pickup.

SYSTEM CONDITION PRIOR TO THE EVENTS

Total system generation prior to the events was 21500 MW, most of it coming from remote power-generating stations at La Grande, Manicouagan and Churchill Falls. Exports to neighboring Systems totalled 1949 MW of which 1352 MW were on DC interconnections. The 735-kV transmission network was loded at 90% of its stability limit.

SEQUENCE OF EVENTS

At 2:45 a.m. on March 13, a very intense magnetic storm led to the consequential trip or shut down of seven SVC's. Containing the impact of the event through operator intervention was impossible all SVC's having tripped or ceased to function within a one minute period.

A few seconds (8–9 s.) after the loss of the last SVC, all five 735-kV lines of the La Grande transmission network tripped due to an out of step condition. These line trips deprived the system of 9500 MW of generation and subsequently led to a complete system collapse.

tection while remaining four SVC's shut down by capacitor voltage unbalance protection. Analysis of voltage and current oscillograms taken at the Chibougamau site before the SVC trips showed the following harmonic contents.

Harmonic Order	AC Voltage at 735 kV	AC Current at 16 kV: TCR Branche	AC Current at 16 kV: TSC Branche
1	100%	100%	100%
2	7%	9%	38%
3	2%	12%	24%
4	3%	1%	16%
5	2%	5%	5%
6	1%	1%	16%
7	3%	3%	4%

Quasi-DC currents generated by the magnetic disturbance, saturating in the SVC coupling transformers are thought to be the cause for such a large second harmonic component of current in the TSC branch.

GENERAL OBSERVATIONS ON THE SYSTEM BEHAVIOR

The system blackout was caused by loss of all SVC on La Grande Network. Seven SVC tripped or stopped functioning. Prior to and during the event all the DC interconnections behaved properly. No relay false trips or misoperation of special protection systems were observed. Telecommunications were not affected. No equipment damage was directly attributable to GIC but once the system split, some equipment was damaged due to load rejection overvoltages.

REMEDIAL ACTIONS TAKEN

Since the event, the following actions were implemented:

- SVC protection circuits have been readjusted on four SVC's so as to render their operation reliable during magnetic storms similar work is being performed on the four remaining SVC's.
- Energy, Mines and Resource Canada now provides Hydro-Québéc with updated forecasts on the probability of magnetic disturbances. These forecasts are used by the System Control Center dispatcher to position the transmission system within secure limits.
- A.C. voltage asymmetry is monitored at four key locations on the system (Boucherville, Arnaud, LG2, Châtgeaguay). Upon detection of a 3% voltage asymmetry at any one location, the system control center dispatcher is alarmed and will immediately take action to position system transfer levels within secure limits if this hasn't already been done because of forecasted magnetic activity.

OPERATING LIMITS DURING MAGNETIC DISTURBANCES (AND ALERT SITUATIONS)

The following operating limits are now being applied:

- 10% safety margin shall be applied on maximum transfer limits.
- Maximum transfer limits shall not take into account the availability of static compensators deemed unreliable.
- Adjust the loading on HVDC circuits to be within the 40% to 90%, or less, of the normal full load rating.

Disturbances On Power Transformers

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This discussion addresses the effects of geomagnetic disturbances on power transformers. The primary effect is due to core saturation resulting from geomagnetically induced currents, GICs. Core saturation can impose severe temperature problems in windings, leads, tank plate and structural members of transformers and place heavy var and harmonic burdens on the power system and voltage support equipment. GIC's of 10 to 100 amperes are more than mere nuisances in the operation of power transformers, the manner of flow can result in saturation of the core and consequent changes in system var requirements, increases in harmonic current magnitudes, increased transformer stray and eddy losses, and problems with system voltage control.

GIC EFFECTS VERSUS CORE AND WINDING CONFIGURATIONS

Principal concerns in this discussion are for EHV systems with grounded Y transformer banks providing conducting paths for GIC and zero sequence currents. Core and winding configurations respond differently to zero sequence open-circuit currents and to GICs. Note: as used here, the term "open circuit" refers to tests performed with all delta connections opened or "broken." For example, the three-phase three leg core form transformers are less prone to GIC induced saturation than three-phase shell form transformers. But, both core form and shell form single phase transformers are susceptible to GIC induced saturation.

Winding and lead arrangements respond differently to GIC induced core saturation as well. For example, the current distribution within parallel winding paths and within low voltage leads depends upon the leakage flux paths and mutual coupling. Losses within windings and leads may change significantly under GIC-induced saturation owing to the change in magnetic field intensity, H, and the resultant changes in the boundary conditions for the leakage field path.

EDDY LOSSES IN STEEL MEMBERS

The changes in the magnetic intensity, H, and the magnetic boundary conditions resulting from the GIC excitation bias can increase the losses in steel plate, the losses for fields parallel to the plane of the plate increase nearly as the square of H. Note also that the level of losses increase approximately as the square root of the frequency of H, owing to the effect of depth of penetration. The magnetic field along yoke clamps and leg plates in core form transformers and in Tee beams and tank plate in shell form transformers closely matches the magnetic gradient in the core. Areas of the tank and core clamps are subjected to the winding leakage field. If the core saturates, the magnetic field impressed upon the steel members may rise ten to one hundred times normal due to the saturation and the effects of the leakage field. The losses in the steel members will rise hundreds of times normal, even under half-cycle saturation. On the steel surfaces, eddy loss density may rise ten to thirty watts per square inch, approaching the thermal flux density of an electric range element.

Surface temperatures rise rapidly with this thermal flux and can result in degradation of insulation touching the steel

ATTACHMENT 3