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Harmonic Effects of Solar Geomagnetically Induced Currents on the Electrical Distribution System in Nuclear Power Plants[1]

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ABSTRACT

Most previous analysis on the effects of geomagnetically induced currents (GIC) on electric utility systems has concentrated on steady-state phenomena, with the main interest in the generator step-up transformer and the off-site power system. This paper begins to investigate the possible effects that a GIC event might have on the power plant itself, by examining the harmonic distortion that could exist at various voltage levels in the on-site distribution system.

This study was carried out using an EMTP (ElectroMagnetic Transients Program) computer simulation of an electrical distribution system of a typical nuclear power plant. Elements of both the on-site and off-site power systems are included for completeness. The simulation employs detailed three-phase models of all system components represented, including distributed-parameter transmission line models in the off-site system, saturation characteristics for all main transformers, and rotating machine models of major motor loads. The simulation also models the essential features of both the nonsafety-related and the safety-related portions in the on-site distribution network.

Studies were performed for various operating configurations and conditions to determine harmonic levels in several parts of the distribution system. Results varied widely with station configuration and operating mode, but total harmonic distortion (THD) ranging from 4 to 11% was observed in some sensitive low voltage busses. The safety-related busses appear to be more susceptible to high harmonics during normal station operation, due to typically light loading conditions. Harmonic levels generally increased with escalating GIC, but not in a linear fashion, since the frequency spectrum of the transformer excitation current also shifts significantly with changing GIC. Very high GIC may actually reduce the higher order excitation harmonics, which in turn can reduce the THD in the distribution network. A major factor in determining the on-site harmonic levels is the high-voltage transmission line, since its harmonic impedance varies sharply with frequency, as determined by the line length and any external impedance. Certain line lengths can produce a very high impedance at one or more of the harmonics generated by transformer saturation, thus forcing large harmonic currents into the on-site network.

Future work will include refined load models, particularly at the lower voltage levels, in order to assess the effect of high harmonics on sensitive control circuits. Work will also evaluate the compounding effects of major system transients (e.g. loss of load or large motor start-up) on plant behavior during GIC events. Finally, the simulation will be used to determine the effectiveness of various GIC mitigation schemes to minimize the impact of in-plant disturbances.

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INTRODUCTION

Transient disturbances in the earth's magnetic field, caused by the interaction with auroral currents (electrojets), can induce electric potential gradients across the earth's surface. The auroral currents are created by complex solar magnetic disturbances [1-3]. The induced potentials, known as earth surface potentials (ESP), are due to portions of the earth's non-homogeneous surface being subjected to the time-varying magnetic field. ESP magnitudes can range from 1.2-6 V/km (2-10 V/mile). They act like quasi-dc voltage sources impressed between the grounded wye (Y) neutrals of transformers at opposite ends of power transmission systems. The results of ESP are geomagnetically induced currents (GIC), which are quasi-dc currents that can have magnitudes many times greater than the RMS ac exciting currents in transformer windings. GIC magnitudes greater than 100 A have actually been measured in transformer neutral leads [4,5].

There are three factors which combine to roughly determine the likelihood that a given power system will experience GIC and its related effects. The first factor is the geological rock formation on which the transmission lines are situated. The resistance posed by igneous rock formations can be thought of as being in parallel with that of the power lines. Because igneous rock has a high resistivity, transmission lines situated on such formations, which have much lower resistances, will allow the GICs to flow through with greater ease. The latitude of the power lines is another factor which determines GIC susceptibility. Lines in the higher northern latitudes, closer to where the aurora appear, are more apt to be susceptible to GIC currents. Finally, the direction the power lines run determines to a lesser degree the magnitude of GIC currents. If the previously mentioned electrojets are idealized as east-west line currents they will induce an ESP in the east-west direction; thus, power lines running east-west may experience higher GICs than those running north-south.

The primary effect that GIC has upon transformers is known as half-cycle saturation. The major consequences of half-cycle saturation are: (1) the potential for drastic stray leakage flux and excessive localized heating; (2) a rich source of even and odd harmonics; and (3) a significant increase in inductive VARS drawn by the transformer. Harmonics, due to transformer saturation, can affect the entire power system in several ways, for example: overloading of capacitor banks, misoperation of relays, and higher recovery voltages for circuit breakers. Many studies have been conducted on the effect of GIC on transformers [6,7], and nearly all of them report potential for crippling damage to the transformer.

Whether the effects of GIC are restricted to the transmission system or not, the potential for impact on a nuclear power station already exists. A loss of offsite power is an example of how GIC can indirectly affect a nuclear plant. A great deal of concern was recently generated over an incidence at Hydro Quebec on March 13, 1989, where the entire province was blacked out as a result of GIC [5]. In total, 21,500 MW of generation was lost. Nine hours later, 17 percent of the province was still without service.

Occurrences at Salem Unit 1, Hope Creek Unit 1, and Three Mile Island Unit 1 have also raised concern over the potential for trouble. Moreover, it is expected that the disturbances which cause GIC will reach their peak activity sometime between 1992 and 1995. Current trends are also indicating that this may be one of the highest peaks in recent decades.

The main purpose of the work reported in this paper was to investigate the manner in which GIC can affect the in-plant electrical distribution system, and to quantify such GIC effects as manifested on the distribution system busses at different voltage levels. A typical electrical distribution system inside a nuclear power plant was modeled in detail using the ElectroMagnetic Transients Program (EMTP). Parametric studies of the subject plant model were performed to simulate the GIC effects on various electrical busses at all voltage levels, including the 120 volt ac safety busses.

COMPUTER SIMULATION STUDIES

Detailed study of power system transients and abnormal steady-state conditions usually are highly complex and nonlinear by nature, and do not generally lend themselves to theoretical analysis. Instead it is often necessary to use simulation techniques to investigate these conditions. Problem areas of this type include system overvoltages (such as lightning and switching surges), fault currents, non-sinusoidal waveforms (such as harmonics and inrush currents), electromechanical oscillations, and various other types of transients.

EMTP is recognized by the power industry as the most comprehensive digital simulation program specifically designed to study power system transients. It has a structure and library of component models well-suited for various types of power system investigations. It has been used in many previous studies ranging from high-frequency phenomena such as switching surges to low-frequency phenomena such as subsynchronous resonance. EMTP usage generally falls into two main categories: system design and analysis of operating problems. System design includes areas such as insulation coordination, specification of equipment ratings, protective device specifications, relay design, control system design, and harmonic filter selection. Operating problems include system outages, equipment failures, harmonics and resonance, fault analysis, voltage instability, and many others.

EMTP Simulation Model

Figure 1 is a one-line diagram of the initial EMTP simulation model of a typical nuclear power plant distribution network and offsite transmission system. The simulation is actually a fully detailed three-phase representation of the system. The generator is represented by either a simple voltage-behind-subtransient-reactance, as shown in the diagram, or it can be represented by a more detailed d-q axis model (Park's equations) with mechanical system and exciter included. Preliminary comparisons between these two approaches showed very little difference in results for problems involving GIC-induced harmonics. Therefore, the simpler generator model is preferred, since it requires much less computer time to implement. If later transient studies require the more detailed generator model, it is ready and available for immediate use. The delta-grounded-wye generator step-up transformer (T1) is modeled in full detail, with core loss, winding loss, leakage inductance, and magnetic saturation all included. The step-up transformer is connected to the transmission system, represented by a single overhead line model connected to an infinite bus. It can easily be expanded later to include more transmission lines if necessary. The overhead line can be modeled in various forms: equivalent PI section(s), a constant-frequency distributed-parameter model, or a frequency-dependent distributed-parameter model. The length of the line, which could have an important influence on system behavior, may also be easily varied in each of the options.

As Fig. 1 shows, this initial simulation attempts to model the essential features of both the nonsafety-related and safety-related systems, without over-complicating the picture. It is important initially to keep things as simple as possible until the basic mechanisms are better understood. This is especially important in using a transients program like EMTP, in order to minimize the computer time spent for each run. Many computer runs are necessary to understand the problem and to acquire enough simulation data for a meaningful evaluation.

Figure 1 shows the system configuration for normal operation, where the normal station service transformer (T2) feeds the nonsafety-related network and the reserve station service transformer (T3) feeds the safety-related, emergency system. The system configuration can easily be changed for other modes of operation by changing the status of the various switches available in the simulation, or by manually changing node names in the EMTP data input file. Both the normal and the reserve station service transformers are represented in full three-phase, three-winding detail, with losses, leakage reactances, and magnetic saturation included. Because of typical system symmetry it is necessary to model in detail only one safety train circuit in the emergency system, and only one of the two 13.8 kV nonsafety-related busses. Note that, although the two systems are not coupled in the plant, there is potential coupling at the transmission level in the offsite power system. The coupling may be important in GIC studies, therefore, it is necessary in this mode of operation to simultaneously represent the nonsafety-related and the safety-related systems together in the simulation.

For the nonsafety-related system, the normal station service transformer (T2) feeds 13.8 kV busses B001 and B003. Bus B003 supplies two 12,000 hp pump motors, a static equivalent of several other motors, and a static equivalent of several 600 V loads connected through 13.8kV/600V delta-wye transformers. The 12,000 Hp motors are modeled in full transient detail as three-phase rotating machines, including losses, magnetizing current, and rotor/load inertia. Bus B003 also feeds two 4.16 kV busses, B013 and B015, through a delta-wye transformer (T4). These busses are loaded with static equivalents of several additional motors, and B015 also feeds a 600 V bus, called BUS6 in the EMTP data file, through another delta-wye transformer (T6). BUS6 in turn supplies a 270 kVA static equivalent load, and feeds a 120/240 V bus, B120N, through a single-phase transformer (T7). This particular 120/240 V bus supplies power to fire protection panels and miscellaneous control circuits.

For the emergency system, the reserve station service transformer (T3) 4.16 kV winding supplies the main bus, BUSD. BUSD in turn feeds several 600 V busses and distribution panels, which are represented by the equivalent bus B600 fed by delta-wye transformer (T5). B600 feeds a static equivalent 535 kVA load, and supplies a 120 V bus, B120E, through a 25 kVA single-phase transformer (T8). B120E is an emergency relay supply panel.

The first objective of the simulation model shown in Fig. 1 is to perform a preliminary evaluation of GIC-induced harmonic magnitudes at various levels and locations in the system, from the station service transformers down to the low voltage control busses. In order to minimize initial model complexity, careful attention was given to bus selection, model parameters and system configuration. Later work will focus on more detailed models, particularly in the critical lower voltage areas, in order to investigate the effect of harmonics on the safety-related control and protective functions. Another objective of this and future simulations is to investigate the compounding effects of normal station transients superimposed on GIC disturbances. The initial simulation model is adequate for some studies of this type, but will again require further detail, particularly in the lower voltage control-related areas.

Input data required by EMTP, which are detailed parameters for each component in the system, were derived from available public documents and power engineering handbooks [8,9]. This was a very time-consuming process, but eventually resulted in a fairly realistic set of system data. Any remaining uncertainty in data can be mitigated by making multiple studies over a reasonable range of the uncertain parameter. Certain data were derived or assumed for the key system components, including the 345 kV overhead line, generator reactance, transformer parameters and saturation characteristics, motor parameters and load data. Future studies should use actual plant component data to facilitate a more detailed and accurate model.

Simulation Study Results

The initial phase of this study involved the steady-state simulation of the model shown in Fig. 1 using the nominal system data. In the results that follow, this mode of operation is referred to as "normal operation" for the system. In this mode the normal station service transformer feeds all nonsafety-related loads, and the reserve station service transformers feed the safety-related loads. It is important to note that in this mode of operation, the normal station loads on the nonsafety-related busses are much greater than the loads on the safety-related emergency busses. As later results will show, this fact makes the emergency system in this mode more susceptible to large harmonic voltage distortion than the nonsafety-related loads. This is primarily due to its relatively high impedance to current flow, including harmonic currents.

Figures 2 - 5 show sample recordings of steady-state operation and a Fourier analysis of the corresponding waveforms in the normal system mode. This first group of recordings was taken for a total GIC of approximately 100 A. Most of this dc current flows through the HV neutral of the generator step-up transformer, although a portion of it also flows through the HV neutral of the reserve station service transformer. This is a consequence of the coupling of the system at the offsite transmission level, where the local 345 kV substation interconnects the 345 kV system and the 115 kV system. Figure 2 shows the three-phase magnetizing currents in the generator step-up transformer. In the simulation these are referred to the 24 kV delta winding on the generator. The peak saturation currents are well over 2000 A, with phase A being the largest, due to a slightly unbalanced system. This compares to a normal unsaturated magnetizing peak of about 137 A. The 100 A GIC is related to the average value of the saturated current wave in Fig. 2 by the winding turns ratio of the transformer, which in this case is

n_1:n_2=345/√3:24. If the saturated current pulse is approximated by a half sine wave, a rough approximation for the peak magnetizing current is given by

$$I_{pk} = \frac{\pi}{2} \frac{n_1}{n_2} I_{neut} \tag{1}$$

where I_{pk} is the peak magnetizing current and I_{neut} is the average neutral (GIC) current. Equation (1) is very conservative for narrow saturation waves like shown in Fig. 2, since this wave has a considerably smaller area than a half sine wave.

Similar results were also obtained for the three-phase magnetizing currents in the reserve station service transformer. Although a small proportion of the total GIC also flows in the HV grounded neutral of this transformer, the magnetizing currents seem unexpectedly high. However, this is explained approximately by equation (1) realizing that the magnetizing current is referred to the 4.16 kV winding, which makes the effective winding turns ratio about six times that of the generator step-up transformer. This is another reason that in the normal operating mode, the emergency system, which is fed by the reserve station service transformer, may be more sensitive to GIC-induced harmonics. The peak saturation current in this transformer is over 1500 A, compared to the normal unsaturated peak current of about 142 A.

For the normal mode of operation the saturation current waves represent system input sources that produce harmonics in the transmission line and also in the station distribution network. Although not always the case, the harmonic levels produced are generally proportional to the magnitude of the transformer saturation currents. The magnitude of these saturation currents depend on the average neutral current, which in turn, depends mainly on the offsite line and ground resistances and the ESP (earth surface potential) produced by the geomagnetic disturbance. On the other hand, the resulting harmonic current flow depends on the impedances of both the onsite and the offsite systems. As shown in Fig. 6, the saturated transformer can be thought of as a current source of harmonics that feeds two parallel branches, representing the onsite and offsite systems. It is clear from this simple model that the distribution of harmonics in the station will depend on many factors, including the characteristics of the transmission network. For example, a low line impedance could result in the majority of induced harmonics being bled off into the transmission system, whereas, a resonant condition could have the opposite effect at one particular frequency.

Another major factor in determining station voltage harmonics is the station loading. Light station loading implies a high impedance to both fundamental and harmonic currents, which in turn means relatively low harmonic voltage drops through the various transformers leading to the sensitive low voltage circuits. Therefore light loading conditions may produce the most severe harmonics at the lower voltage levels. Of course, the original source of these harmonics is the nonlinear saturation current, which in itself is not a fixed quantity. For example, as the saturation level increases, the magnetizing current pulses change shape, typically becoming broader at the base, appearing more like a half sine wave. This has some effect on the frequency spectrum, and therefore, the frequencies of harmonics in the station will also vary with saturation level.

Figure 3 shows the frequency spectrum of the A-phase magnetizing current in the generator step-up transformer, and a similar spectrum was also obtained for the reserve station service transformer. In addition to the normal odd harmonics produced by symmetrical saturation, there are some very strong low order even harmonics that can be particularly troublesome. Although the triplen harmonics will be effectively blocked by the delta windings, the other strong lower order harmonics could propagate into the station circuits. For the 4.16 kV voltages on the LV winding of the reserve station service transformer, the triplen harmonics are effectively blocked from entering the station by the delta winding, but several other harmonics have not been attenuated significantly by the transformer, mainly due to the very light loading of this emergency circuit. The THD at this voltage level was measured at 3.97%. Figure 4 shows the voltage waves at the selected 120 V points in the simulation. The voltages in the nonsafety-related system appear nearly sinusoidal with very little visible distortion, while the emergency system voltages are much more distorted. Again this is due to the significant difference in loading between the two systems, which accounts for the filtering effect of the transformers in the nonsafety-related system. Figure 5 shows the frequency spectrum for the 120 V emergency system voltage shown in Fig. 4. Comparing this with that of the reserve station service transformer indicates very little filtering between the 4.16 kV and the 120 V level, with all significant harmonics showing very little reduction, and the THD remains over 3% at the low voltage level.

In order to explore the effects of higher transformer saturation currents, studies were also performed at 200 A and 500 A GIC levels. Figure 7 summarizes the effect of different GIC magnitudes on the harmonic levels at various points in the simulated system. The THD is plotted versus transformer neutral current for the three cases considered. As indicated in the graph, harmonics generally increased with neutral current at low to moderate levels of GIC, but tended to fall off at higher GIC levels, due mainly to the shift in frequency spectrum of the transformer magnetizing currents. It is difficult to generalize from these results, which were obtained for one specific system in a specific operating condition. However, this example does reveal the complexity of the problem, and that it may be inaccurate to assume that harmonic levels are always proportional to the GIC magnitude.

The next study considered in the simulation, concerned the coupling at the transmission level of the nonsafety-related system with the emergency system. In the previous case the 115 kV offsite supply, which feeds the emergency system through the reserve station service transformers, emanates from the local 345 kV substation, which also connects to the main 345 kV line out of the plant. Since the previous case study revealed the saturation sensitivity of the reserve station service transformer to relatively low GIC levels, it was deemed to be prudent to make further studies assuming that no coupling exists that would limit dc neutral current in the reserve station service transformer. Therefore the simulation was modified to include a separate 115 kV overhead line to this transformer, supplied from an independent source. The transmission line was assumed to be 50 miles long with typical tower configuration and conductor data. The GIC level in both the step-up transformer and the reserve station service transformer was assumed to be 100 A.

Figure 8 shows the magnetizing current in the reserve station service transformer for this new case, which is nearly double the previous case with a total GIC of 100 A. Figure 9 shows the frequency spectrum for the A-phase magnetizing current pulses, which again is a rich source of low frequency harmonics. Figure 10 shows the reserve station service transformer voltages on the 4.16 kV side, and Fig. 11 shows the frequency spectrum of the A-phase waveform. The voltage waves are highly distorted, and the spectrum plot confirms this observation showing a variety of strong harmonics present in the wave over a wide frequency range. We see this spectrum is quite different than in the previous case study. The overall harmonic level is also significantly larger than before, with a THD of 8.93%. Fig. 12 shows the normal and emergency system voltages at the selected 120 V busses, and again the emergency system voltage is highly distorted. This is also verified by the frequency spectrum plot of this voltage, shown in Fig. 13, which reveals a wide range of relatively strong frequency components. The spectrum in Fig. 13 is similar to that in Fig. 11, with only a slight attenuation of harmonics from the 4.16 kV level to the 120 V level. The overall harmonic level is also only slightly reduced, with a THD of 8.23%.

The next case study considered was for plant operation in one stage of the start-up mode. In this case it was assumed that the normal station service transformer is disconnected from the normal onsite distribution system. Instead, the reserve station service transformers are assumed to carry the entire onsite load, including the nonsafety-related and the emergency system loads. Therefore, the only source of harmonics in the plant are from a GIC flow through the grounded neutrals of the reserve station service transformers. Even if GIC flows through the step-up transformer there is no path for harmonics to enter the station. Referring to the simulation model in Fig. 1, this study was performed by opening the breakers from the normal station service transformer (T2) to the 13.8 kV busses B001 and B003, then closing the NO breaker from the reserve station service transformer (T3) to bus B003. One additional feature was also added to the simulation: a 0.15 pu source reactance was placed in series with the remote voltage source at the far end of the 345 kV line. This is to model the finite short circuit capacity of the remote source. It may have the effect of increasing harmonic levels in the station, by further blocking harmonic current flow into the transmission system.

For the assumed start-up mode of operation, the reserve station service transformer magnetizing currents were higher than previous cases, with a GIC of only 50 A at the 345 kV transmission level. Since the GIC appears at this high voltage level, and the magnetizing current is referred to the 4.16 kV winding of the transformer, the current pulses are higher for the reserve station service transformer. Based on previous observations, this would seem to imply a potentially high harmonic level at the lower frequencies, unless some resonant condition develops at higher harmonics. Simulation results verify this for the 4.16 kV side of the reserve station service transformer, and the spectrum reveals several low frequency components and a partial resonance at the tenth harmonic. This is probably due to an interaction between the station impedance and the transmission line. The THD at the 4.16 kV voltage level is 4.94%. Figure 14 shows normal system and emergency system voltages at the 120 V level. Again the emergency system voltages are visibly distorted. Figure 15 shows the frequency spectrum of the 120 V emergency system voltage, which has similar characteristics as the 4.16 kV level. This again indicates very little harmonic attenuation through the lightly-loaded emergency system.

Frequency Analysis of Nominal Case Studies

EMTP simulation studies and Fourier analysis of the waveforms taken from these simulations have shown that the harmonic levels present on the plant distribution busses depends on several factors. These include the magnitude of the GIC, the loading of the distribution busses, the transformer saturation characteristics, and the transmission line configuration, line length and magnitude of remote source impedance. Among these factors the transmission line characteristics may be the most important in determining both the magnitude and dominant frequency of harmonic currents forced into the station circuits. This is best explained by referring to the circuit analogy of the process suggested by Fig. 6. The step-up transformer and/or the reserve station service transformer, whichever is fed through grounded wye-connected windings from the line side, acts essentially as a current source of various harmonic frequencies. These harmonic currents may flow into either the transmission system or the station distribution system, depending on the relative impedances of the two sides of the circuit. The effective harmonic current source amplitude falls off sharply with frequency, as both the distribution circuit impedance and transmission line impedance generally increase with frequency. However, the transmission line may reach its resonant point near one of these higher harmonics, which results in a very sharp increase in line impedance. This causes most of the harmonic current at that frequency and nearby frequencies to be forced into the distribution system. The transmission line thus acts like a frequency-sensitive valve, which acts to either drain off and dissipate harmonic currents in the transmission network, or block these currents and force them into the station circuits. Once the harmonic currents enter the distribution network, the harmonic voltage levels at the various busses depends on the relative circuit impedances. The dominant impedances in the distribution network are inductive, due to the various transformer leakage reactances and the major loads. The network impedance therefore increases with frequency, and is generally higher under light loading conditions. Thus the harmonic voltages can be quite high at high frequencies, even if harmonic current injection is low, especially for light loads.

In order to test this theory, the Frequency Scan feature of EMTP was used to compute transmission line impedance functions, as viewed from the excitation branch of the step-up transformer and/or the reserve station service transformer. These impedance functions were computed using the complete system models used in the previous time simulations, by injecting harmonic currents into the transformer excitation circuits, then measuring the harmonic voltages produced at the terminals of the transmission line. Since these impedance functions are computed using the total current injection, including that flowing into the distribution network, they are not true measurements of the line impedance, but serve only as a convenient measure of the blocking ability of the line over the frequency spectrum of interest.

Figure 16 is a plot of the 50 mile, 345 kV transmission line impedance function versus frequency, for normal station configuration and nominal system parameters. This plot shows a relatively sharp resonance near the 19^{th} harmonic, which explains the strong presence of this frequency component. Figure 17 shows a plot of the transmission line impedance functions versus frequency, for the 50 mile 345 kV line and the 50 mile 115 kV line, for the case of separate 115 kV service with nominal system parameters. The 345 kV line still resonates near the 19^{th} harmonic, while the 115 kV line produces an even sharper resonance slightly above the 15^{th} harmonic. In this case the 19^{th} harmonic resonance has little effect on the distribution system, because very little excitation current is produced at that frequency. Also the potential effect of the 15^{th} harmonic resonance, which is a multiple of the 3^{rd} harmonic, is mitigated by the delta windings present in nearly all major transformers. However, the combined impedance of the two lines does produce significant harmonic flow into the station distribution system at several notable frequencies. This is corroborated by the Fourier analysis of the simulated waveforms of the reserve station service transformer voltage and the 120 V emergency system voltage, as shown in Figs. 11 and 13.

Figure 18 shows a plot of the transmission line impedance function versus frequency, for the 50 mile 345 kV line, during station start-up mode with nominal system parameters and remote source impedance included. The 345 kV line now exhibits a double resonance near the 9th and 10th harmonics. In this case the 9th harmonic resonance has little effect on the distribution system, because it is a multiple of the 3rd harmonic, and is mitigated by the delta windings present in the various transformers. However, the 10th harmonic line impedance does force significant harmonics into the station in this mode of operation. This is again corroborated by the Fourier analysis of the simulated waveforms of the reserve station service transformer voltage and the 120 V emergency system voltage.

Extended Case Studies

From the above discussion it is clear that the transmission line configuration and its resonant frequency play a significant role in determining harmonic levels in the station distribution circuits. Moreover, the line length is the main parameter that determines the resonant frequency for a given line type. Since line length is generally not an adjustable parameter, but is determined by geographic conditions, various resonant frequencies are possible. The situation is further complicated since most transmission systems are interconnected networks, not a single line, therefore several different resonant frequencies are possible. Furthermore, it is possible that one or more of these resonant frequencies in the transmission system may be excited by a relatively strong harmonic component of the transformer excitation current. In the following case studies, the line lengths of the transmission system were modified from the original studies performed earlier, in order to further illustrate the influence of this important parameter.

Figure 19 shows the impedance function for the 345 kV transmission line with the line length changed to 49.07 miles and no remote source impedance. Otherwise, the system is in the normal operating mode with nominal system parameters, like the case shown in Fig. 16. In this case, however, the main resonant peak is tuned exactly to the 19th harmonic, which should result in increased harmonic levels at that frequency. Further simulation studies verified this in the reserve station service transformer voltage (4.16 kV), and the 120 V normal and emergency system voltages, with normal station operation and 100 A GIC. The apparent waveform distortion and the THD is significantly increased from the earlier case at both these voltage levels.

For the next case, the impedance functions for the system with a 50 mile 345 kV transmission line, and a separate 115 kV line with the line length changed to 69.55 miles were considered. Otherwise, the system is in the normal operating mode with nominal system parameters, like the case shown in Fig. 17. The resonant peak of the 115 kV line has moved from near the 15th to the 11th harmonic, which should result in significantly increased harmonic levels, especially since this new resonant frequency will not be affected by the transformer delta windings. Further simulation studies verified this in the reserve station service transformer voltage (4.16 kV), and the 120 V normal and emergency system voltages, with normal station operation and 100 A GIC. The dominant harmonic due to the changed length of the 115 kV line is the 11th, although there still remains significant levels of other harmonics. The apparent waveform distortion and the THD (about 12%) is also significantly increased from the earlier case at both voltage levels.

Another case considered a modified impedance function for the 345 kV transmission line for the start-up mode of operation, with the line length changed to 42.38 miles. The system is operating with nominal system parameters, including a remote source impedance, like the case shown in Fig. 18. In this case, with the shorter line, the main resonant peak moves up to the 11th harmonic with a secondary peak at a slightly lower frequency, which should result in increased 11th harmonic levels in the station. Again, simulation studies verified this in the reserve station service transformer voltage (4.16 kV), and the 120 V normal and emergency system voltages, with the start-up mode of operation and 50 A GIC. The dominant harmonic due to the changed line length is moved up from the 10th to the 11th. The visible waveform distortion and the THD is also significantly increased from the earlier case at both these voltage levels.

CONCLUSIONS AND FUTURE WORK

EMTP (ElectroMagnetic Transients Program) simulations were performed to investigate the onsite effect of geomagnetic induced currents (GIC) on nuclear power plant operation. Models were developed to simulate the behavior of a typical electrical distribution system within the plant for the nonsafety-related and the safety-related (emergency) circuits. The offsite transmission system was also modeled. Studies so far have concentrated mainly on steady-state harmonic effects at the various voltage levels in the system. Voltage harmonics levels have been evaluated for several system configurations and operating conditions. Total Harmonic Distortion (THD) levels ranging from 4 to 11% have been observed in the simulation, at selected low voltage busses, for certain assumed conditions and GIC levels. The emergency busses appear to be more susceptible to high harmonics due to the normally light load conditions. The magnitude of harmonic currents forced into the station distribution system depends on a number of factors, such as GIC magnitude, distribution bus loading, transformer saturation characteristics, but the high voltage transmission line(s), particularly line length, appears to be a key parameter in determining harmonic levels.

It is probably too early to reach any general conclusions from these preliminary results. More exhaustive studies are needed to explore other system configurations and conditions. More advanced power plant models that include more circuit detail and representations of sensitive control/protective equipment would be needed. This must be accompanied by actual data on switchyard transmission system inter-connections at the plant, and in-plant distribution system configurations and components. In addition to the mostly steady-state harmonic analysis performed so far, future investigations should also include simulations of transient conditions occurring during GIC events. Further studies are also needed to determine the possibility of GIC-induced equipment interactions at the low voltage busses.

REFERENCES

[1] Cleveland, F., Malcom, W., Nordell, D. E. and Zirker, J., "Solar Effects on Communications," Geomagnetic Storm Cycle 22: Power System Problems on the Horizon, Special Panel Session Report, IEEE, 90TH0357-4 PWR.

[2] Joselyn, J. A., "Real-Time Prediction of Global Geomagnetic Activity," Solar Wind-Magnetosphere Coupling, Terra Scientific Publishing Company, Tokyo, 1986, pp. 127-141.

[3] Balch, C. C., "Real-Time Monitoring and Predicting of Geomagnetic Activity," Effects of Solar-Geomagnetic Disturbances on Power Systems, Special Panel Session Report, IEEE, 90TH0291-5 PWR.

[4] Albertson, V. D., "Geomagnetic Disturbance Causes and Power System Effects", Effects of Solar-Geomagnetic Disturbances on Power Systems, Special Panel Session Report, IEEE, 90TH0291-5 PWR, 1989.

[5] Larose, D., "The Hydro-Quebec System Blackout of March 13, 1989," Effects of Solar-Geomagnetic Disturbances on Power Systems, Special Panel Session Report, IEEE, 90TH0291-5 PWR.

[6] Kappenman, J. G., "Transformer DC Excitation Field Test and Results," IEEE Special Publication - Effects of Solar Geomagnetic Disturbances on Power Systems. 90TH0291-5, pp. 14-22.

[7] Gattens, P. R., Waggel, R. M. , Girgis, R., Nevins, R., " Investigation of Transformer Overheating Due to Solar Magnetic Disturbance," Presented at Geomagnetic Disturbance Panel Session at 1989 IEEE Summer Power Meeting, July 1989.

[8] Electrical Transmission and Distribution Reference Book, Westinghouse Electric Corp., 4th ed., Pittsburgh, PA, 1964.

[9] Transmission Line Reference Book (345 kV and Above), Electric Power Research Institute, 2nd ed., Palo Alto, CA, 1982.

DISCLAIMER

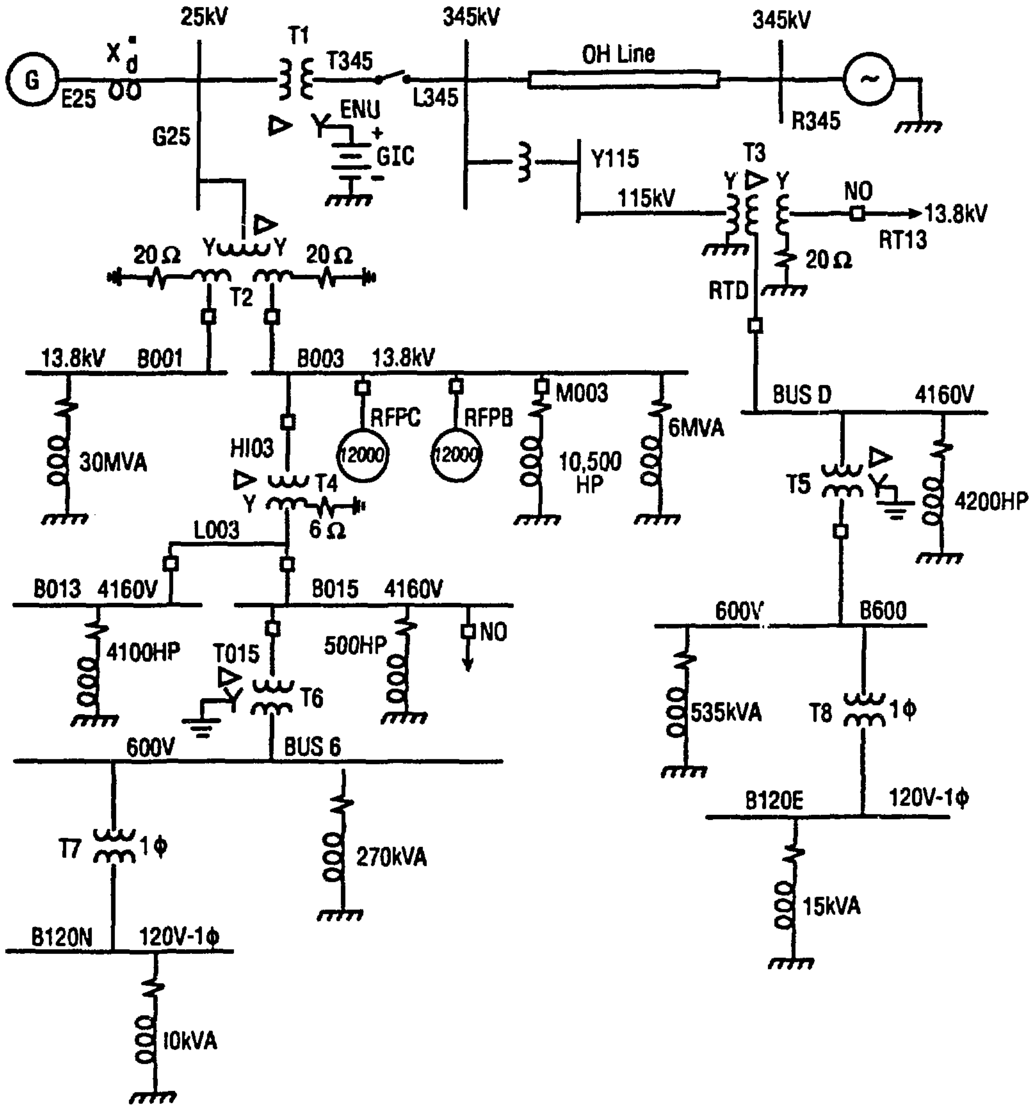

Figure 1. EMTP Simulation Model

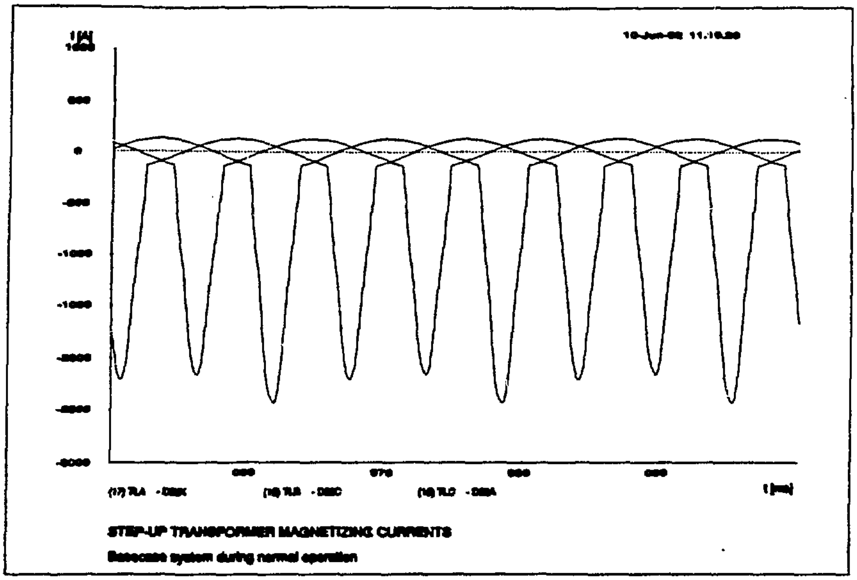

Fig. 2. Step-up transformer magnetizing currents during normal operation with 100 A GIC.

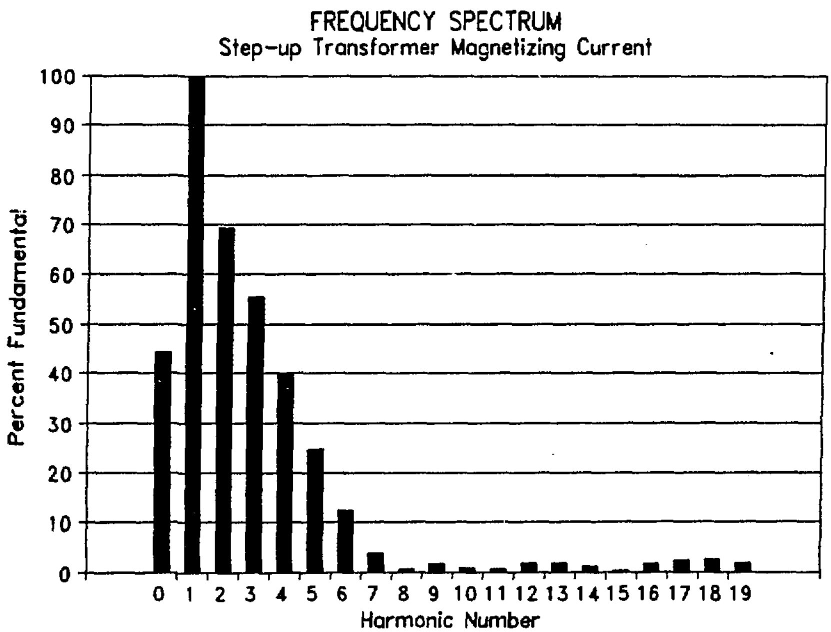

Fig. 3. Frequency spectrum of generator step-up transformer magnetizing current.

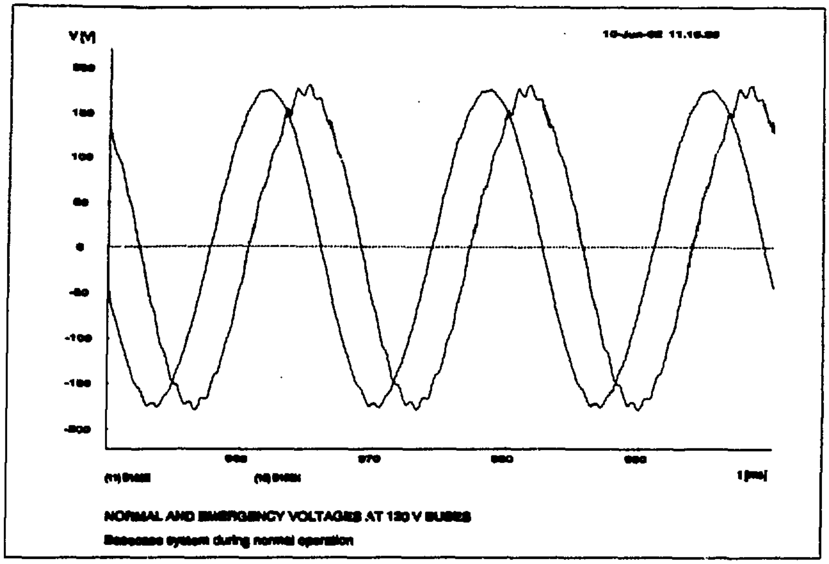

Figure 4. Normal and emergency system voltages at 120 V busses during normal operation with 100 A GIC.

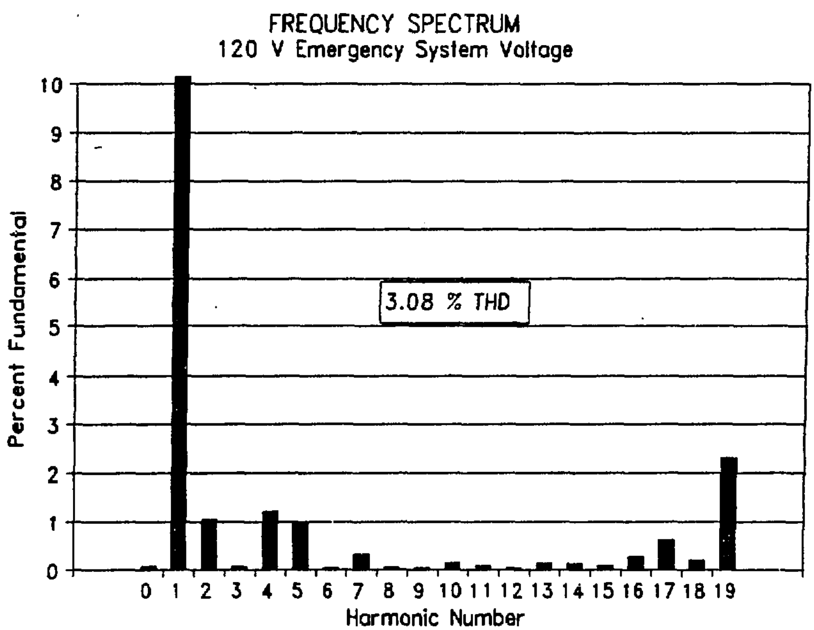

Figure 5. Frequency spectrum of 120 V emergency system voltage.

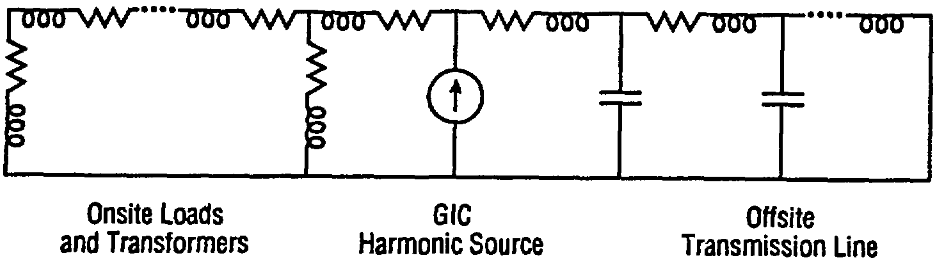

Figure 6. Simple model for distribution of GIC-induced harmonics between power station and transmission system.

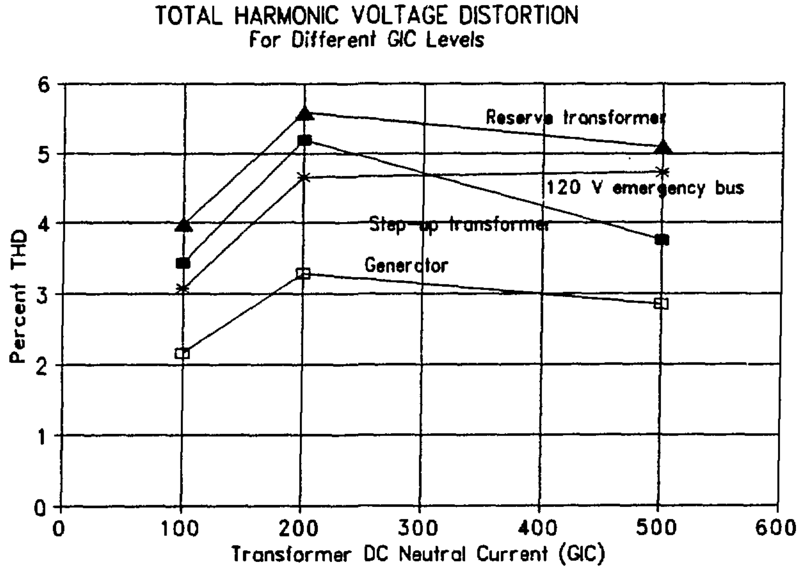

Figure 7. Comparison of THD for different GIC levels.

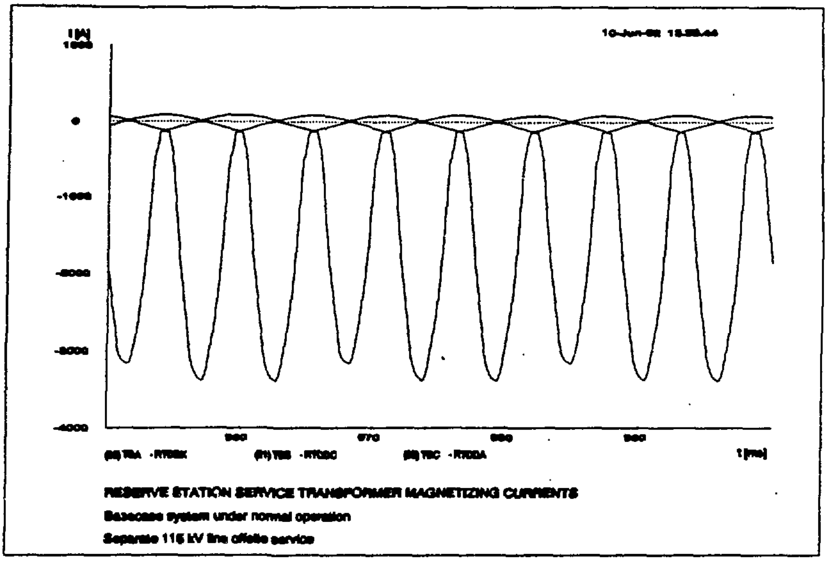

Figure 8. Reserve station service transformer magnetizing currents during normal operation with 100 A GIC and separate 115 kV line.

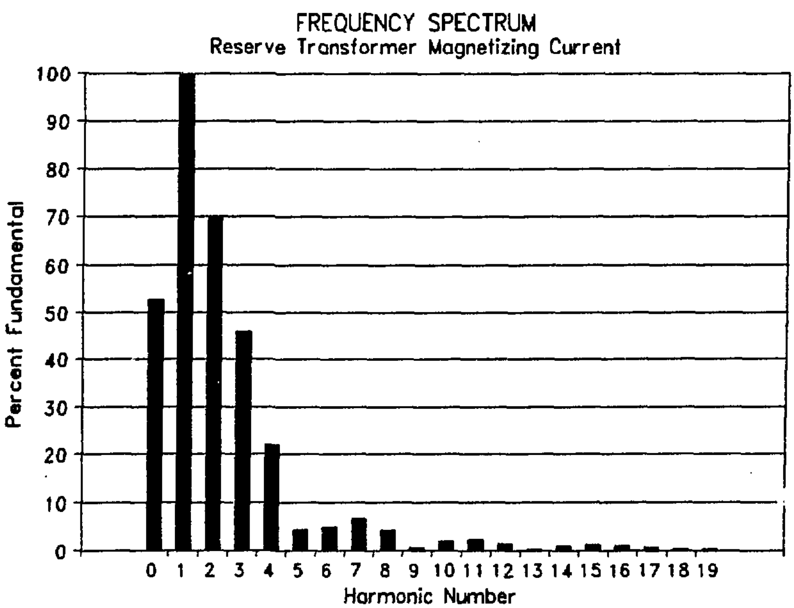

Figure 9. Frequency spectrum of the magnetizing current in the reserve station service transformer, with separate 115 kV line.

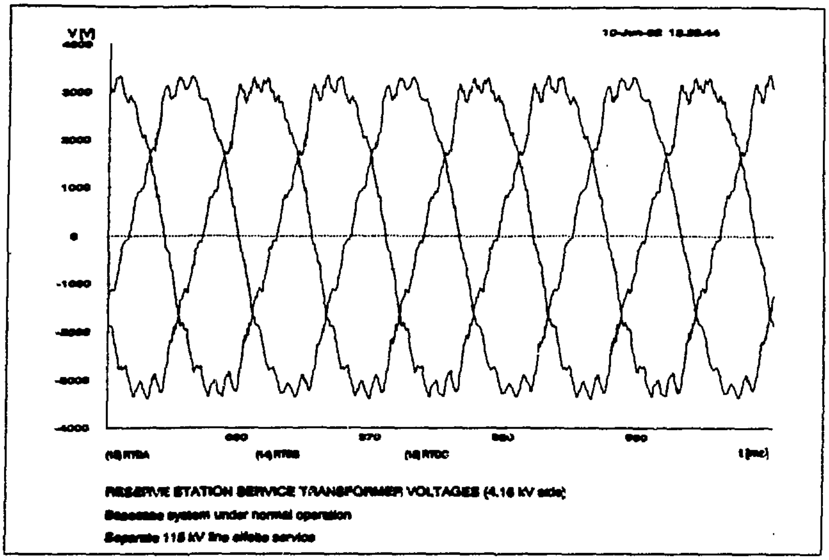

Figure 10. Reserve station service transformer voltages on 4.16 kV side during normal operation with separate 115 kV line.

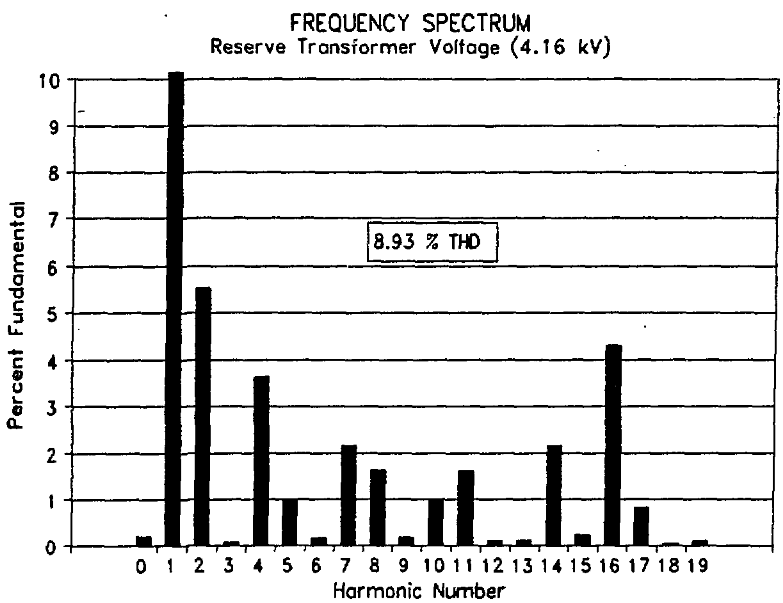

Figure 11. Frequency spectrum of A-phase reserve station service transformer voltage on 4.16 kV side, with separate 115 kV line.

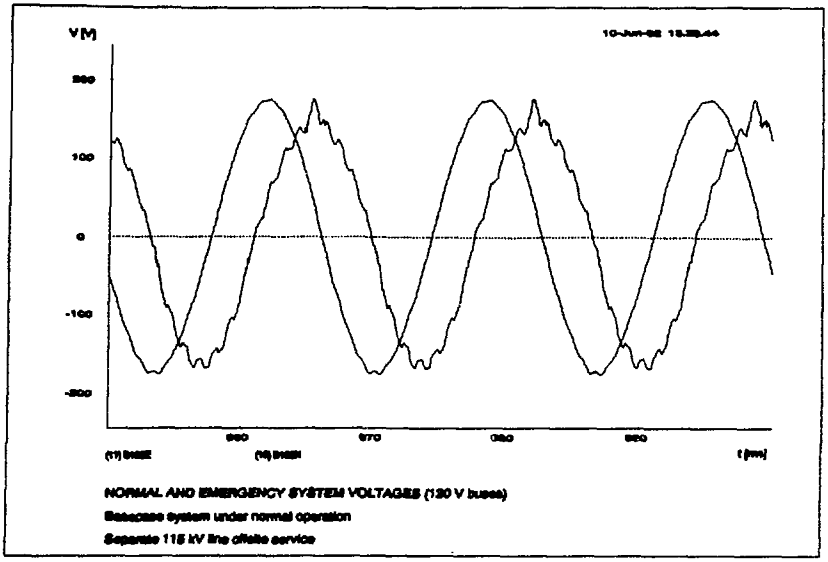

Figure 12. Normal and emergency system voltages at 120 V buses during normal operation with separate 115 kV line.

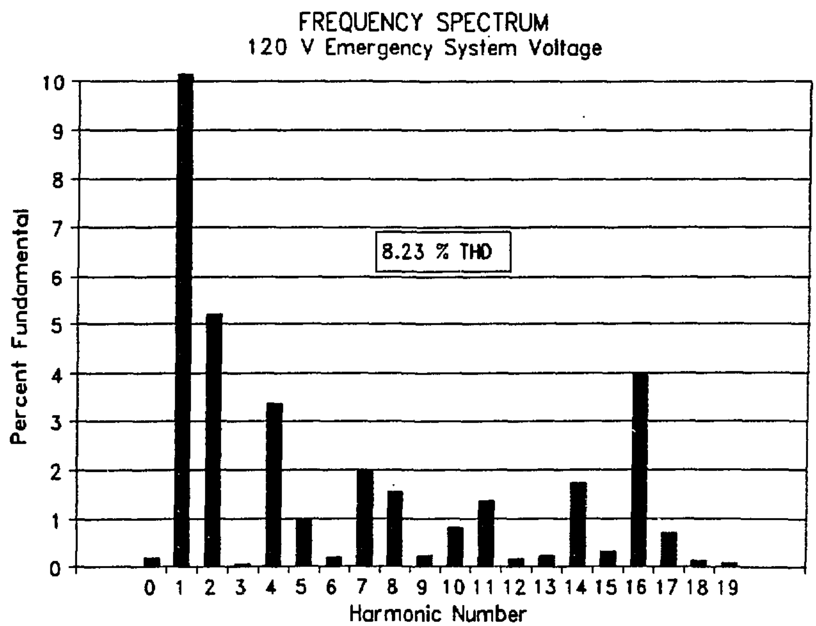

Figure 13. Frequency spectrum of 120 V emergency system voltage, with separate 115 kV line to reserve station service transformer.

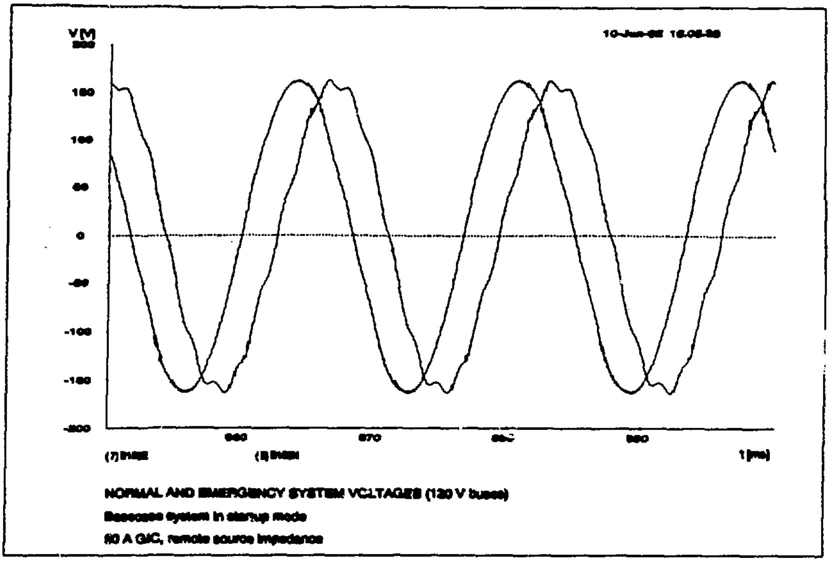

Figure 14. Normal and emergency system voltages at 120 V buses during startup mode with 50 A GIC and remote source impedance.

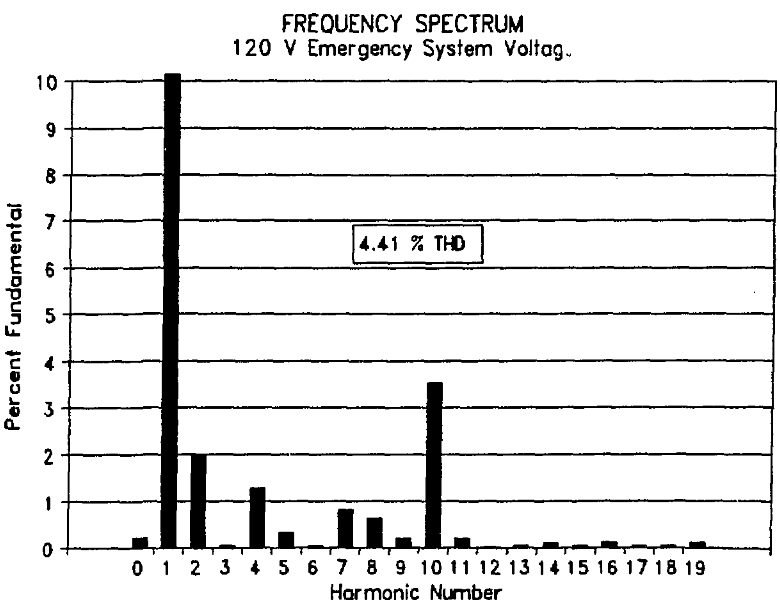

Figure 15. Frequency spectrum of 120 V emergency system voltage, during start-up mode.

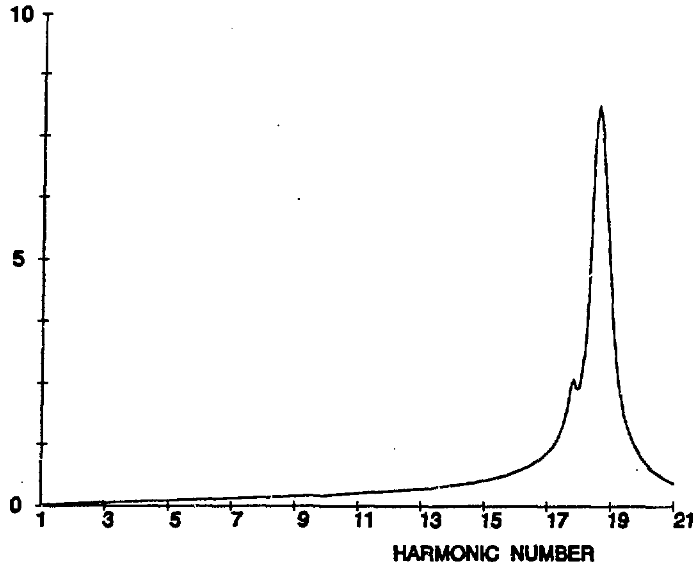

Figure 16. Transmission line impedance function for normal station configuration and nominal system parameters.

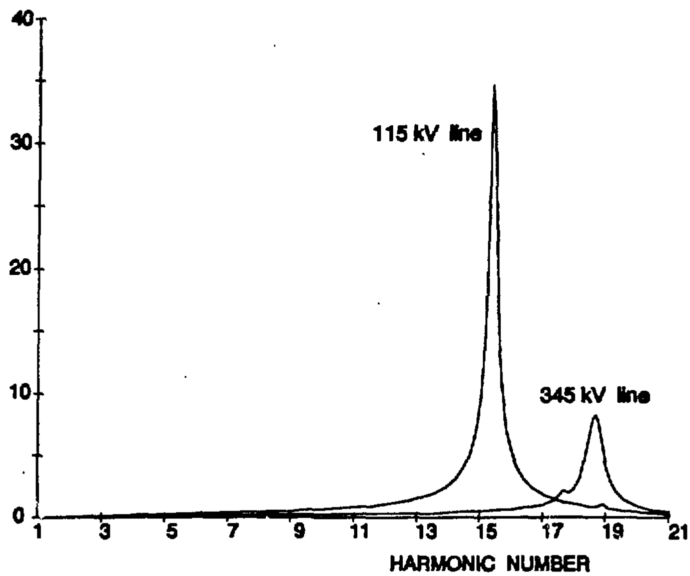

Figure 17. Transmission line impedance functions for station with separate 115 kV service and nominal system parameters.

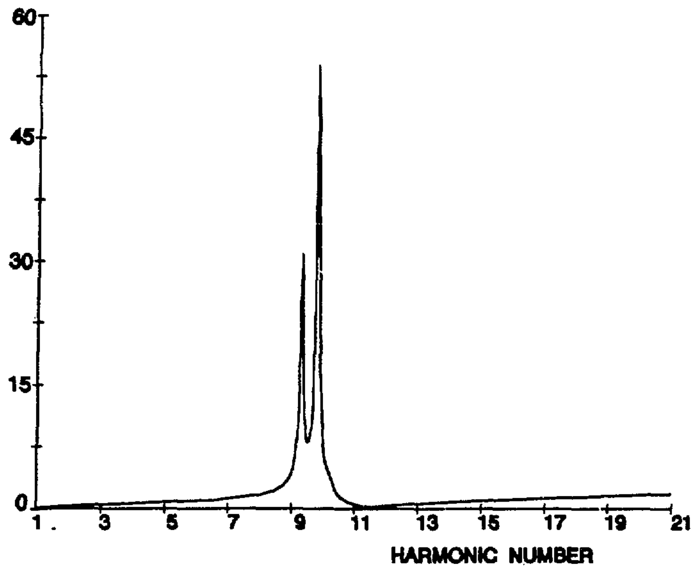

Figure 18. Transmission line impedance function for station start-up mode with nominal system parameters.

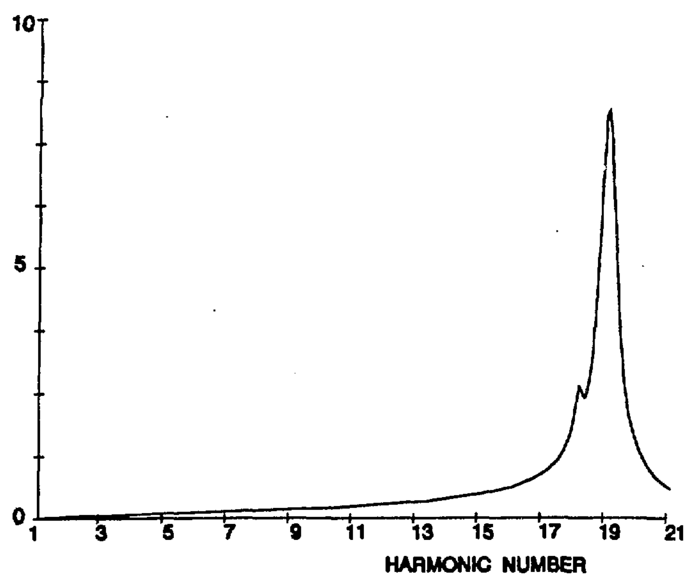

Figure 19. Transmission line impedance function for normal station configuration with 49.07 mile line.