

CONTINUITY OF ELECTRIC POWER AT THE AGS

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ADDENDUM TO

AGS DIVISION TECHNICAL NOTE

No. 148

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J. Curtiss

December 14, 1978

Coincidence

Rumors to the contrary, I did not arrange the December 13th (lucky date!) Lab-wide power outage to demonstrate the reliability of our Accelerator Department diesel generators. Let me point out, however, that all our emergency generators performed perfectly during this period.

I feel somewhat like a Jonah. Brookhaven has had only one major power outage over the past thirty years. What is the probability of a second incident, simultaneously disabling both primary and alternate LILCO lines, within a week after distribution of a Tech Note praising our reliable LILCO service?

Discussion

BNL is supplied electric energy at 69 kV via two overhead transmission lines from LILCO's Brookhaven substation, located just outside the Lab boundary. LILCO provides two separate circuits to increase reliability, normally transferring power to the Lab on a "preferred" line, with an energized "alternate" line available. At about 1500 hours on December 13th, BNL lost power for about 100 minutes due to two separate troubles, one associated with each of LILCO's 69 kV buses.

/lsk

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AGS DIVISION TECHNICAL NOTE

No. 148

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J. Curtiss

November 8, 1978

Introduction

Continuity of electric power is important to uninterrupted operation of our accelerator. While our utility provides relatively continuous power, increased continuity of operation is provided by our ungrounded 480 volt distribution system which permits localizing and removing faults without interrupting the circuit.

Continuity of Electric Service

Interruption of power during the bottom of the ninth that blanks out the TV is an inconvenience. Interruption of power in a process can be catastrophic: a five minute interruption is barely acceptable in a molten glass plant, while a half hour interruption will solidify the melt and destroy the furnace.¹

The operation of an accelerator and its personnel safety and equipment protection systems is a process. An interruption of electric service to the AGS would cause, at worst, a single lost pulse scraped off on ring components, followed by shutdown of many operating systems. More frequently, a brief "flicker" will not cause motor dropouts (due to the addition of time delay relays across starter contacts), power supplies are reset by computer and our operation

continues. The loss of electric power will have a more severe impact on ISABELLE. Each power interruption will cause a beam dump.. Each subsequent ISABELLE refill will require interrupting the current AGS HEP program. Each ISABELLE refill, including acceleration to 400 GeV, will require at least half an hour.

We have at our Accelerator facility three classes of power. We receive power from tie-lines to our utility, we have emergency power systems, and we provide certain equipment with uninterrupted power.

Our LILCO 69 kV input power is remarkably reliable.² We are occasionally subject to interruptions caused by lightning strikes on the transmission line or, more infrequently, accidents to LILCO's transmission facilities. These brief interruptions are typically three cycles, a maximum of thirteen cycles, and occur with a frequency of about 25 to 30 per year. These brief interruptions aside, BNL has suffered no major loss of power over the last thirty years, with the single exception of the Northeast Power Blackout which occurred in November, 1965. Interestingly, LILCO was the first utility back on the grid.

We have interruptions of power more frequently in our own distribution system than we suffer from LILCO. To protect personnel and plant during a power outage, the AGS has one 150 kW and four 350 kW emergency diesel generator sets.^{3,4} These generators power "normal/emergency" loads such as roof fans and overhead door operators in areas likely to contain hydrogen, air compressors, mechanical vacuum pumps to maintain beam-line vacuum, sewage ejectors, and emergency lighting. The diesels are exercised once each week,⁵ and the alternator voltmeters show an assumed load within 4.5 seconds after a power failure. AGS maintenance is superb: during the Northeast Power Blackout, all AGS diesels started automatically and ran throughout the power interruption. In twenty

years of operation the AGS has had one emergency generator failure, detected during a weekly test run. The malfunctioning pump which transfers diesel fuel (cetane rating of 50) from below ground storage tanks to the elevated day tank was replaced within a few hours. Our one failure in an estimated 7000 operating cycles compares favorably with the expected 60 failures in 7000 cycles listed in reliability data published for use in evaluating systems in nuclear generating stations.⁶

Uninterrupted Power Supplies

Certain systems demand the application of continuous power. Obviously our computer systems require an uninterrupted power supply. Not so obviously, our personnel access security system requires an uninterrupted power supply. Our primary security system is hard wire and relays. ISABELLE's will be hard wire and relays. A power interruption which releases all line supervising relays in our fail-safe equipment will require resecuring the facility--an operation which could take hours. Certain other equipment is also supplied by sources of uninterrupted power. Various control systems that maintain the operation of vacuum or process-type equipment are so supplied, as are the emergency communications facilities provided by our public address system and interphone.

A rotating uninterrupted power supply (UPS) was installed⁷ at the AGS in 1966. The alternator and flywheel are driven by an electric motor or by a diesel started on power drop outs. The device is subject to the maintenance problems of any rotating equipment.

Solid state uninterrupted power supplies are available in small sizes for application on individual gear or in larger sizes to power significant loads in our facility. An AGS specification for a 100 kW UPS was written in anticipation of replacing our present rotating set.⁸ The ISABELLE Service Building will house one such UPS in an 18 x 35 foot basement room for the computer,

communication and security systems.⁹ Solid state uninterruptured power supplies have special application problems, including large battery banks with enormous short circuit capability and considerations of maximum available fault current. When connected to conventional distribution equipment, the UPS must deliver sufficient current to enable proper operation of conventional circuit disconnect devices. In addition, breaker let-thru fault current must not cause malfunction of the UPS system. These problems are unique enough to merit extensive review before a high-power solid state UPS is applied to power multiple circuits.

Low Voltage Power Distribution

The preceding discussion considered continuity of electric power to an entire plant. Interruption of power on one circuit in a parallel process, say a machine shop, is an inconvenience. Interruption of power on one circuit of a block-long newspaper press will halt production. The continuous operation of an accelerator depends upon the continuous operation of all of its parts. The operational probability of each part is an independent event, so the probability of machine operation is a product determined by the ability of each device to remain on-line.

Larger, more important equipment, is generally operated at higher voltages while incidental heaters, pumps, or other small gear is generally powered by 120/208 volt systems. Malfunctioning 120/208 volt equipment should be quickly separated from our distribution system. This is accomplished by fuses or circuit breakers through fault current drawn from our solidly grounded 120/208 volt transformers. It is more important to keep operational the equipment powered by our 480 volt circuits. This is accomplished by providing 480 volt distribution by an ungrounded delta system. While in all voltage classes solidly grounded systems are less expensive than any other type of grounding,¹⁰

on a solidly grounded system all faults are cleared immediately by opening the line. The principal virtue of an ungrounded system lies in the ability to alarm, identify and clear ground faults without circuit interruption.¹¹

Standard nominal 480 volt systems are referred to by other associated nominal voltages, depending upon one's point of view. If we allow for a voltage drop of about five percent between system components, then we have 480 volt transmission, 460 volt distribution and 440 volt utilization equipment. Insulation levels are commonly tested by subjecting the wiring to a voltage stress of "twice rated plus one thousand" per USASI, or 1920 volts for 460 volt equipment.¹²

While there is no code requirement for grounding 480 volt systems,¹³ the IEEE "Greenbook"¹⁴ discusses grounding of industrial and commercial power systems as a guide for the selection of grounding method, and provides references for further study. Our major interest is service continuity and, unfortunately, the "Greenbook" section addressing this topic¹⁵ is less than definitive. Several papers are referenced that may be used as guides and are among those cited in this report.

Ungrounded power systems are capacitively coupled from each line to ground with the system effective neutral normally within a few volts of ground. Early transmission systems were installed with their neutrals free until the phenomenon of "arcing grounds" became prominent in the eyes of utility engineers.¹⁶ An arcing ground fault that restrikes on voltage peaks acts like a rectifier and can store charge in the cable-to-ground capacitance between successive restrikes, thereby shifting the system neutral possibly by several hundred volts.¹⁷ By 1920 most systems were solidly grounded or grounded through resistance.

Subsequent transient-overvoltage comparisons between isolated and grounded systems has shown ungrounded systems to give higher overvoltages, but not of magnitudes formerly suspected. Operating records of remaining ungrounded systems after general grounding conversions in the early 1900's did not show greater equipment failure rates than grounded systems. This fact was obscured by improvements in apparatus while changeovers to grounded operation were taking place and net system performance improvements were being attributed to grounding. Many ungrounded 480 volt systems have a history of good continuity of service and freedom from multiple equipment failures or evidence of damaging overvoltages.¹⁸ There is as yet no preponderance of evidence to indicate that the ungrounded system is generally unsatisfactory from an overvoltage standpoint.¹⁹ Furthermore, 480 volt equipment is tested to withstand overvoltage stress of 1.92 kV for motors, 2.2 kV for switchgear, 4.0 kV for dry type transformers and 10.0 kV for liquid transformers.²⁰ Westinghouse notes that the relatively high insulation level relative to the rated voltage of low-voltage equipment explains the historical infrequency of overvoltage-failures in ungrounded systems.²¹

When Faults Occur

The term "ungrounded" is strictly one of definition, indicating no physical connection of any kind between the system neutral and ground.²² Since, however, there is distributed capacitance between the three phases of the system and ground, the system is effectively grounded through the capacitance. Charging current flows between each conductor and ground under normal conditions. In the event of a single line-ground fault, the corresponding line to ground capacitance is shunted out and the delta unbalanced with respect to ground. While a 480 volt system normal line-to-ground voltage is 277 volts, under a grounded phase condition the two remaining lines are at 480 volts with

respect to ground. Since all cable and apparatus on 480 volts systems is rated for 600 volt service, we should experience no failures by this mechanism. The lowest previously listed test voltage (1.92 kV for 480 volt motors) provides a 4.0 factor of safety,²³ even under a grounded phase condition.

Solidly grounding a system means that the occurrence of an accidental ground immediately takes the faulted circuit out of operation.²⁴ Bolted-fault short circuit currents may approximate 3-phase fault current if the system is solidly grounded.²⁵ Ground-fault currents are generally somewhat greater in normally grounded systems than in normally ungrounded systems.

In ungrounded systems practically no current flows when only one ground fault occurs.²⁶ (When two simultaneous grounds occur on different phases of an ungrounded system, impedance of the two faults involved would be in series. This limits the current since fault impedance is generally the major factor in determining the amount of fault current.) In a small isolated neutral installation, the ground-fault current for a single line-to-ground fault may be well under 1 ampere while the largest plant containing miles of cable may produce not more than 20 amperes of ground-fault current.^{27,28,29}

Since the full current for single line-ground faults on an ungrounded system is very small, overcurrent relays cannot be used for fault detection.³⁰ Voltage relays will detect the presence of the voltage unbalance produced by the fault, but will not selectively determine its location in the system.

Fault detectors in all 33 AGS substations with ungrounded delta 480 volt systems are annunciated at a central panel. In accordance with long standing procedures,^{31,32} all ground alarms are checked out immediately. The two to four ground faults we acquire each year on feeders are isolated within a few hours. Once, a conscious decision was made by AGS power engineers to run one additional

day with a ground on a system rather than interrupt a particular experiment--a degree of freedom that is nice to have available.

System Reliability

The "Greenbook" provides a reference to a paper by H. B. Thacker, a Westinghouse distribution engineer, who concludes³³ that "in general the grounded system is preferable, but that in plants where it is required, the ungrounded system can provide an additional valuable degree of service continuity under proper operation and maintenance conditions." A graph³⁴ relating a number of grounds per year to probable circuit outage time indicates that if grounds are removed in a short time after occurring, the number of grounds experienced per year must be quite high before the grounded system shows less outage time than the ungrounded system. For our typical two to four feeder grounds per year, we should experience an outage of 0.00001 years per year (about 5 minutes) vs. about 5×0.001 years per year (about 44 hours) outage should we adopt a grounded distribution system. Minor vacuum pumps, compressed air dryers, cooling tower pump motors and other equipment on branch circuits can provide a grounded-phase condition of up to two occurrences each month. Even considering this rate, we should experience an outage of about 5×0.0001 years per year (about 4.4 hours) on our ungrounded delta system. Repeating here the author's observation: "If we assume ten grounds per year on the grounded system, the total outage time given by the curves is 0.01 years per year. The ungrounded system can experience about 70 grounds per year before accumulating as much outage time as the grounded system. The curves indicate that the occurrence of ground faults must be 400 or 500 times per year before the ungrounded system can stand no more grounds than the grounded system without sacrificing continuity."

Perhaps even more spread out than our facility and exposed to more severe operating conditions are installations at major industrial plants. During a discussion following presentation of Thacker's 1954 paper, E. L. Anderson, Electrical Department Superintendent at the Johnstown Plant of Bethlehem Steel³⁵ reported on their operating experience. Operating experience on their ungrounded 2300, 440 and 220 volt systems has been entirely satisfactory and they "are of the opinion that outages to the operating units have been greatly reduced due to operating ungrounded."

The Johnstown plant still runs their thousands of motors, some of 5500 HP, on ungrounded delta distribution systems.³⁶ While Anderson retired in 1964, the present staff feel that their ungrounded distribution provides greater operational reliability and new equipment is still being ordered and installed ungrounded.

Any power system will experience overloads and short circuits. An overload is detected and cleared usually within ten seconds. A short circuit, a fault condition, will be cleared in about 50 msec by the 30 to 40 thousand amperes either a grounded wye or double faulted delta can supply. As described above, an ungrounded delta distribution system will have significantly fewer outages since in any distribution system incidents of double line-to-ground faults are fewer than the total number of line-to-ground shorts.

The Arberry paper³⁷ cited in the "Greenbook" reports extensive damage from a bad fault on an ungrounded system. The substation involved was unattended and equipped with reclosing relays on the main feeder breakers in an effort to improve service continuity. Several thousand dollars damage was reported after three reclosures on an existing fault.

The Accelerator Department does not have automatic reclosers. Should a substation breaker trip, the fault is investigated and a maximum of one manual reclosure permitted without extensive circuit segregation and troubleshooting.

Arberry reports his experience to be: "The first ground remains on the system because we cannot open the feeder breakers to hunt it. The result is that the system operates with two phases at line-to-line voltage to ground, and the operating electrician hopes that no other grounds occur before he has an opportunity to find the first one." His plants were changed to a grounded wye distribution system, and the decision to open branch circuits was then made automatically rather than by convincing management. He reports that his electricians are enthusiastic about the change.

In Addition

Two financial considerations should be considered in continuing and extending our ungrounded delta system. The Accelerator Department owns many very large experimental magnet power supplies, each powered with a delta-connected primary. A ground within a power supply could cause extensive damage should the supply be connected to a grounded distribution system, while the same short could be harmlessly detected, disconnected and repaired when connected to an ungrounded system. These supplies represent a valuable departmental resource for our ever-changing experimental programs. Concurrent with the shifting programs are shifting demands for experimental power. We possess 33 substation transformers, each with delta-connected secondaries, each 2,500/3125 KVA, each worth about \$100,000.

Finally, it is difficult to argue with demonstrated success. The AGS has run ungrounded delta 480 volt distribution systems for the last twenty years, and the Cosmotron since twelve years before that.

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Distribution:

A.D. Engineers

Dept. Administrators

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