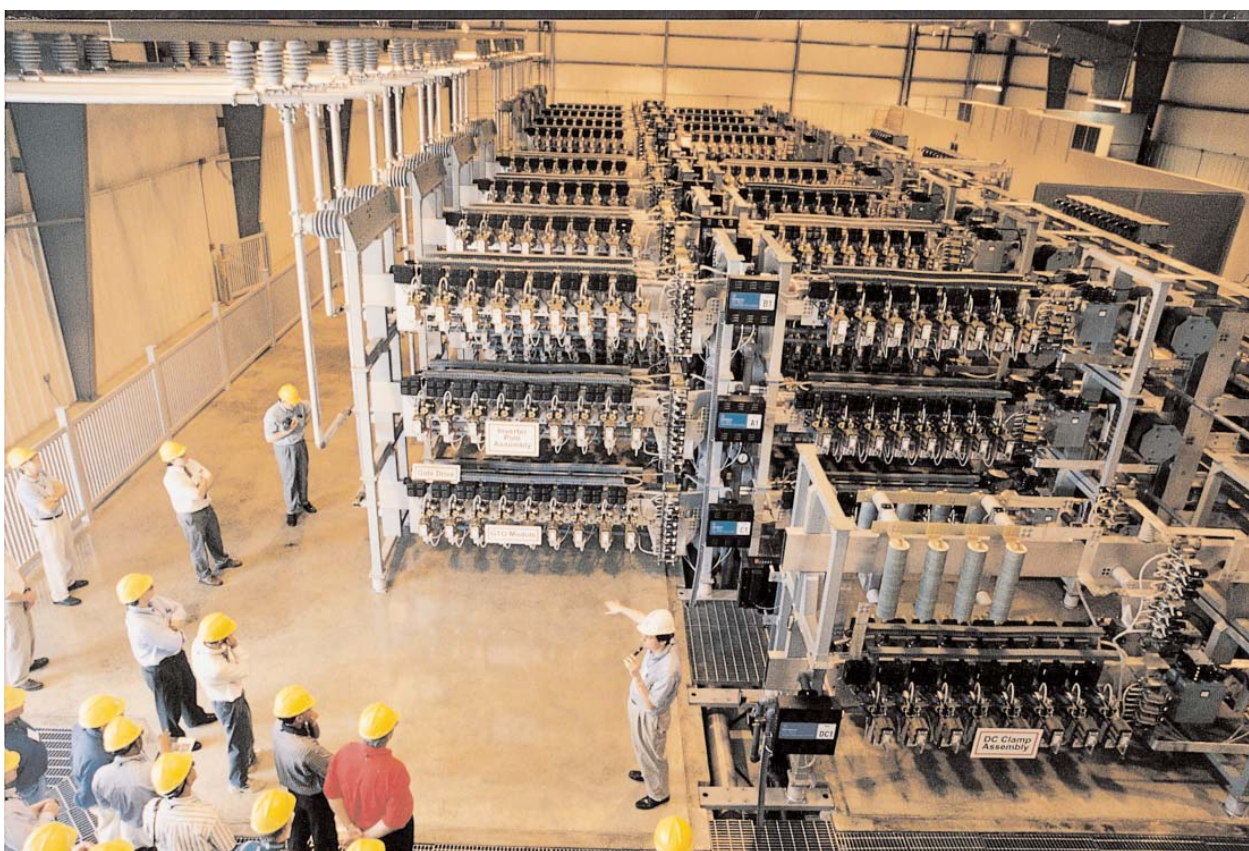


Electromagnetic Interference Emission Measurements Near FACTS Devices

Technical Report



Electromagnetic Interference Emission Measurements Near FACTS Devices

1005416

Interim Report, December 2002

Cosponsors
Americal Electric Power
1 Riverside Plaza
Columbus, OH 43215

Project Manager
B. Mehraban

New York Power Authority
123 Main Street
White Plains, NY 10601

Project Manager
B. Farnadesh

EPRI Project Manager
B. Cramer

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

American Electric Power

The Ohio State University

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CITATIONS

This report was prepared by

American Electric Power
1 Riverside Plaza
Columbus, OH 43215

Principal Investigators
D. Nichols
D. Klinec

The Ohio State University
Department of Electrical Engineering
Columbus, OH 43210

Principal Investigators
S. Sebo
L. Xu

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REPORT SUMMARY

The expanded application of flexible ac transmission system (FACTS) technology to the electric transmission and distribution systems frequently provides the best means of insuring the needed levels of capacity and reliability. This interim report provides a detailed look at the electromagnetic emissions from the first two FACTS systems tested. Equipment immunity requirements from several potentially applicable standards are provided, along with immunity data for nationwide differential global positioning system (NDGPS) and broadcast radio receivers. This data will help engineers apply FACTS technology to enhance the grid without excessive interference with other devices.

Results & Findings

Electromagnetic interference (EMI) emissions from the tested FACTS equipment vary widely. Some of the data indicate potentially significant levels of interference, while other locations are relatively benign. This highlights the need to be aware of the EMI issues when designing and applying FACTS devices to insure troublesome levels of emissions are avoided.

Challenges & Objectives

Personnel involved in designing FACTS devices and components, as well as electric company personnel who specify, purchase, and apply these systems, should review the information in this report. The most cost-effective approach to EMI is a system designed to avoid problems. If mitigation is necessary, the best time to install it is during the device installation. The worst-case scenario is for the Federal Communications Commission (FCC) to order your facility shut down until mitigation is complete. The goal is to eliminate the worst-case scenario by applying the information in this document when designing and installing FACTS devices.

This interim report presents two thirds of the work completed during the project's first year. If sufficient funding is available, subsequent work will further identify the relationships between device design and resulting interference. This work would include testing of devices from different manufacturers, in different configurations, and with different switching technologies. Mitigation options will also be studied.

Applications, Values & Use

To date, FACTS devices have been applied mostly to transmission and mostly in remote areas. As the application of FACTS technology spreads, it will be used more on distribution and in populated areas. The impact of possible EMI issues will increase with this evolution. As FACTS machines become more wide spread, the interference that can result could become a major issue.

EPRI Perspective

The involvement of EPRI in the development of FACTS technology places it in perfect position to address the possible EMI issues. The existing staff and network of FACTS experts, together with EPRI's EMC staff and network, provide all the resources needed to study FACTS EMI. EMI is often overlooked in the rush to market products. But, the Electromagnetic Compatibility Program at EPRI has the specific task of reviewing technological developments to insure that EMI problem do not interfere with the application of these needed devices.

Approach

This research provides detailed information on electromagnetic emissions in and around substations with operational FACTS devices. These measurements include radiated and conducted emissions, various locations, and frequencies from 9 kHz to 30 MHz. The goal is to provide manufacturers and users of FACTS devices enough information to insure that electromagnetic emissions do not exceed equipment immunity.

Keywords

FACTS

EMC/EMI

UPFC

STATCOM

Interference

Emissions

Immunity

ABSTRACT

Flexible ac Transmission System (FACTS) devices are installed in substations in order to enhance the operation of the electric power transmission and distribution system. To accomplish that, solid-state electronic devices are used to modify the characteristics of the power frequency system voltages and currents. In addition to their intended function, these devices (e.g., thyristors) inject high frequency voltages and currents into the power system. These currents as well as the electromagnetic fields generated by them have the potential to interfere with the operation of nearby electronic devices.

This interim report reviews the first two measurement series conducted at Inez Station (KY), owned and operated by American Electric Power (AEP), and Sullivan Station (TN), owned and operated by Tennessee Valley Authority (TVA), accomplished with a specially equipped EMI van owned and operated by AEP. The vehicle and its instrumentation were utilized to make measurements of the conducted and radiated radio frequency emission in the 9 kHz to 30 MHz frequency domain. Measurements were made inside the FACTS stations, and in the vicinity of the stations as well. The measurements were conducted under several operational and load conditions of the FACTS stations.

The measurement data will facilitate the characterization of the electromagnetic environment produced by FACTS devices, and will produce guidance as to what, if any, future work is required. The ultimate goal is to facilitate the continued application of FACTS devices in the electric power system. Upon collection of all data, the final report will be generated that will give details on the electromagnetic environment caused by FACTS devices, will evaluate the potential for interference within and outside FACTS stations, and will evaluate the need for additional work.

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1

INTRODUCTION

An increasing number of Flexible AC Transmission System (FACTS) devices are used by electric power utility companies in order to enhance the controllability and power transfer capability of ac power systems. FACTS devices involve fast conversion and switching power electronics. Typical applications are the thyristor controlled series capacitors (TCSC), static synchronous compensators (STATCOM), static synchronous series compensators (SSSC), convertible static compensator (CSC), unified power flow controllers (UPFC) and high voltage dc (HVDC) converters.

FACTS devices generate steady state electromagnetic (EM) high frequency noise by their power electronic components (e.g., thyristor valves). This steady state noise is the result of the continuous stream of turn-on and turn-off transients of each valve of the FACTS device. Due to conduction, induction and radiation, this noise may affect the performance of various power, communication, control, computer and microelectronic equipment in the vicinity of the FACTS devices, or of the device itself.

There are several books covering the subject of FACTS technology. One of the most comprehensive ones is [1], authored by N. G. Hingorani and L. Gyugyi.

Main Objectives of the Research Project

- Electromagnetic noise emission features of FACTS devices (including the coupling modes and propagation of the noise) are to be measured and evaluated.
- Relevant aspects of electromagnetic interference (EMI) and electromagnetic compatibility (EMC) issues, such as susceptibility and immunity, associated with FACTS devices and nearby equipment are to be described and analyzed.
- EMC related information from FACTS device manufacturers are to be summarized if available.
- Relevant EMI and EMC related standards published by various organizations pertinent to the operation of FACTS devices and nearby equipment are to be reviewed and summarized.
- An assessment of any known or suspected EMC problem (reported by users) caused by FACTS devices is to be performed.
- Specific techniques to mitigate EMI (circuit improvement, filtering, shielding), and protection/reduction devices are to be reviewed and recommended.
- Specifications for FACTS devices that manufacturers can use for their products are to be developed.
- The ultimate goal is to have FACTS devices and systems with intrinsic immunity to EMI and do not cause interference.

Scope of the Project

- FACTS devices to be covered by measurements are STATCOM and UPFC.
- Various operating and load conditions of FACTS devices are to be covered.
- Typical “nearby equipment” selected and defined are control room facilities, and protection equipment, e.g., power line carrier (PLC).
- Definitions, terminology, specific limits, and facilities relevant to the project to be reviewed are emission, susceptibility and immunity levels; limits applied; instrumentation and probes.

EMI/EMC Field Measurements

- Quantities to be measured at specific test locations are: electric field strength (E), magnetic flux density (B), currents (I), or voltages (V).
- These quantities will be evaluated in terms of their frequency spectra, for various operating and load conditions, and at various test point locations (including locations in control rooms) in the vicinity of FACTS devices.
- Ambient levels, and quantities emitted (radiated and conducted) are to be measured.
- The measurements can be made using quasi-peak (QP) detectors observing CISPR rules, as well as RMS and average detectors. CISPR is the abbreviation of the Comité International Spécial des Perturbations Radioélectriques, i.e., the International Special Committee on Radio Interference of the International Electrotechnical Commission (IEC).

2

PROJECT PARTICIPANTS

EPRI Project Managers: Michael Silva, Brian Cramer

American Electric Power: David K. Nichols, David A. Klinec

The Ohio State University: Stephen A. Sebo, Longya Xu, Xin (Carol) Liu

Consultants:

- Robert G. Olsen, Washington State University
- Jerry Ramie, Compliance Systems Corp.

Hosts:

- American Electrical Power (AEP) and Inez Station: Ben Mehraban, Charles M. Smith, Douglas Williams
- Tennessee Valley Authority (TVA) and Sullivan Station: B. David Till, James B. Cutshall, Daniel Widener
- New York Power Authority (NYPA) and Marcy Station: Bruce Fardanesh, Thomas Shust, Raymond Senus

3

EMC ASPECTS OF FACTS DEVICES

Inez Station (AEP) FACTS Device Description

The Inez FACTS device, Unified Power Flow Controller (UPFC), consists of two Gate Turn-Off Thyristor (GTO) based dc-ac inverters, interfacing transformers, step-up transformers, and associated controllers. The two inverters, sharing a common dc bus voltage, invert the dc voltage into two separate, controllable ac voltages, one in parallel and the other in series with respect to the power grid for power flow control, voltage support, VAr (leading or lagging) compensation, and/or stability enhancement. The FACTS device is rated ± 320 MVA. Though there are some other configurations for connecting two inverters to the power grid, one inverter in parallel and another in series in connection to the power grid is the most common.

The dc bus voltage of the Inez FACTS device is rated in the range of 18-22 kV, supported by a bank of capacitors. The dc bus voltage is further divided into three levels, positive, middle, and negative. In operation, the three-level dc voltages are all accessible by the ac side grid through GTO switching devices.

The GTO used in the inverter circuit acts as a controllable and fast switching device. By proper switching the ac voltage produced by the inverter circuit has an adjustable magnitude and phase angle with respect to the grid voltage and, thus, can accomplish various control functions determined by the power system controller. According to measurements performed as a part of this project, the switching frequency for pulse width modulation (PWM) of each inverter is about 3 kHz. The estimated voltage rise time and fall times of a single GTO during switching are in the order of 100-150 μ sec. Due to fast switching, very high frequency voltage and current ringing phenomena (in the order of several hundred kHz) are observed in the surrounding electric and magnetic fields, and in the ground current.

The interfacing transformer plays the role of synthesizing the overall voltage from the four individual voltages. Among the three-phase voltage outputs from the inverter, each single-phase voltage is actually synthesized by four separate harmonic-rich voltages separately generated by four sub-switching poles. In effect, the interfacing transformer not only adds the fundamental components but also cancels out dominant low-order harmonics of the four output voltages from the four switching poles. The adding and canceling functions of the interfacing transformer are accomplished through its specially arranged windings, which makes the interfacing transformer design substantially different from those of a conventional transformer.

The step-up transformer following the interfacing transformer raises the voltage to the proper level for power grid connections.

While the inverters and controls are installed indoors, the interfacing and step-up transformers with major breakers and by-pass switches are placed outdoors in a fenced area.

The controllers of the Inez FACTS device include inverter gating signal control, the inverter voltage and current control, and the power system level control. The control system also includes cooling, monitoring, diagnosis, protection, etc. In addition, the power line controllers are integrated into the control room. All controls are housed in a control room close to the inverter hall, where two high power inverters are installed. Power and control areas are separated by walls in space and interfaced with each other using optical fibers.

Sullivan Station (TVA) FACTS Device Description

The Sullivan FACTS device consists of a single inverter fed from a two-level dc bus voltage at about 10 kV. The FACTS device is designed to give only parallel compensation (leading or lagging) to the power grid to influence power flow, support voltage, improve transient stability, etc. Interfacing inductor banks (“interface magnetics”) and harmonic blocking transformers (HBT) are used between the inverter circuit and a step-up transformer. The major components of the FACTS device are a dc-ac inverter, interfacing inductor banks, harmonic blocking transformer, step-up transformer, and associated control hardware and software. The FACTS device installed in the TVA Sullivan station is rated at 100 MVA.

The inverter circuit in the Sullivan station FACTS device is GTO based and it shares certain similarities with those of the Inez FACTS device, including GTO switches, four branches of sub-switching poles for overall phase voltage synthesizing, and gating circuitry. However, there are major differences between the Inez and Sullivan inverter circuits. The dc bus voltage is substantially different at these two sites. One is a three-level system (Inez), the other has two levels (Sullivan). The dc bus voltage of Sullivan is only half of that at the Inez site. GTO switching characteristics, rise time and fall times are believed about the same at both places.

The voltages generated from the inverter circuit in the Sullivan Station are treated by two-stage synthesis and filtering: interfacing inductors and harmonic blocking transformer. This is another major difference between the Sullivan and Inez FACTS devices. At the Sullivan FACTS device, each inverter circuit in the four separate switching poles generates part of the final voltage, with a slight phase shifting from each other. The fundamental components (60 Hz) of two partial voltages from the four switching poles are added together in two groups using the interfacing inductors. Meanwhile, some low order harmonics from each pole are cancelled out by the interfacing inductors. The voltages from the first stage inductor are not the final voltages and go further to the harmonic blocking transformer. In the second stage of the harmonic-blocking transformer, the final form of the three phase voltages is obtained and all unwanted, low order harmonics are cancelled. However, neither the first stage inductor bank nor the second stage harmonic blocking transformer are meant for filtering out the very high frequency voltage and current ringing due to the GTO fast switching. The very high frequency components in the order of several hundred kHz or higher are virtually attenuated according to the damping factor along the path of their propagation.

In the Sullivan FACTS device, the inverter circuit, controls and interfacing inductor bank are housed indoors. The controller circuit is separated from the inverter circuit by walls. However, it is observed that at the Sullivan Station, the physical distance between the high power inverter hall and the low power control room is much closer than that at the Inez station.

Marcy Station (NYPA) FACTS Device Description

The Marcy FACTS device, called Convertible Static Compensator (CSC), consists of two voltage source inverters fed from one or two three-level dc buses at about 20 kV. The three-level inverters in Marcy are almost the same as those used in the Inez FACTS device. The two inverters can be connected at Marcy to the 345 kV ac grid and two power lines through coupling transformers. The rated capacity of each inverter in Marcy is 100 MVA, smaller than that of Inez.

The two inverters have either one interconnected or two independent dc buses, pending on the operation mode selection. So, the dc bus of the two inverters in Marcy is slightly different from that of the Inez FACTS device. In fact, the connection of the two inverters is very flexible according to the design, including 11 different types of configurations and operation modes. The basic operation modes are as follows: both inverters are connected as parallel compensators, or both are connected as series compensators, or one is connected as a parallel and the other one as a series compensator. One inverter in operation as a parallel or series compensator is also allowable.

To meet the flexible connections, the Marcy FACTS device requires four coupling (step-up) transformers, two in parallel and two in series, to bring the inverter voltages into the power grid. The two parallel coupling transformers are actually merged into a single compound transformer.

Similar to the Inez FACTS device, there are two harmonic interfacing transformers, one for each inverter, between the coupling (step-up) transformers and GTO switching poles. The interfacing transformer plays the role of synthesizing the overall voltage from the four individual pole voltages. This is done because every single-phase voltage is actually synthesized by four separate harmonic-rich voltages separately generated by four sub-switching poles. In effect, the interfacing transformer not only adds the fundamental components but also cancels out dominant low-order harmonics of the four output voltages from the four switching poles. The adding and canceling functions of the interfacing transformer are accomplished through its specially arranged windings, which makes the interfacing transformer design substantially different from those of a conventional transformer.

Another major difference in the inverter in Marcy from the inverter in either Inez or Sullivan is that there are three outdoor inductors inserted in one of four GTO poles to attenuate harmonic voltages produced by the inverters. The pole equipped with the inductors is different from the other three poles in that the output voltage from the pole is connected directly to the coupling (step-up) transformer without going through the interfacing transformer.

While monitoring the FACTS operation in the control room next to the inverter hall, the actual issuing and execution of the control command is accomplished through a control panel located in another building nearby the inverter hall.

The operation of the FACTS devices in Marcy is presently limited to parallel compensation because the coupling transformers for series compensation have not been installed.

GTO Switching Characteristics

For the three FACTS devices (Inez, Sullivan and Marcy) measured in the course of this project, the switching poles are based on GTO technologies. It is the rapid GTO turn-on and turn-off actions that excite the neighboring circuits. These circuits consist of inductances and capacitances wanted for the GTO normal operation. However, there are unwanted parasitic inductances and capacitances as well. If the hidden circuits, consisting of unwanted parasitic inductances and capacitances are excited and disturbed by the very fast changing voltages (dv/dt) and currents (di/dt) caused by GTO switching, the surrounding electromagnetic field would emit energy in the form of electromagnetic noise. Therefore, it is worth observing the GTO turn-on and turn-off details at each instant of the transition.

In describing the GTO switching characteristics, one normally should include GTO snubber circuits for any realistic discussion of the GTO switching behavior. The snubber circuits are employed in order to protect the GTOs from thermal, overcurrent and overvoltage stresses. Note that the detailed GTO circuits were not available for this analysis, but waveform measurements related to the electric field strength were used to derive and describe the possible GTO switching operations.

GTO Turn-On Switching

GTO turn-on is initiated by a pulse of the gate current. The sequence of events inside the GTO during the turn-on process is almost the same as that of a conventional thyristor. During turn-on, both the rate of rise and magnitude of the gate current should be large to ensure that all cathode islands begin to conduct and that there is a good dynamic sharing of the anode current. If there is only a small number of islands of the GTO carrying the total current, then localized thermal runaway can occur, resulting in the destruction of the GTO.

In the normal turn-on process, a large value of gate current (i_g) is wanted first for a sufficient length of time ($>10\ \mu s$) and followed by a smaller gate current, called “backporch” current - see Figure 3-1, based on [2].

The large current at the beginning is used to spread the conducting plasma into the GTO body in order to establish a good conductive cross-section. The “backporch” current is for the situation when the anode current is not large enough first and subsequently it increases to very large values. Without the “backporch” current, the large and late-coming anode current may be concentrated to a small number of islands causing thermal runaway.

According to the even sequence of the GTO turn-on, the entire turn-on process can be divided into three phases. In the first phase, labeled as t_d , the GTO appears to remain in the voltage blocking state without anode current (i_A). However, the gate current during this time is injecting a large amount of plasma into the GTO body, pushing the GTO (breakover). At this point, numerous cathode islands gain some conduction capabilities. In this way, the anode current begins to increase, marking the end of t_d . The t_d interval lasts about $10\ \mu s$.

In the second phase, t_r , a large density of plasma is built up in the vicinity of gate regions, and then spreads to the cathode until the entire cross-section of the GTO is filled with a high density of conducting plasma. The plasma spreading time is also marked on Figure 3-1, it is t_{ps} . The voltage across the GTO is v_{AK} .

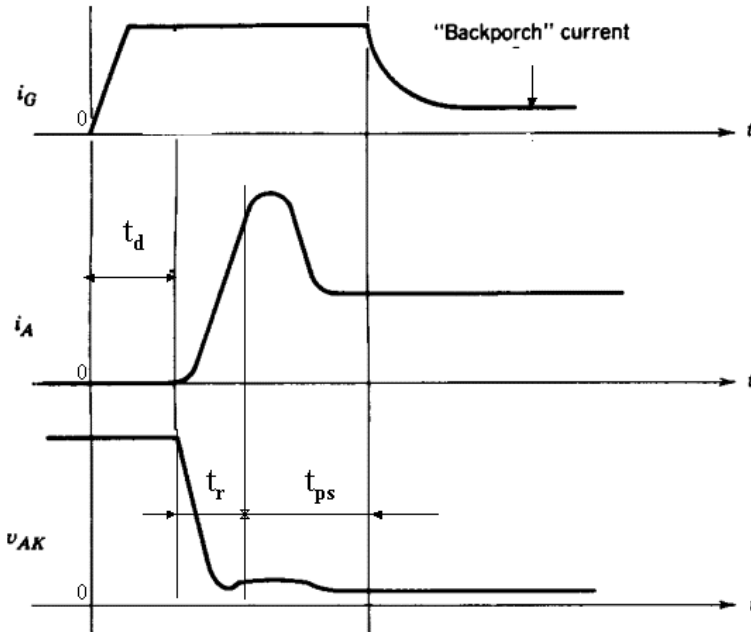


Figure 3-1
GTO Turn-On Transients

GTO Turn-Off Switching

The major difference between a GTO and a thyristor is that the GTO can be turned off by the gating current; that is the GTO is turned off by applying a large impulse negative gate current. The electric and magnetic field strength measurements very close to a switching GTO reflect the voltage and current transients of the GTO.

Figure 3-2 shows a representative electric field strength related measurement (E_1 , 10 μ s/division time scale) during the GTO turn-off process captured by a digital scope. E_2 is the same as E_1 , but its time scale is 2 μ s/division.

It can be seen that the rising waveform of the non-even electric field strength defines a multi-phase GTO turn-off process, corresponding to the GTO multi-mode turn-off transitions. The entire turn-off process can be divided into four major phases. In the first phase, characterized by the storage time t_s , a very large and growing negative gating current is sent into the GTO, for removing the plasma spread over and stored in the gating PN junction and at the periphery of the cathode islands. In this phase, the action of removing the stored plasma grows and expands the plasma-free regions centered on the cathode islands. Eventually this process breaks the regenerative conduction mechanism of the GTOs. Examining the electric field strength variation waveform, one can recognize that the first phase takes about 6-8 μ s.

In the second phase, the negative gating current continues to grow to the negative maximum. Meanwhile, the GTO anode current falls rapidly because the regenerative mechanism of the GTO is stopped. The voltage across the turn-off GTO rises rapidly as well. That is what one can see from Figure 3-1, i.e., that the related electric field strength increases rapidly. The second phase is marked as t_f and lasts about 3-4 μ s as shown in Figure 3-1 while the voltage across the GTO is increasing.

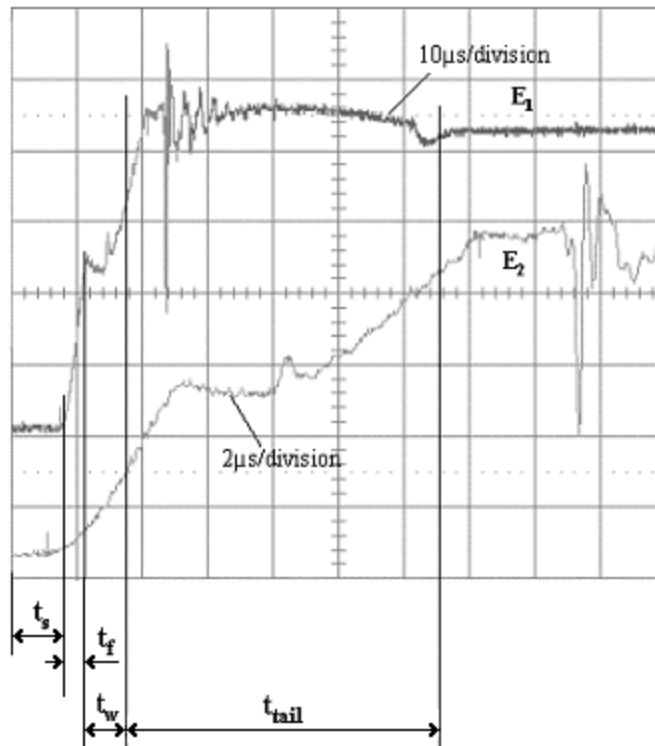


Figure 3-2
GTO Turn-Off Transients. Time Intervals (t_n) apply to E_1 Curve (10 μ s/division).

In the third phase, marked as t_w , the magnitude of the negative gate current starts to shrink from the negative maximum. During the third phase the gate current, though becoming smaller and smaller, continues to sweep out the plasma, as much as possible, inside the GTO body. The third phase typically lasts another 6-8 μ s. At the end of this phase, the GTO current is reduced to 10% or less of the full current and the voltage across the GTO is restored to 80% or more of the full voltage.

However, the GTO is not fully turned off at the end of the third phase because the plasma, inside the GTO semiconductor body and mainly in the two base areas, is not completely cleaned out. The fourth phase, called tail current phase t_{tail} , follows, continuing a small anode-gate current, to sweep out the remaining plasma. The fourth phase is quite long, compared to the previous phases, about 40-50 μ s as shown in Figure 3-1. This is the phase resulting in most of the turn-off losses while the previous phases are very short with the largest voltage and current changes. Therefore, the first, second and third phases, perhaps, emit most and the strongest of the EMI signals. The total turn-off time shown in Figure 3-1 is about 70 μ s.

An overvoltage snubber circuit is used in GTO inverters, and the resulting voltage is used as can be observed from the electric field strength related measurements. It is shown in Figure 3-1 that the voltage across the GTO during turn-off switching has a plateau during the period of t_{tail} . It can also be observed that the GTO voltage during this interval is higher than the final GTO voltage but not as high as the rising rate initially indicated. This type of voltage waveform suggests that during the voltage rising process, the GTO voltage is somehow clamped by an overvoltage

protection snubber as soon as the voltage reaches a preset value. Consistently, one can see that at the time of overvoltage clamping, the measured electric field strength waveform shows a ringing, verifying that the overall circuit has changed structure and operating mode due to the overvoltage snubber activation.

Note that the rise time and fall time of the voltage and current of GTO's are in the range of several microseconds, so the corresponding frequency of the noise would appear to be at most 100 kHz. However, the rise and fall processes of the voltage and current are not smooth but they contain much higher frequency components. Once the surrounding circuits, consisting of unwanted parasitic inductances and capacitances, are excited, it is the resonant frequency of the circuits that largely determines the noise frequency. Figure 3-2 shows that there is always very high frequency ringing (1-2 MHz) after switching.

4

INSTRUMENTATION AND MEASUREMENT TECHNIQUES

AEP EMI Test Van Instrumentation

EMI Measurement System

Electro-Metrics, EMC-30 MK IV precision RF selective voltmeter

Frequency range: 9 kHz-1000 MHz, 15 RF octave bands; bands used for the 9 kHz-30 MHz range are 1: 9-35 kHz, 2: 35-75 kHz, 3: 70-150 kHz, 4: 120-250 kHz, 5: 250-500 kHz, 6: 0.5-1.1 MHz, 7: 1.1-2.4 MHz, 8: 2.4-5.5 MHz, 9: 5.5-12.5 MHz, 10: 12.5-30 MHz.

Accuracy: ± 0.1 dB

Bandwidths: from 200 Hz to 1 MHz, selectable in five equal steps

Standard detectors available: peak, quasi-peak (CISPR), average, RMS, slideback peak

Sensitivity floor: -35 dB, reference: 1 μ V/50 ohms

Calibrated Antennas Used

Both on tripod, both for 9 kHz – 30 MHz frequency range

Electro-Metrics, RVR-30, serial 120, vertical rod antenna for electric field strength measurements, above 0.6 m x 0.6 m area ground plane

Electro-Metrics, ALR-30, serial 121, loop antenna for bi-directional magnetic field strength measurements (E-field shielded)

Oscilloscope

Yokogawa DL-1450, 8 bits, 200 Ms/s, 150 MHz, configured as a calibrated spectrum analyzer

The system is interfaced with a notebook computer via an IEEE 488 General Purpose Interface Bus. All measurements are traceable to the National Institute of Standards and Technology to conform to applicable ANSI and IEEE Standards and the International Electrotechnical Commission's Special Committee on Radio Interference (CISPR).

Miscellaneous Equipment

On-board calibrators: signal generator: Marconi 2022D, 10 kHz-1000 MHz and impulse generator: Electro-Metrics CIG-25

RF current transformers (RFCT), 9 kHz-110 MHz frequency range: Electro-Metrics PCL-25 with 1-1/4" window, and Eaton RF current transformer with 5" window

Portable EMI Instrumentation: RF Sniffer: Radar Engineers, ranges are 200-450 kHz and 2-11 MHz

RF power meter: Signalcrafters 70

Measurement Techniques

The instrumentation used for radio noise measurements, and the procedures for the measurement of radio noise in the frequency range of 9 kHz-30 MHz followed ANSI/IEEE Std 430-1986, IEEE Standard Procedures for the Measurement of Radio Noise from Overhead Power Lines and Substations [2].

The detector of the radio noise and electric field strength meter is a QP (CISPR) detector.

Measurements obtained with the loop antenna whose antenna factors are in electric field strength units (dB μ V/m) were converted to magnetic flux density units (dB μ A/m) by subtracting 51.5 dB from the measurements.

Clip-on type radio frequency current transformers (RFCT) were used for the measurement of structure currents in ground leads, as well as for the measurement of RF noise coupled onto cabling (in Marcy Station only).

Conclusions

The data sets were collected using QP (CISPR) detection with ANSI/IEEE Std 430-1986 as guide.

During the review and reduction process the data showed electromagnetic threats to the control equipment. Such threats are addressed only in MIL-STD 461E type of tests, such as

- magnetic fields simulated by RS101
- electric fields simulated by RS103
- structure currents in the switchyard simulated by CS109
- common-mode currents on the control equipment's power and I/O lines simulated by CS114.

The MIL-STD 461E tests refer to peak values.

Measurements conducted during the project used a commercial QP (CISPR) detector with a 9 kHz bandwidth in order to allow for easy comparison among data collected at the Inez, Sullivan, and Marcy FACTS stations.

5

LIMITS APPLIED

Introduction

In order to evaluate the performance of the FACTS facilities in the Inez, Sullivan, and Marcy Stations, each noise spectrum measured in the 9 kHz - 30 MHz frequency range was compared to one or more appropriate limits set by various standards and guidelines. This chapter reviews the limits applied.

The standards and guidelines applied are as follows:

- Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, MIL-STD-461E, August, 1999 [4]
- Limits and Measurement Methods of Electromagnetic Noise from AC Power Systems, 0.15-30 MHz, CAN3-C108.3.1-M84, May 1984 [5]
- Transmission Line Reference Book, 345 kV and Above, Second Edition, EPRI, 1984 [6]
- Wide Band Noise (WBNoise) Predictions [7] (for a typical 500 kV power line described in [6])
- Nationwide Differential Global Positioning System (NDGPS) information

Radiated Susceptibility, Magnetic Field, RS101 of [4]

This requirement is applicable to equipment and subsystem enclosures, including electrical cable interfaces. The equipment under test (EUT) shall not exhibit any malfunction, degradation of performance, or deviation from specified indications, when subjected to the magnetic fields shown in Figures 5-1 (Navy applications) and 5-2 (Army applications). The Navy levels are more severe than the Army levels. Both limit lines are legitimate and both of them are shown for comparison purposes.

Figures 5-1 and 5-2 can be used for the frequency range of 9 kHz-100 kHz. They are applied to all control room, inverter hall, and switchyard magnetic field (loop antenna) measurements.

The limit numbers shown in Figures 5-1 and 5-2 are peak values. They will be changed to QP (CISPR) by subtracting 2 dB from the values shown in Figures 5-1 and 5-2.

For sinusoidal signals, the reason for the 2 dB difference is that while MIL-STD-461E requires 10 kHz bandwidth with peak detection, the noise measurements used a QP (CISPR) detector and 9 kHz bandwidth.

This requirement is specialized and intended primarily to ensure that the performance of equipment potentially sensitive to low frequency magnetic fields is not degraded.

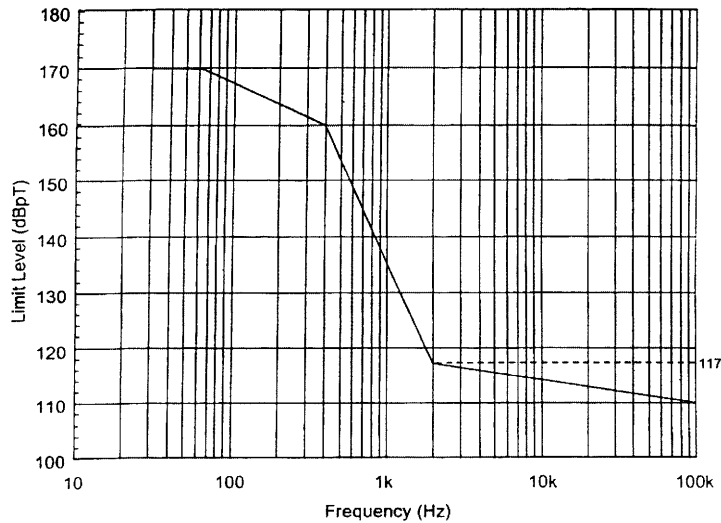


Figure 5-1
RS101 Limit for All Navy Applications [4]. The Figure Shows the Levels Before the 2dB Adjustment.

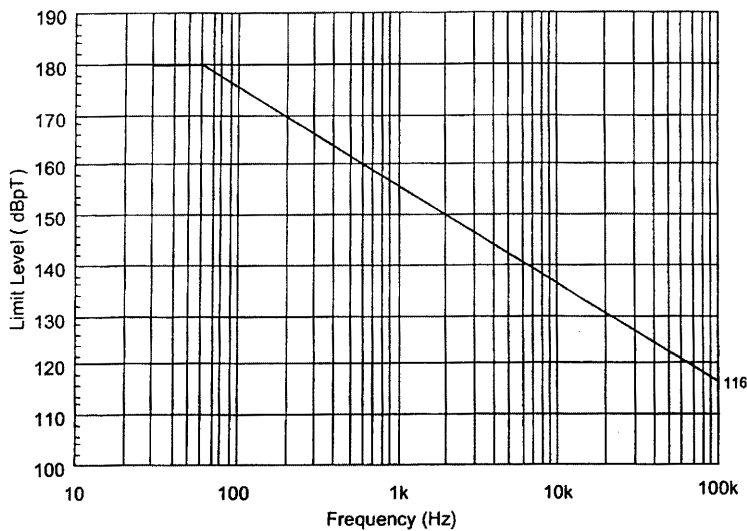


Figure 5-2
RS101 Limit for All Army Applications [4]. The Figure Shows the Levels Before the 2dB Adjustment.

Radiated Susceptibility, Electric Field, RS103 of [4]

This requirement is applicable to equipment and subsystem enclosures and all interconnecting cables. The equipment under test (EUT) shall not exhibit any malfunction, degradation of performance, or deviation from specified indications, when subjected to the radiated electric fields shown in Figure 5-3 (it is Table VII in [4]).

The values shown in Figure 5-3 are peak values.

For “ground” equipment the Navy limit is 10 V/m, i.e., 140 dB μ V/m, and the Army limit is 50 V/m, i.e., 154 dB μ V/m. The Navy level is more severe than the Army level. Both limit lines are legitimate and both of them are shown for comparison purposes.

Figure 5-3 can be used for the frequency range of 2 MHz to 30 MHz. It is applied to all control room, inverter hall, and switchyard electric field (rod antenna) measurements.

Similar to the RS101 limits, these limit numbers will also be changed to QP (CISPR) by subtracting 2 dB from the limit levels given in Figure 5-3.

This requirement is specialized and intended primarily to ensure that the performance of equipment potentially sensitive to electric fields is not degraded.

TABLE VII. RS103 limits.

PLATFORM FREQ. RANGE		LIMIT LEVEL (VOLTS/METER)							
		AIRCRAFT (EXTERNAL OR SAFETY CRITICAL.)	AIRCRAFT INTERNAL	ALL SHIPS (ABOVE DECKS) AND SUBMARINES (EXTERNAL)*	SHIPS (METALLIC) (BELOW DECKS)	SHIPS (NON- METALLIC) (BELOW DECKS)	SUBMARINES (INTERNAL)	GROUND	SPACE
2 MHz ↓ 30 MHz	A	200	200	200	10	50	5	50	20
	N	200	200	200	10	50	5	10	20
30 MHz ↓ 1 GHz	AF	200	20	-	-	-	-	10	20
	A	200	200	200	10	10	10	50	20
1 GHz ↓ 18 GHz	N	200	200	200	10	10	10	10	20
	AF	200	20	-	-	-	-	10	20
18 GHz ↓ 40 GHz	A	200	200	200	10	10	10	50	20
	N	200	200	200	10	10	10	50	20
40 GHz	AF	200	60	-	-	-	-	50	20
	A	200	60	-	-	-	-	50	20

Figure 5-3
RS103 Limits (A-Army, N-Navy, AF-Air Force) [4]

Conducted Susceptibility, Structure Current, CS109 of [4]

This requirement is applicable to structure currents.

Figure 5-4 can be used for the frequency range of 9 kHz to 30 MHz. It is applied to all structure and ground lead current measurements conducted with radio frequency current transformers (RFCT) in switchyards.

The limit numbers shown in Figure 5-4 are peak values. Similar to the RS101 and RS103 limits, these limit numbers will also be changed to QP (CISPR) by subtracting 2 dB from the values shown in Figure 5-4.

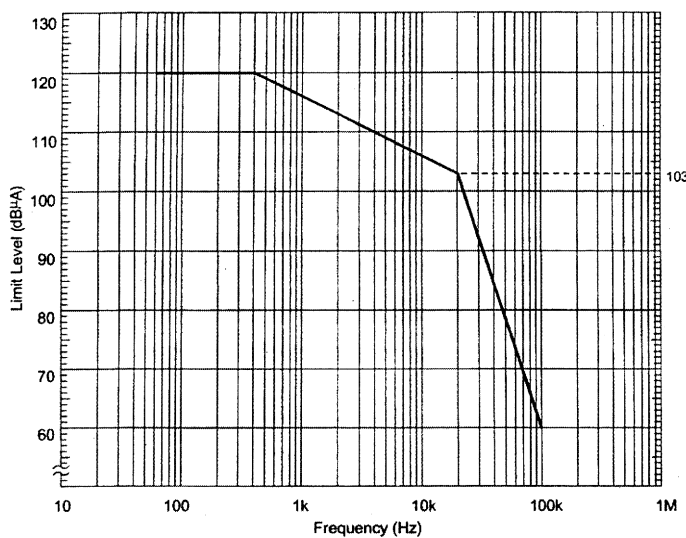


Figure 5-4
CS109 Limit for All Applications [4]

Conducted Susceptibility, Bulk Cable Injection, CS114 of [4]

This requirement is applicable to all interconnecting cables, including power cables. The equipment under test (EUT) shall not exhibit any malfunction, degradation of performance, or deviation from specified indications, when subjected to an injected current level shown in Figures 5-5 and 5-6.

Figure 5-5 (it is Table VI in [4]) and Curve 5 of Figure 5-6 can be used for the frequency range of 10 kHz to 30 MHz. Curve 5 was selected to represent the limits applied. It is applied to all control room cable common mode I/O current (RFCT) measurements conducted at Marcy.

The limit numbers shown in Figure 5-6 are peak values. The limit numbers will be changed again to QP (CISPR) by subtracting 2 dB from the values shown in Figure 5-6.

This requirement is applicable to all electrical cables interfacing with the EUT enclosures.

TABLE VI. CS114 limit curves.

PLATFORM FREQ. RANGE		LIMIT CURVE # FROM FIGURE CS114-1							
		AIRCRAFT (EXTERNAL OR SAFETY CRITICAL)	AIRCRAFT INTERNAL	ALL SHIPS (ABOVE DECKS) AND SUBMARINES (EXTERNAL)*	SHIPS (METALLIC) (BELOW DECKS)	SHIPS (NON- METALLIC) (BELOW DECKS)	SUBMARINES (INTERNAL)	GROUND	SPACE
10 kHz ↓ 2 MHz	A	5	5	2	2	2	1	3	3
	N	5	3	2	2	2	1	2	3
	AF	5	3	-	-	-	-	2	3
2 MHz ↓ 30 MHz	A	5	5	5	2	4	1	4	3
	N	5	5	5	2	4	1	2	3
	AF	5	3	-	-	-	-	2	3
30 MHz ↓ 200 MHz	A	5	5	5	2	2	2	4	3
	N	5	5	5	2	2	2	2	3
	AF	5	3	-	-	-	-	2	3

Figure 5-5
CS114 Limit Curves (A-Army, N-Navy, AF-Air Force) [4]

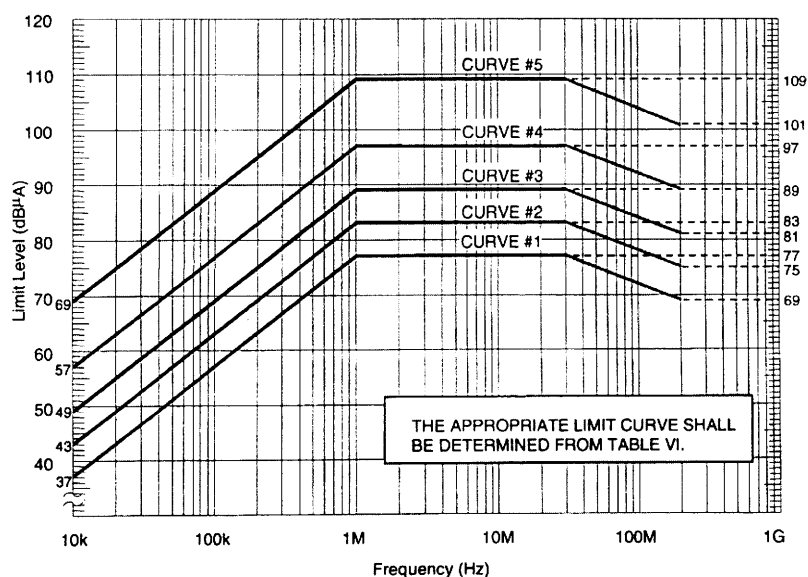


Figure 5-6
CS114 Limits: Curve #5 is Appropriate for All Applications [4]

Electromagnetic Noise from AC Power Systems, Power Lines and Stations, Canadian Standard [5]

This requirement is applicable to the RF noise originating from ac power lines and stations, from 150 kHz to 30 MHz, during normal operating conditions, at 15 m lateral distance from the outermost conductor of the power line, and it applies during fair weather conditions.

Table 5-1 and Curve 1 of Figure 5-7 can be used for the frequency range of 150 kHz to 30 MHz, for 400-600 kVrms nominal line-to-line voltages. They are applied to all power line measurements.

The explanation for the use of the Canadian “Fair Weather” standard is that fair weather (unlike “foul weather” conditions) exists most of the time. Thus, since the FACTS device is “on” most of the time, the “on” condition is similar to the “fair weather” condition.

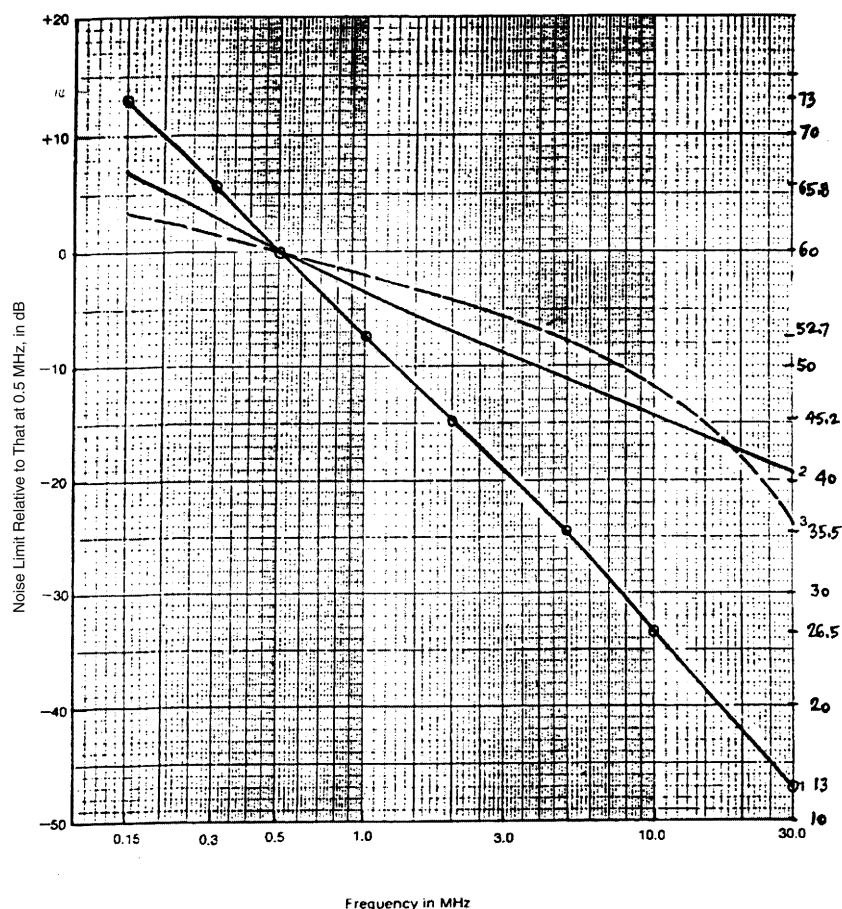
The particular level quoted here for power lines is the 400-600 kV range. Lines of lower voltage have lower limits.

Table 5-1
Noise Limits vs. Frequency for AC Power Lines and Stations in Fair Weather

Frequency	Noise Limit in dB μ V/m for QP (CISPR) Readings
150 kHz	73
300 kHz	65.8
500 kHz	60
1 MHz	52.7
2 MHz	45.2
5 MHz	35.5
10 MHz	26.5
30 MHz	13

Average Stable Foul Weather Radio Noise [6, 7]

RF noise from a typical 500 kV power line (defined in [6]) from 100 kHz to 2 MHz, during normal operating conditions, at 15 m lateral distance from the outermost conductor of the power line, in average stable foul weather conditions can be calculated.



where
 1 = transmission lines
 2 = distribution lines
 3 = substation

Figure 5-7
Frequency Spectrum of RF Noise from Power Lines and Stations—Curve 1:
Transmission Lines [5]

Table 5-2 can be used for the frequency range of 100 kHz to 2 MHz. It is applied to all power line measurements.

Table 5-2
RF Noise Levels vs. Frequency for 500 kV Line in Average Stable Foul Weather

Frequency	RF Noise, dB μ V/m for QP (CISPR) Readings
100 kHz	67.4
300 kHz	69.5
500 kHz	68.1
1 MHz	64.4
2 MHz	57.7

Limits Applied Considering NDGPS Systems

The frequency range of the differential signal for the Nationwide Differential Global Positioning System (NDGPS) is from 283.5 to 325 kHz in the spectrum allocated for marine radio navigation. In areas claimed by the U.S. Government to be covered, the minimum NDGPS signal level is often specified as 37.5 dB μ V/m RMS. However, an estimate of a typical value of the NDGPS signal level is about 46 dB μ V/m RMS. A reasonable estimate of the minimum signal-to-noise ratio (SNR) required for proper reception of the NDGPS correction is about 7 dB for a good digital receiver. It should be noted that there is variability in receiver design and some receivers may require a different minimum SNR for proper operation.

The bandwidth of an NDGPS signal (and hence, an NDGPS receiver) is 117 Hz or 234 Hz, depending on the NDGPS site transmission rate. And, the signal levels are specified using RMS values. The measurements of radiated interference in this project are made using a quasi-peak (QP) detector and a 9 kHz bandwidth receiver per CISPR standards. To provide a useful comparison of NDGPS signal strength to measured interference levels, equivalent NDGPS signal levels are used with corrections made for detection technique (RMS vs. QP) and bandwidth (234 Hz vs. 9 kHz). Estimates of receiver performance made by using noise and signal levels to compute an SNR must account for these differences. These corrections are explained below.

A correction has been applied to the NDGPS signal levels given above (i.e., minimum 37.5 dB μ V/m RMS, and typical 46 dB μ V/m RMS) to convert them from RMS levels into what would be measured with a QP (CISPR) detector. It has been assumed here that the conversion required for NDGPS signals is +5 dB, the same as the difference between the RMS and QP levels for noise signals from the FACTS devices at Sullivan and Marcy. Thus, the minimum NDGPS signal level is given as 42.5 dB μ V/m QP, and the typical value of NDGPS signal is given as 51 dB μ V/m QP. However, another correction is necessary for the difference in bandwidth for an NDGPS receiver and the measurement instrumentation bandwidth.

The interference, or noise, level measured by a 234 Hz bandwidth receiver will be substantially less than the level measured by a 9 kHz receiver. That difference can be found using the following formula:

$$10 \log_{10}(234/9000) = 10 \log_{10}(0.026) = -16 \text{ dB}$$

To adjust the NDGPS signal for comparison to the measured interference levels, we add 16 dB (effectively reducing the noise by 16 dB). Thus, adding the 16 dB bandwidth correction to the RMS/QP corrected values above gives the following equivalent values of NDGPS signal levels:

- Minimum NDGPS signal level = 58.5 dB μ V/m (QP, 9 kHz BW)
- Typical NDGPS signal level = 67 dB μ V/m (QP, 9 kHz BW)

The corrections above for RMS/QP and bandwidth could have been applied by subtracting 21 dB from the measured noise level, instead of by adding 21 dB to the receiver signal - both result in the same relative difference between the noise and signal levels (SNR). If the resulting noise level is more than 7 dB below (at least for the assumed typical digital receiver) the signal level then the NDGPS receiver will operate properly.

In this report, the NDGPS frequency range is represented by two vertical lines at 283.5 and 325 kHz on the appropriate power line and switchyard noise spectrum measurement figures. The equivalent NDGPS signal levels given above (i.e., minimum 58.5 dB μ V/m, and typical 67 dB μ V/m) are represented by two horizontal lines.

6

EM NOISE MEASUREMENTS AT INEZ STATION (AEP)

Introduction

The FACTS facility at Inez Station (Kentucky), owned by AEP, is a Unified Power Flow Controller (UPFC), the first such operating device in the world. It has been in service since 1998. It is used for power flow and voltage control. The rating of the UPFC is ± 320 MVA. It regulates the power flow (real and reactive), controls the voltage support of the 138 kV buses, and several 138 kV capacitor banks as well. Figure 6-1 shows the simplified diagram of the UPFC installed in Inez Station [1]. Figure 6-2 is the simplified layout of the UPFC building including the main UPFC components [1]. Figure 6-3 is the aerial view of Inez Station [1].

Measurements at Inez Station were conducted from April 15 to April 19, 2002.

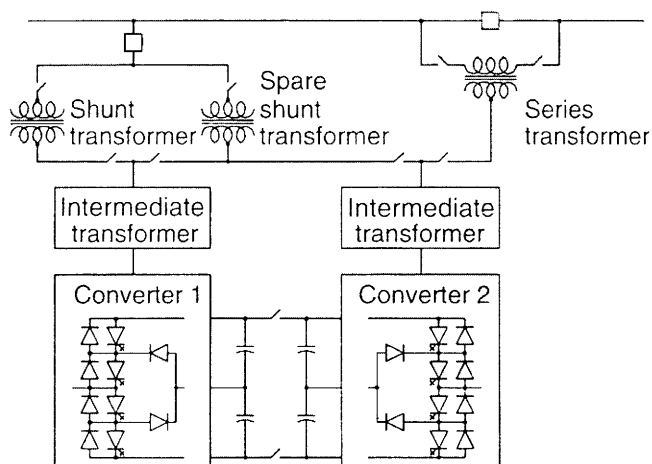


Figure 6-1
Simplified Diagram of the UPFC Installed at Inez Station [1]

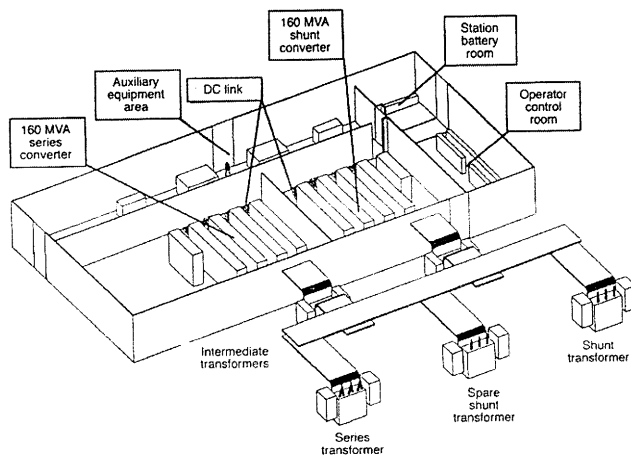


Figure 6-2
Simplified Layout of the UPFC Building at Inez Station [1]

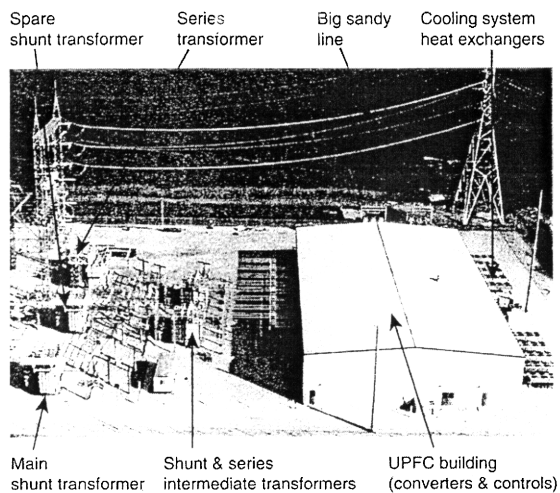


Figure 6-3
Aerial View of Inez Station [1]

Operational Cases

There were six operational cases observed at Inez Station:

- Normal case, both shunt and series inverters were on, at normal load and voltage levels.
- Gating was off, power supply of gating was also off ("off/off" case).
- Gating was off, but power supply of gating was on ("off/on" case).

- Worst case in terms of radio frequency (RF) noise: both inverters were on, the per unit (p.u.) voltage was at low level (e.g., 0.98 p.u.), capacitor banks BB and CC at Inez were off, Big Sandy line power was at maximum level, and the inverter absorbed a high MVar flow. (Absorbing reactive power is considered to be positive at Inez. Reactive power is absorbed when the inverter is inductive. Note that the same case is considered to be negative at Sullivan.)
- Shunt unit was the only unit on, series unit was disconnected (STATCOM, i.e., static synchronous compensator mode), voltage was at 0.98 p.u. level, capacitor banks BB and CC at Inez were off—it was the worst case in terms of RF noise in this mode.
- Series unit was the only unit on, shunt unit was disconnected (SSSC, i.e., static synchronous series compensator mode), voltage was at 1.0 p.u. level, capacitor banks BB and CC at Inez were off—it was the worst case in terms of RF noise in this mode.

Several sub-cases were also reviewed, mostly for the power line carrier (PLC) measurements, pending on capacitor bank switching on or off conditions at Inez Station.

General Measurement Information

For the selection of so-called “hot spots” in the control room and at other locations in the station a portable EMI instrument (RF Sniffer) was used. Both frequency spectrum ranges (200-450 kHz and 2-11 MHz) were utilized for such measurements.

The frequency spectrum for all Ez, Bx, By measurements was from 9 kHz to 30 MHz.

The frequency spectrum for all RFCT measurements was from 9 kHz to 30 MHz.

The frequency spectrum for all PLC measurements was from about 70 kHz to 270 kHz (Bands 3 and 4).

For all test points of power line and ambient field measurements the following conditions were recorded (see Table 6-1):

- latitude, and longitude information, obtained by a GPS system
- temperature, pressure, and relative humidity of the ambient air.

In all cases the height of the antenna ground plane was 1 meter.

Table 6-1
Test Locations and Atmospheric Conditions at Inez Station

Test Location	Latitude (North) and Longitude (West) Info.	Temp., Pressure, and Relative Humidity Info.
Inez-Johns Creek Line Location #1	N 37 deg 45' 45.1" W 82 deg 28' 32.3"	88 deg F, 28.99 inHg, 40 % RH
Inez-Johns Creek Line Location #2	N 37 deg 45' 8.9" W 82 deg 29' 15.2"	79 deg F, 28.96 inHg, 52 % RH
Inez-Johns Creek Line Location #4*	N 37 deg 42' 49.8" W 82 deg 29' 52.5"	79 deg F, 28.96 inHg, 48 % RH
Test Location for Ambient Field Level	N 37 deg 45' 0.8" W 82 deg 28' 29.6"	Not taken

* Measurements at Location 3 were not feasible, however, the location numbers (1-2-3-4) were not changed.

Control Room Measurements

Measured quantities were E_z , the vertical component of the electric field strength, and B_x and B_y , the two horizontal components of the magnetic flux density.

To define the terminology, the term “parallel position” is used when the plane of the loop (of the loop antenna) was vertical and parallel to a well-defined facility, such as a panel, bus or a wall in the area of the measurement location. The term “perpendicular position” is used when the plane of the loop (of the loop antenna) was kept vertical but rotated by 90 degrees, and it became perpendicular to the same well-defined facility.

Two measurement locations were selected in the Inez Control Room. Figure 6-4, the layout of the Inez FACTS Station, shows both locations, denoted by 1 and 2.

The first control room location at Inez (marked by 1) was close to the south corner of the control room, 0.6 m (2 ft) from the dc panels along the southwest side short wall of the control room, and 3.05 m (10 ft) from the door of the long wall.

“Parallel” means that the plane of the loop was parallel to the dc panels, “perpendicular” means that the plane of the loop was perpendicular to the same panels. At Location 1 the “perpendicular” direction of the plane of the loop happens to be parallel to the buses between the inverter equipment and the outdoor switchyard.

Measurements at the first control room location were conducted for all six operational cases.

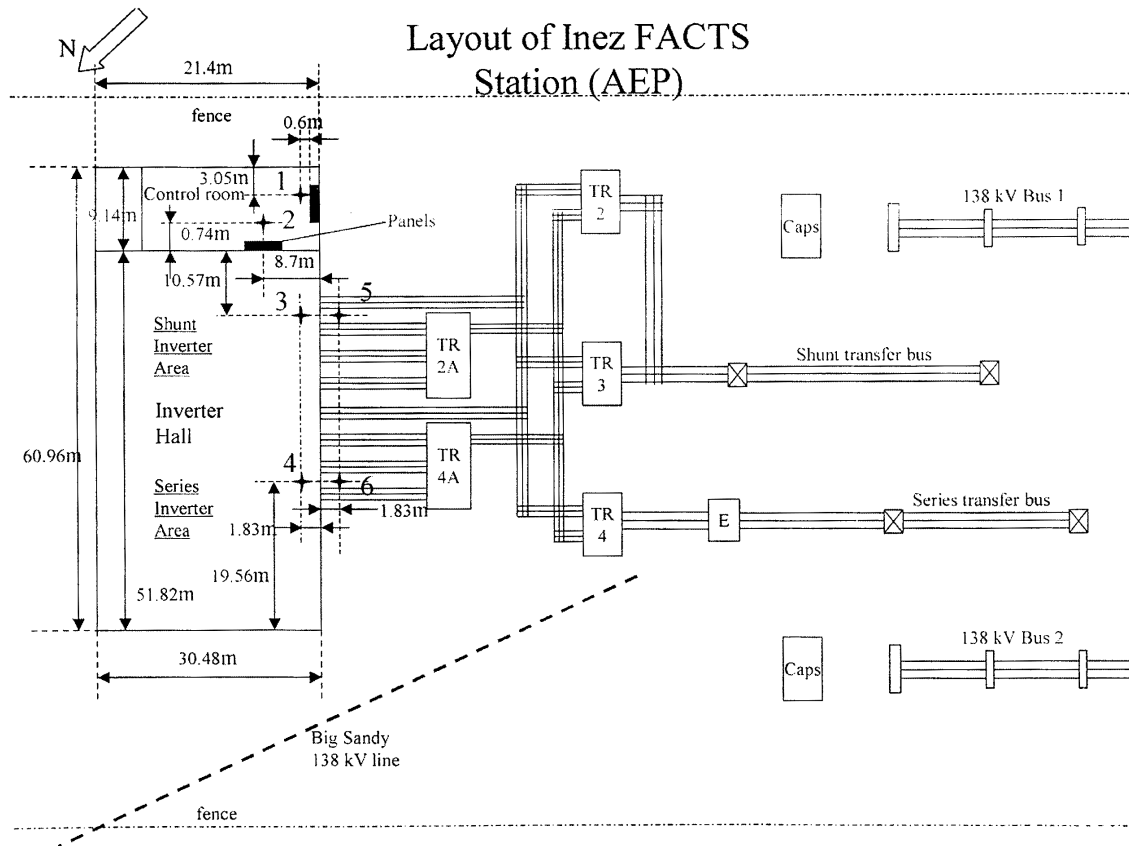


Figure 6-4
Layout of Inez FACTS Station with Measurement Locations 1-6

Figures 6-5 and 6-6 show the measured radio frequency (RF) noise levels and the appropriate radiated susceptibility limit lines. Operational conditions “normal,” “worst,” “shunt,” and “series” resulted in levels higher than in the other 2 cases when gating was off. Figures A-1 to A-6 of Appendix A show more measurement details.

The second control room location at Inez (marked by 2) was close to the wall separating the inverter hall and the control room, 0.74 m (29 in) from the telephone panels along that wall, 8.7 m (28.5 ft) from the southwest side short wall of the control room.

“Parallel” means that the plane of the loop was parallel to the telephone panels, “perpendicular” means that the plane of the loop was perpendicular to the same panels. At Location 2 the “parallel” direction of the plane of the loop happens to be parallel to the buses between the inverter equipment and the outdoor switchyard.

Measurements at the second control room location were conducted for 2 operational cases, normal case, and when gating was off and power supply of gating was also off (“off/off” case).

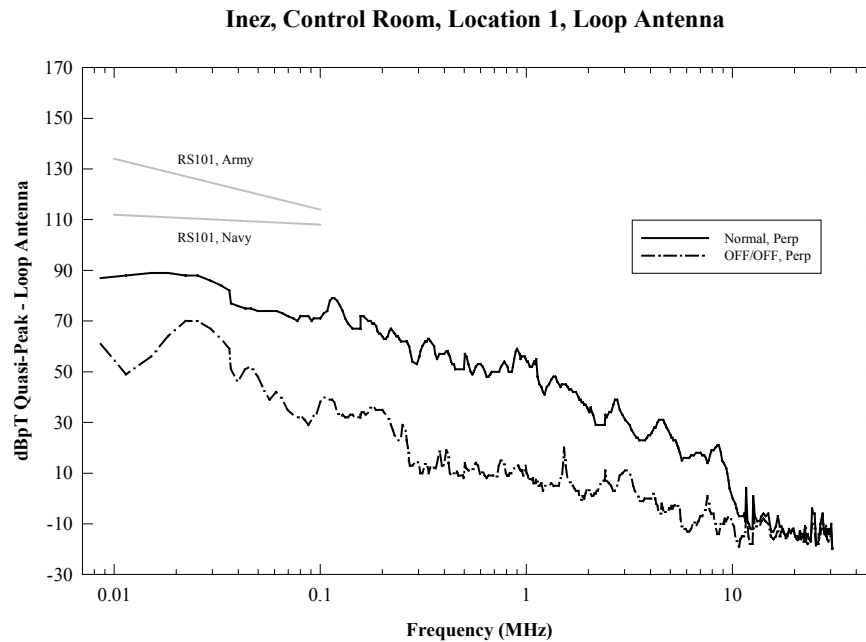


Figure 6-5
Inez, Control Room, Location 1, Loop Antenna Measurements and RS101 Limit Lines

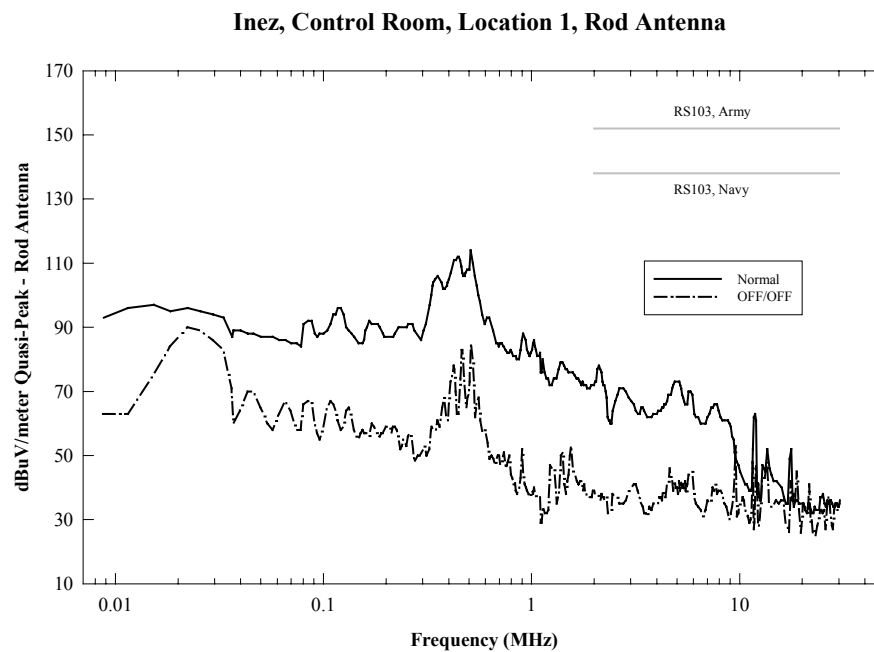


Figure 6-6
Inez, Control Room, Location 1, Rod Antenna Measurements and RS103 Limit Lines

Figures 6-7 and 6-8 show the measured noise levels and the appropriate radiated susceptibility limit lines.

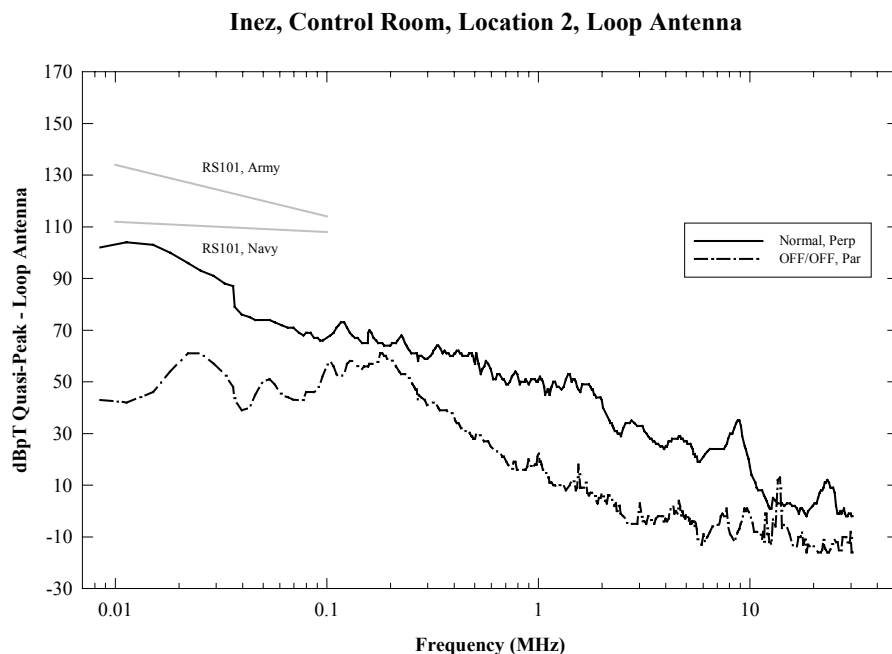


Figure 6-7
Inez, Control Room, Location 2, Loop Antenna Measurements and RS101 Limit Lines

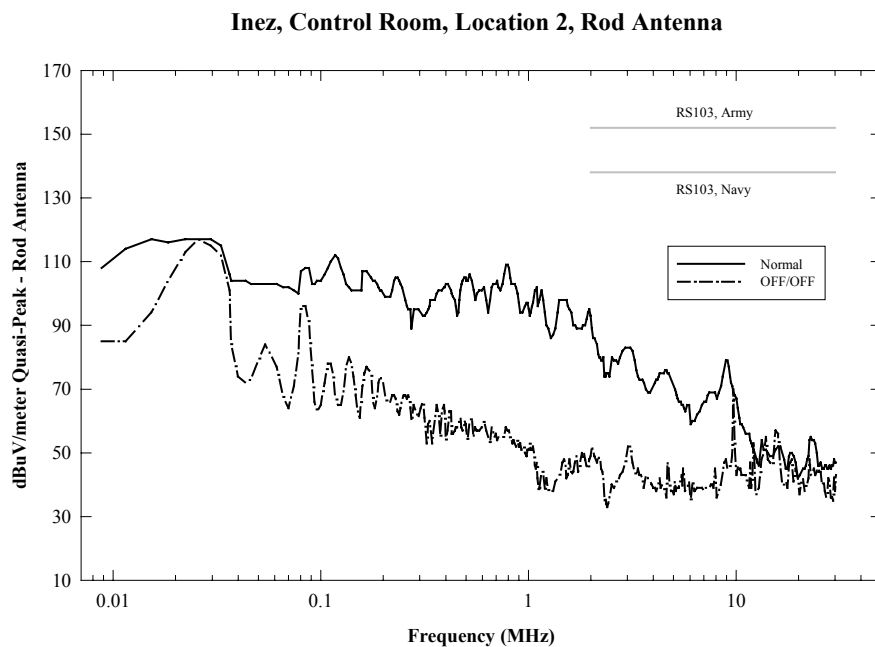


Figure 6-8
Inez, Control Room, Location 2, Rod Antenna Measurements and RS103 Limit Lines

Inverter Hall Measurements

Measured quantities were E_z , the vertical component of the electric field strength, and B_x and B_y , the two horizontal components of the magnetic flux density.

The “parallel” direction is defined as the plane of the loop (of the loop antenna) positioned parallel to the southwest (long) wall of the inverter hall. The “perpendicular” direction means that the plane of the loop was perpendicular to the same wall, after a 90 degree rotation.

Two measurement locations were selected in the Inez Inverter Hall. Figure 6-4, the layout of the Inez FACTS Station, shows both locations, denoted by 3 and 4.

The first inverter hall location (marked by 3) was under the *shunt* inverter ac bus, halfway between poles A1 and A2, 1.83 m (6 ft) from the long wall, and 10.57 m (34 ft 8 in) from the short wall common with the control room. At Location 3 the “perpendicular” direction of the plane of the loop happens to be parallel to the buses between the inverter equipment and the outdoor switchyard.

The second inverter hall location (marked by 4) was under the *series* inverter ac bus, halfway between poles E1 and E2, 1.83 m (6 ft) from the wall, and 19.56 m (64 ft 2 in) from the northwest side short wall. Similar to Location 3, at Location 4 the “perpendicular” direction of the plane of the loop happens to be parallel to the buses between the inverter equipment and the outdoor switchyard.

Measurements at both inverter hall locations were conducted only for the normal operational case.

Figures 6-9 and 6-10 show the measured noise levels and the appropriate radiated susceptibility limit lines.

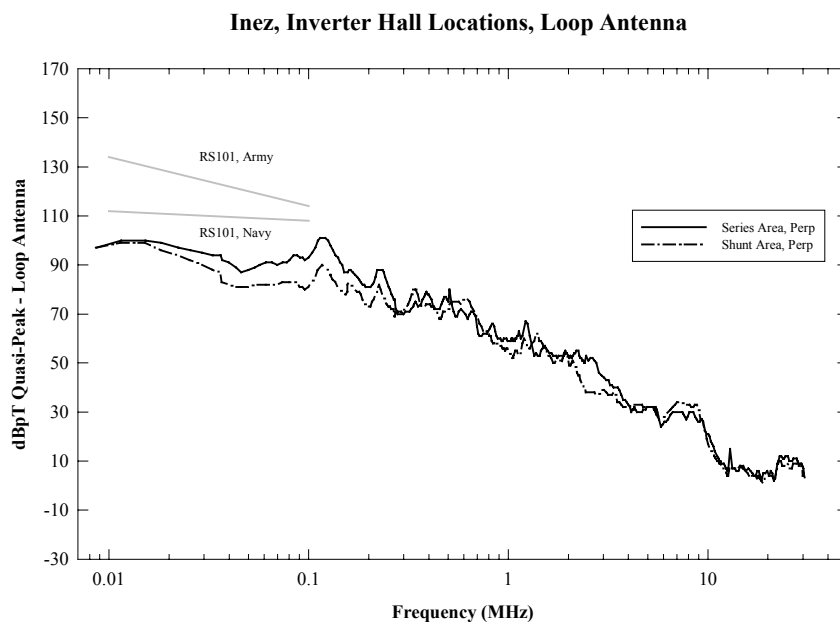


Figure 6-9
Inez, Inverter Hall, Loop Antenna Measurements with RS101 Limit Lines

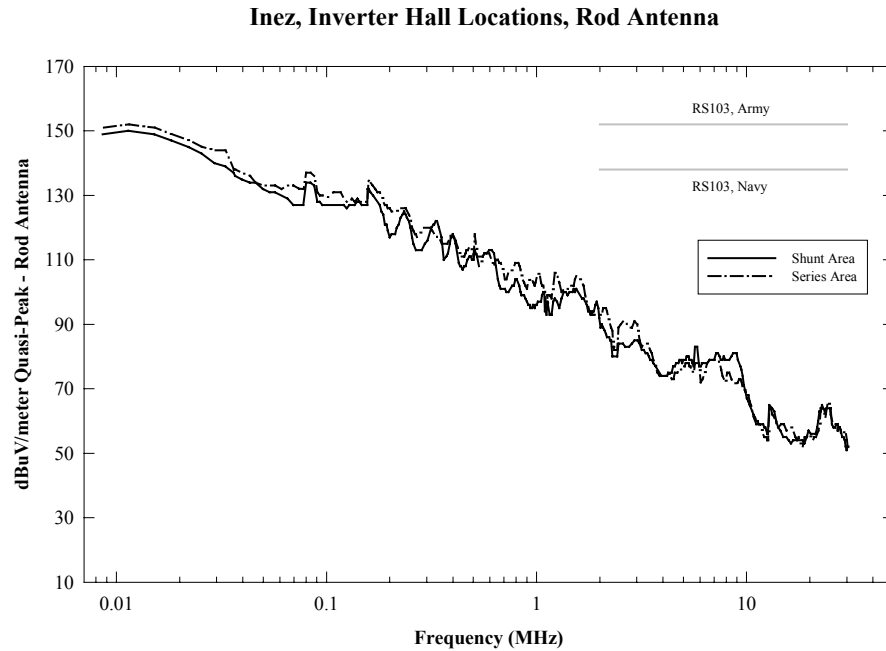


Figure 6-10
Inez, Inverter Hall, Rod Antenna Measurements with RS103 Limit Lines

Measurements Outside the Inverter Hall, in the Switchyard

Measured quantities were E_z , the vertical component of the electric field strength, and B_x and B_y , the two horizontal components of the magnetic flux density.

The “parallel” direction is defined as the plane of the loop (of the loop antenna) positioned parallel to the southwest (long) wall of the inverter hall. The “perpendicular” direction means that the plane of the loop was perpendicular to the same wall, after a 90 degree rotation.

Two measurement locations were selected in the Inez outdoor FACTS switchyard. Figure 6-4, the layout of the Inez FACTS Station, shows both locations, denoted by 5 and 6.

The first outdoor switchyard location (marked by 5) was under the *shunt* inverter ac bus, halfway between poles A1 and A2, 1.83 m (6 ft) from the wall, aligned with Location 3 inside the inverter hall. At Location 5 the “perpendicular” direction of the plane of the loop happens to be parallel to the buses between the inverter equipment and the outdoor switchyard.

The second outdoor switchyard location (marked by 6) was under the *series* inverter ac bus, halfway between poles E1 and E2, 1.83 m (6 ft) from the wall, aligned with Location 5 inside the inverter hall. At Location 6 the “perpendicular” direction of the plane of the loop happens to be parallel to the buses between the inverter equipment and the outdoor switchyard.

Measurements at both switchyard locations were conducted only for the normal operational case.

Figures 6-11, 6-12 and 6-13 show the measured noise levels and the appropriate limit lines:

- for Figure 6-11, the RS101 lines (radiated susceptibility, magnetic field),
- for Figure 6-12, the RS103 lines (radiated susceptibility, electric field),
- for Figure 6-13, the NDGPS signal level lines.

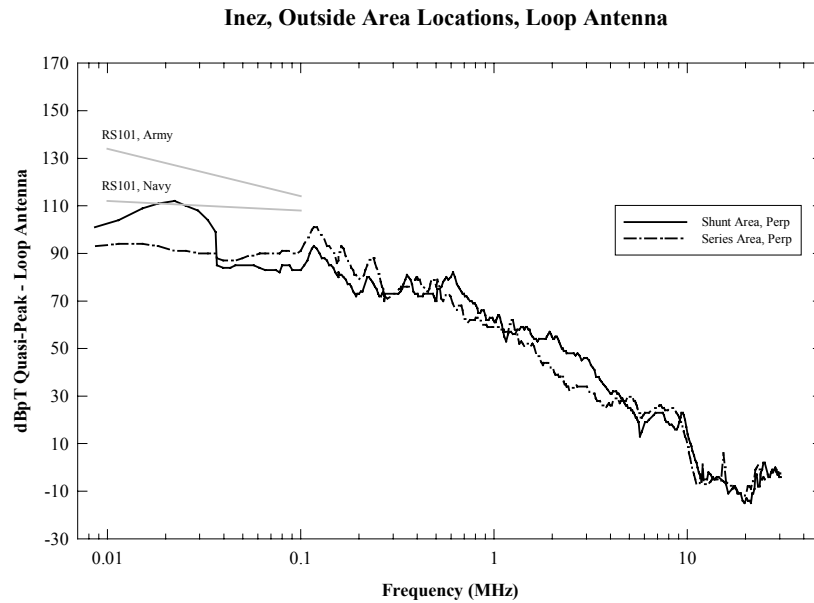


Figure 6-11
Inez, Switchyard, Loop Antenna Measurements with RS101 Limit Lines

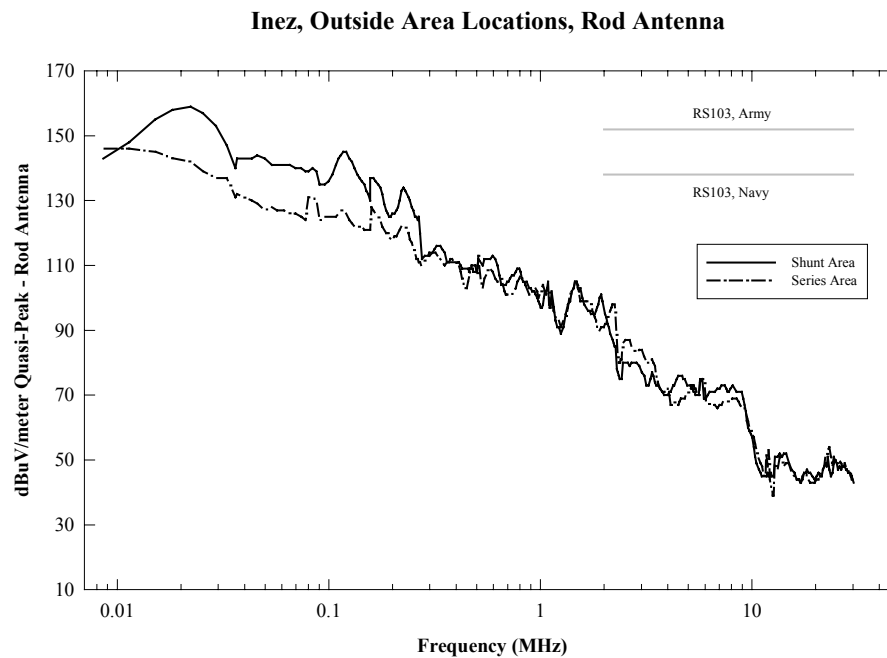


Figure 6-12
Inez, Switchyard, Rod Antenna Measurements with RS103 Limit Lines

Inez, Outside Area Locations, Rod Antenna

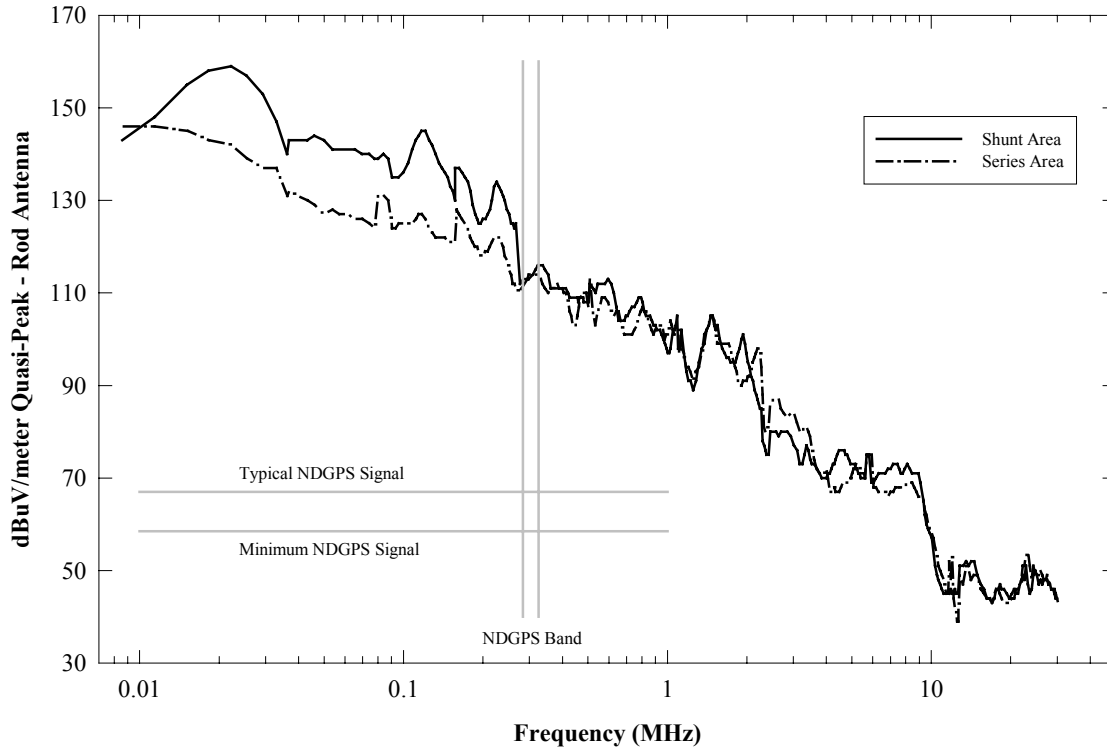


Figure 6-13
Inez, Switchyard, Rod Antenna Measurements with NDGPS Signal Levels
Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

Conducted Noise Measurements with RFCT

The output of the Electro-Metrics RFCT was monitored at three structure grounding locations in the switchyard:

- the grounding of the supporting post of the A2-B2-C2 pole
- the grounding of the intermediate transformer
- and the grounding of the supporting post of the AH-BH-CH pole.

Measurements at these three locations were conducted only for the normal operational case.

Figure 6-14 shows the measured noise levels and the appropriate CS109 (conducted susceptibility, structure current) limit lines.

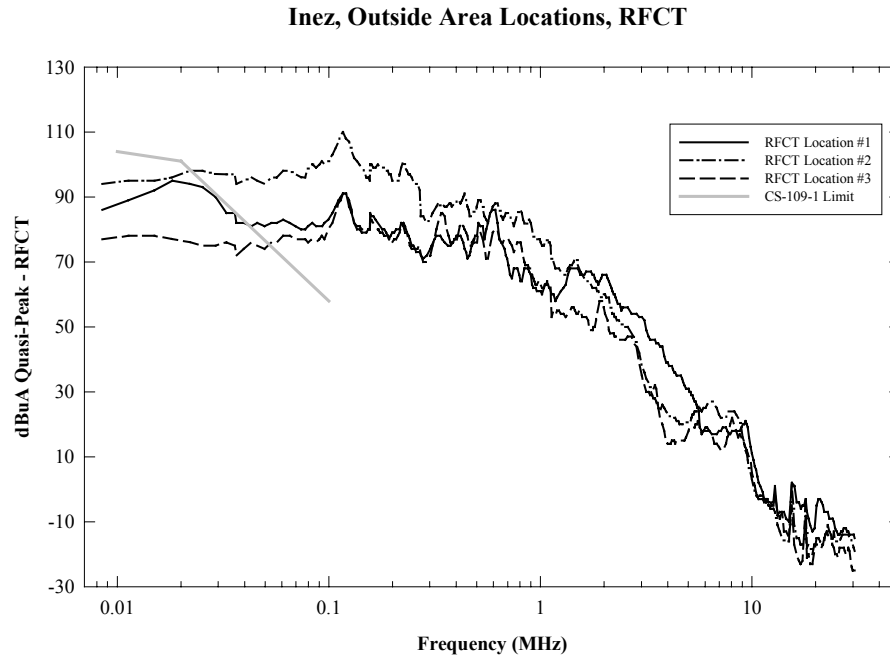


Figure 6-14
Inez, Switchyard, RFCT Measurements with CS109 Limit Lines

Power Line Measurements

Power line: Inez-Johns Creek, 138 kVrms line-to-line voltage, with horizontal arrangement of the three-phase conductors.

Measured quantity was Bx only, i.e., B component perpendicular to power line direction, at 1 m height above ground. The plane of the loop (of the loop antenna) was parallel with the power line conductors.

Phasing: All line measurements were conducted on the side of Phase C (or 3).

Distances of the measurement locations from Inez were

- at Location 1: 581 m (0.36 mi),
- at Location 2: 2123 m (1.3 mi), and
- at Location 4: 6721 m (4.16 mi).

Measurements at Location 3 were not feasible, however, the location numbers (1-2-3-4) were not changed.

At Location 1, the lateral distances of test points from the outside conductors were 15, 45, 90, and 135 meters. (Note: the “135 meter” point was at a distance of 128 meters from the Inez-Martiki 138 kV line. That is a short line, feeding the Martiki 138/69 kV station, close to the “135 meter” point.)

At the other locations, lateral distances were 15 meters only.

Conductor elevations above ground were in the range of 13-15 meters.

Figures 6-15, 6-16 and 6-17 show the power line measurement locations.

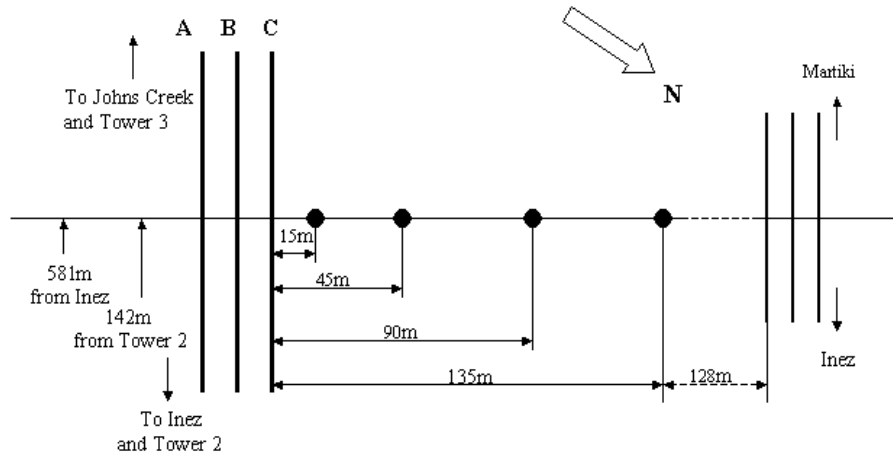


Figure 6-15
Inez-Johns Creek Line, Location 1

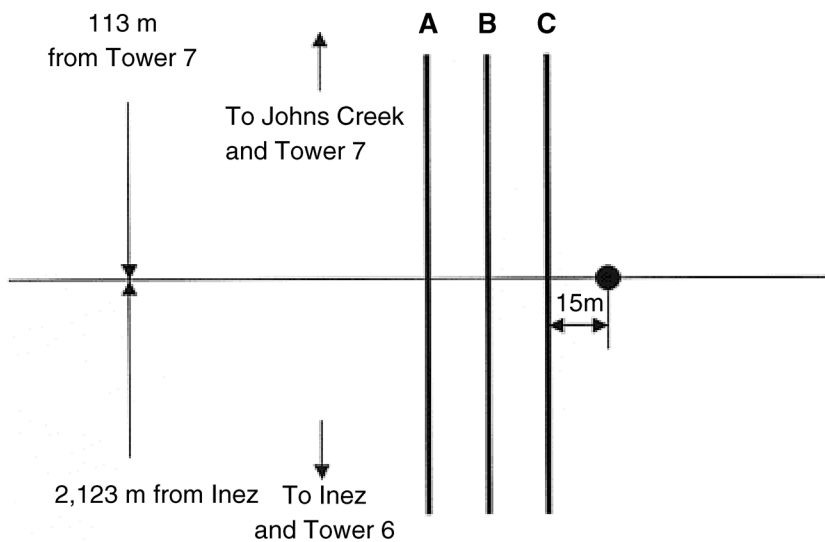


Figure 6-16
Inez-Johns Creek Line, Location 2

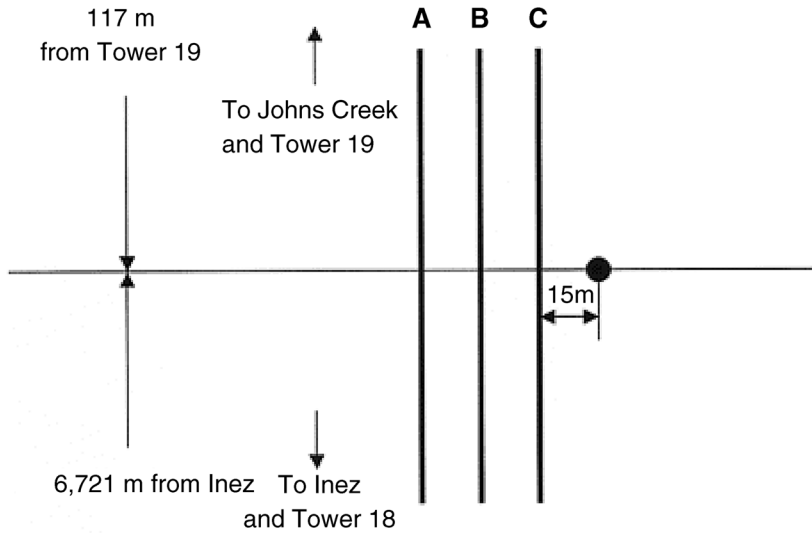


Figure 6-17
Inez-Johns Creek Line, Location 4

At Location 1, Bx measurements were performed for the 6 operational cases above. At all other locations, tests were made only for the normal case.

Figure 6-18 shows Bx levels at Location 1, at 15 m distance, for the normal case and for the case when gating was off and power supply of gating was also off. The loop antenna readings at the remote ambient location, and two limit lines (Canadian standard for fair weather, and foul weather radio noise prediction levels) are also shown.

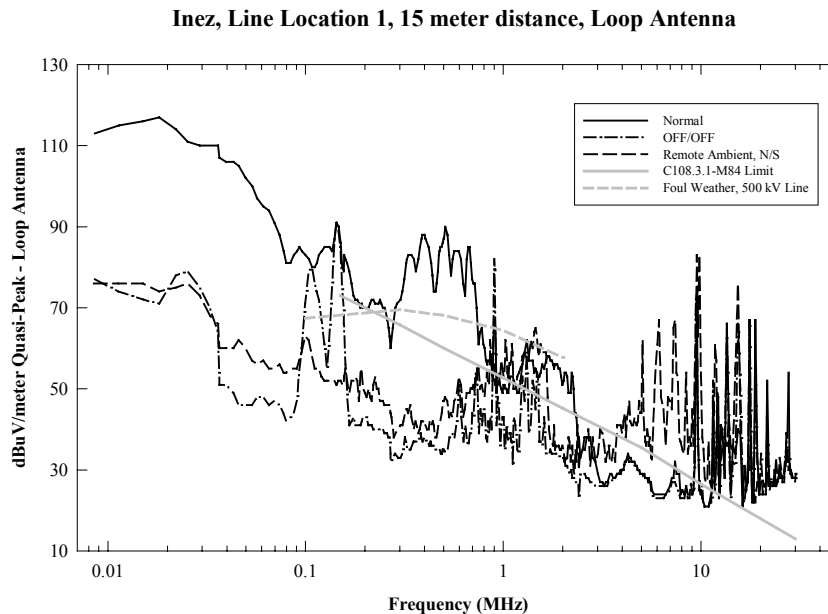


Figure 6-18
Inez-Johns Creek Line, Location 1, 15 m Distance, Normal and Off/Off Cases, Loop Antenna Measurements with Limit Lines

Please see Chapter 9 (Conclusions) for more discussion and analysis.

Figure 6-19 shows the same Bx levels at Location 1, at 15 m distance, for the normal case and for the case when gating was off and power supply of gating was also off. The loop antenna readings at the remote ambient location, and NDGPS signal level lines are also shown.

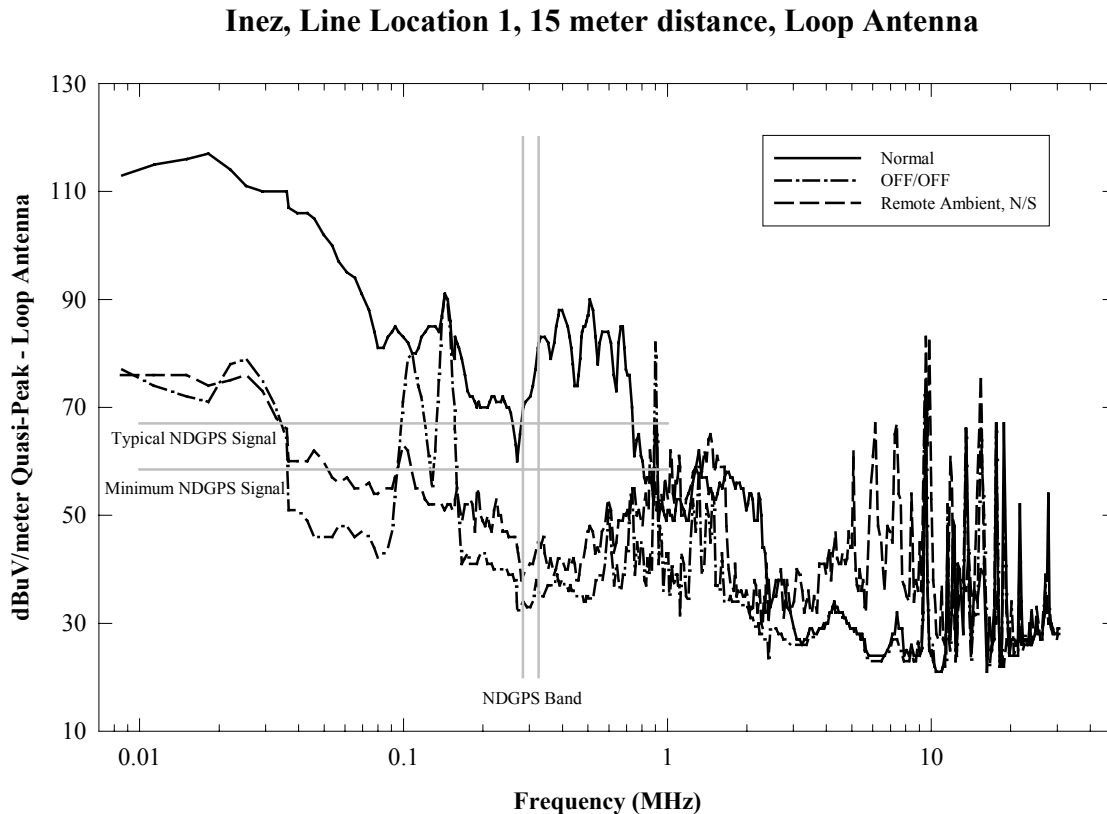
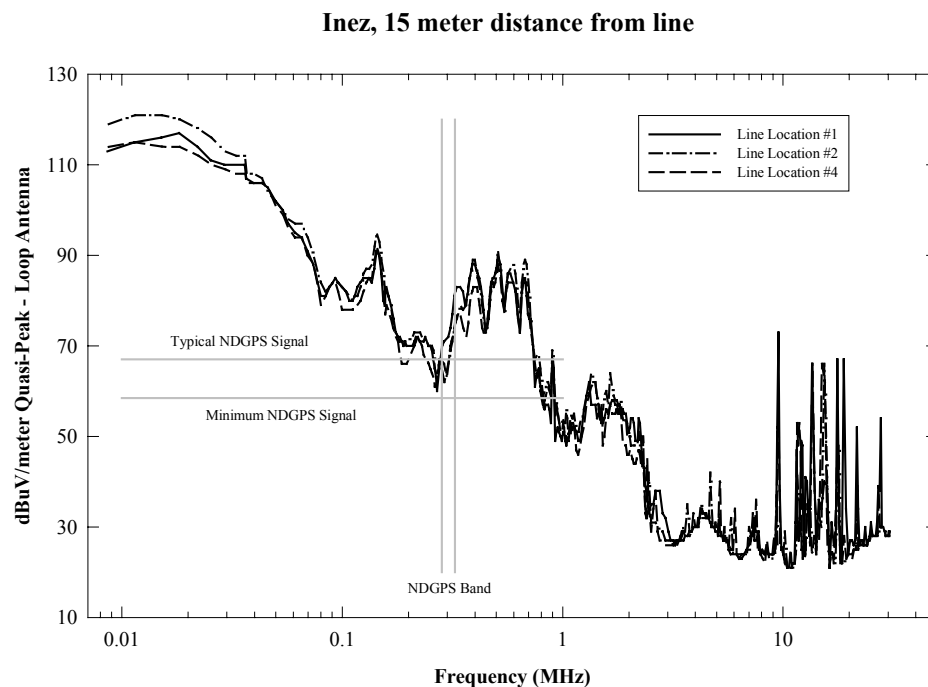
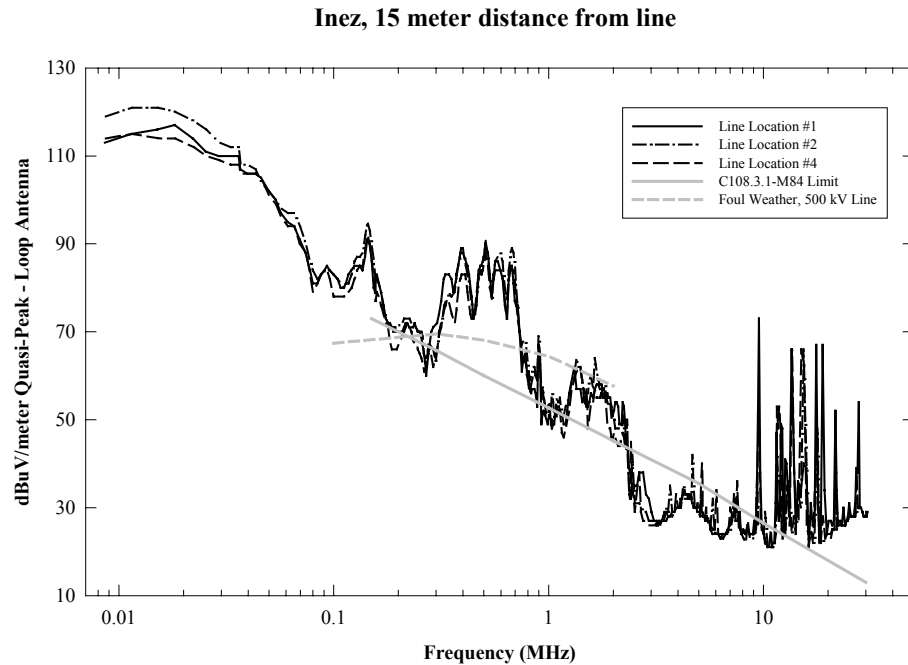


Figure 6-19
Inez-Johns Creek Line, Location 1, 15 m Distance, Normal and Off/Off Cases, Loop Antenna Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

Figures 6-20 and 6-21 may give some information related to attenuation along the Inez-Johns Creek power line. Limit lines are also shown.

More measurement details are shown in Appendix A (see Figures A-7 to A-12).



PLC Measurements

The power line protection at Inez utilizes the directional comparison blocking scheme, using power line carrier (PLC).

First, PLC measurements were conducted at Inez, with the Signal crafters 70 device on the Inez-Johns Creek line, for the same 6 operational cases listed above, in the “forward” and “reverse” test cases, with capacitor banks at Inez switched on or off.

Two measurements were conducted for each operational case. They are called in the report “Forward” and “Reverse,” following the names of the test connections and toggle switch positions of the Signal crafters 70 device.

Also, codes E-R used in the list of cases (see Figures 6-22 to 6-24, and A-13 to A-15 of Appendix A) are internal codes for identification.

Figures 6-22 to 6-24 show the forward and reverse measurement results for the normal, “off/off” and “worst” operational cases. The carrier frequency appears to be untouched. Even in the worst case, the differences between the “Forward” and “Reverse” test cases are slightly larger than 20 dB. (The horizontal lines mean the noise floor of the instrumentation.)

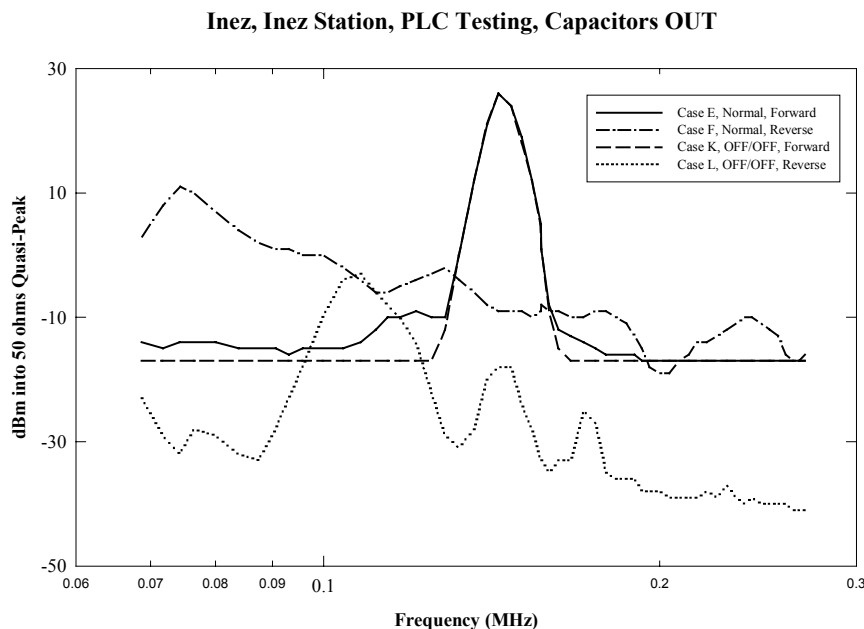


Figure 6-22
PLC Testing at Inez, Normal and Off/Off Cases, Capacitors Out, Forward and Reverse Test Cases

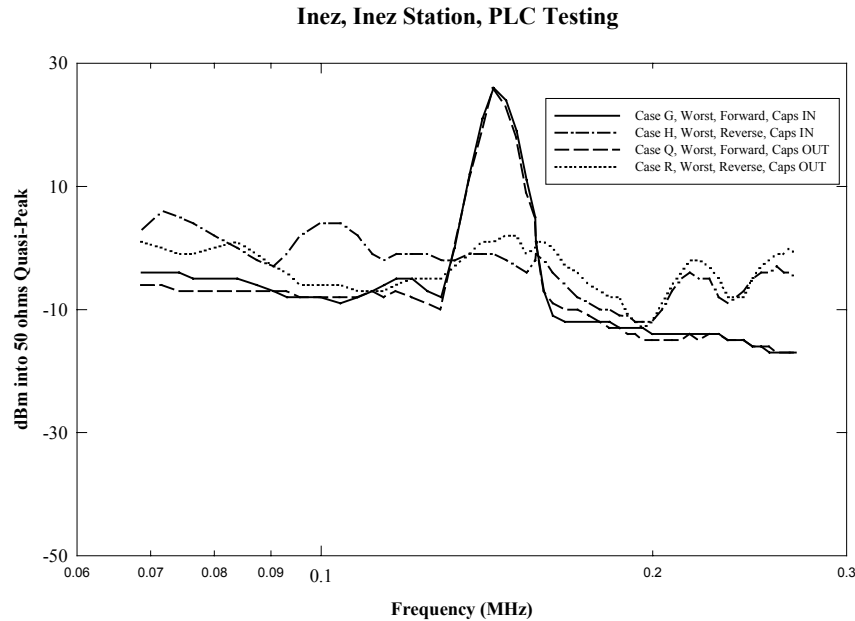


Figure 6-23
PLC Testing at Inez, Worst Case, Capacitors In and Out, Forward and Reverse Test Cases

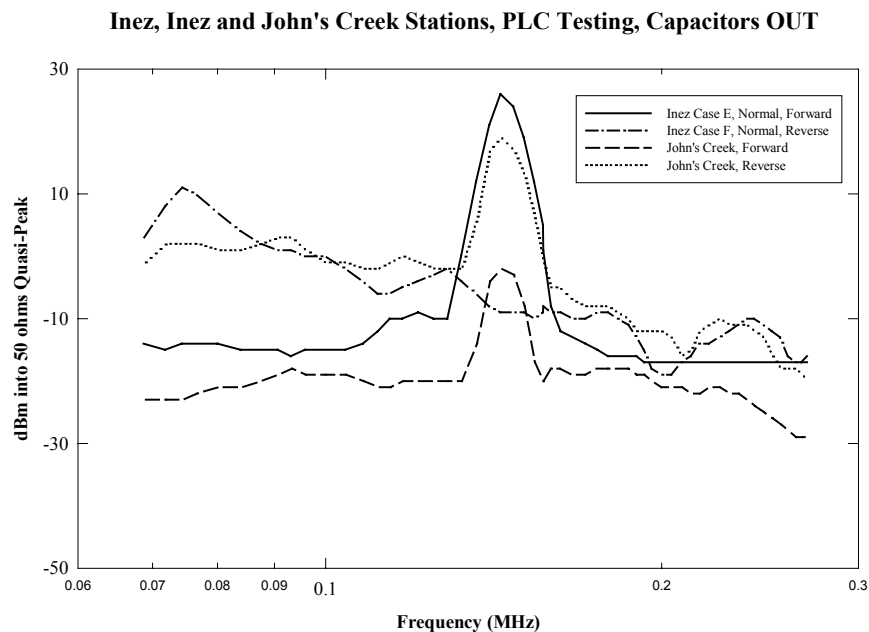


Figure 6-24
PLC Testing at Inez and Johns Creek, Normal Case, Capacitors Out, Forward and Reverse Test Cases

Then, similar measurements were conducted at the Johns Creek Station, with the Signal crafters 70 device on the Inez-Johns Creek line, only for the normal operational case, in the “Forward” and “Reverse” test cases, with capacitor banks at Inez switched on or off.

Figure 6-23 shows the effect of capacitors in the “Forward” and “Reverse” test cases. The carrier frequency was 141 kHz. Again, the carrier frequency appears to be untouched.

Similar measurements were conducted at the Beaver Creek Station, with the Signal crafters 70 device on the Beaver Creek-Johns Creek line, only for the normal operational case, in the “Forward” and “Reverse” test cases, with capacitor banks at Inez switched on or off. Beaver Creek is the second station from Inez, shown by Figure 6-25.

More measurement details are shown in Appendix A (see Figures A-13 to A-16).

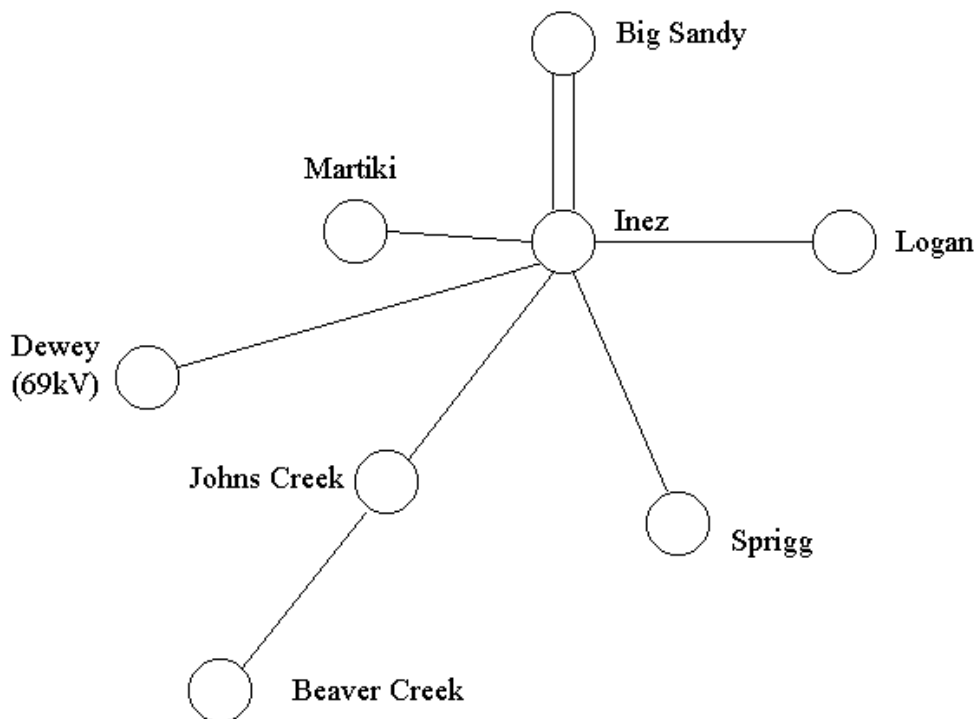


Figure 6-25
Interconnections of Stations Inez, Johns Creek, and Beaver Creek

Ambient Noise Level Measurements

Measured quantities were E_z , the vertical component of the electric field strength, and B_x and B_y , the two horizontal components of the magnetic flux density.

The ambient noise levels were measured at a reasonably remote location, close to 8:30 PM on April 18, 2002. The weather was fair; there were no storms in the area.

Figure A-17 of Appendix A shows the measured noise levels. Figure A-17 also shows that there were no strong AM radio broadcast signals at the test location. The short wave radio broadcast signal band was strong, though, compared to the ambient noise level.

Summary

The method of application of limits, and the reasons for the limits applied are described and discussed in Chapter 5.

The main characteristics of the RF noise performance of the Inez Station can be summarized as follows:

Radiated Susceptibility Limit, Magnetic Field (RS101) Limit:

- Figure 6-11 shows that the magnitude of the actual RF noise in the switchyard (shunt area, normal condition) due to the FACTS device slightly exceeds the RS101 susceptibility limit line (limit level) at about 20 kHz.
- Figures 6-7 and 6-9 show that the RF noise magnitudes in the control room (Location 2, normal condition, when the loop antenna is in the “perpendicular” direction) and in the inverter hall (both series and shunt areas, normal condition, when the loop antenna is in the “perpendicular” direction) are close to the RS101 susceptibility limit levels.
- Figures 6-5: actual RF noise levels do not exceed the RS101 susceptibility limit levels in the control room (Location 1, normal condition).

Radiated Susceptibility Limit, Electric Field (RS103) Limit:

- Figures 6-6, 6-8, 6-10, 6-12 show that the actual RF noise levels do not exceed the RS103 susceptibility limit levels at the control room, inverter hall, and outside area (switchyard) locations.

Conducted Susceptibility (Structure Current, CS109) Limit:

- Figure 6-14 shows that the three measured structure current magnitudes (normal condition) exceed the CS109 limit above a specific frequency. For instance, at Location 2 the limit is exceeded at frequencies over 25 kHz.

Canadian Standard for Fair Weather:

- Figure 6-18 shows that the measured RF noise levels at Line Location 1, 15 m distance (normal condition), due to the FACTS device exceed the limit line in a broad frequency range.

Foul Weather Radio Noise Prediction Levels:

- Figure 6-18 also shows that the measured RF noise levels (in fair weather) at Line Location 1, 15 m distance (normal condition), due to the FACTS device exceed the foul weather related limit line up to about 0.9 MHz.

NDGPS Signal Levels:

- Figure 6-13 shows that the RF noise level in the switchyard exceeds the typical NDGPS signal level.

- Figures 6-19, 6-21, and Figures A-8, A-10 and A-12 of Appendix A show that the RF noise level at Line Location 1, 15 m distance (normal condition), is close to or higher than the typical NDGPS signal level after the corrections discussed in Chapter 5.

PLC:

- Figures 6-22, 23, 24 show that during the measurements taken, the carrier frequency appears to be untouched.
- Figure 6-24 shows the smallest PLC signal-to-noise ratio of all cases measured at Inez; it is about 22 dB.

RF noise features along the Inez-Johns Creek 138 kV power line:

- Attenuation of the radiated RF noise laterally from the Inez-Johns Creek power line is shown in Figures A-11 and A-12 in Appendix A.
- Slight attenuation of the conducted RF noise along the Inez-Johns Creek power line is shown in Figures 6-20 and 6-21.

These characteristics of the RF noise performance of the Inez Station can be extended to cover conditions other than the normal—please review the additional measurement related figures in Appendix A.

7

EM NOISE MEASUREMENTS AT SULLIVAN STATION (TVA)

Introduction

The FACTS facility at Sullivan Station (Tennessee) owned by TVA is a Static Synchronous Compensator (STATCOM), the first such high-power facility in the United States. It has been in service since 1995. It is used for voltage control and for power system stabilization purposes. The rating of the STATCOM is ± 100 MVA. It regulates the voltages of the 161 kV buses, and it controls a 161 kV, 84 MVar capacitor bank. Figure 7-1 shows the simplified diagram of the FACTS (STATCOM) facility installed in Sullivan Station [1]. Figure 7-2 is the simplified layout of the FACTS building including the main components [1]. Figure 7-3 is the aerial view of the FACTS facility at Sullivan Station [1].

Measurements at Sullivan Station were conducted from May 13 to May 17, 2002.

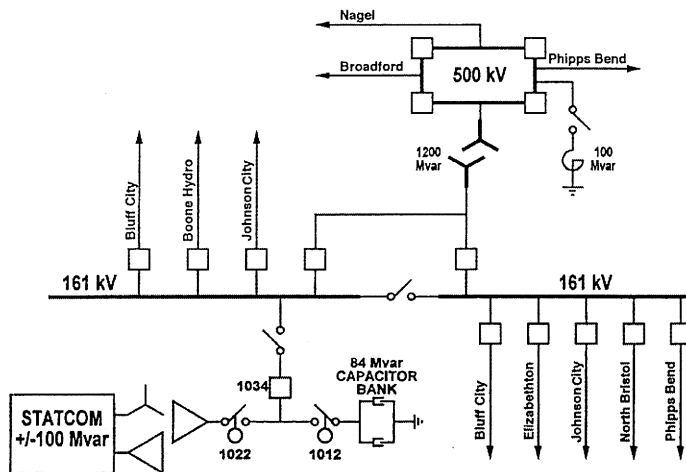


Figure 7-1
Simplified Diagram of the STATCOM Installed at Sullivan Station [1]

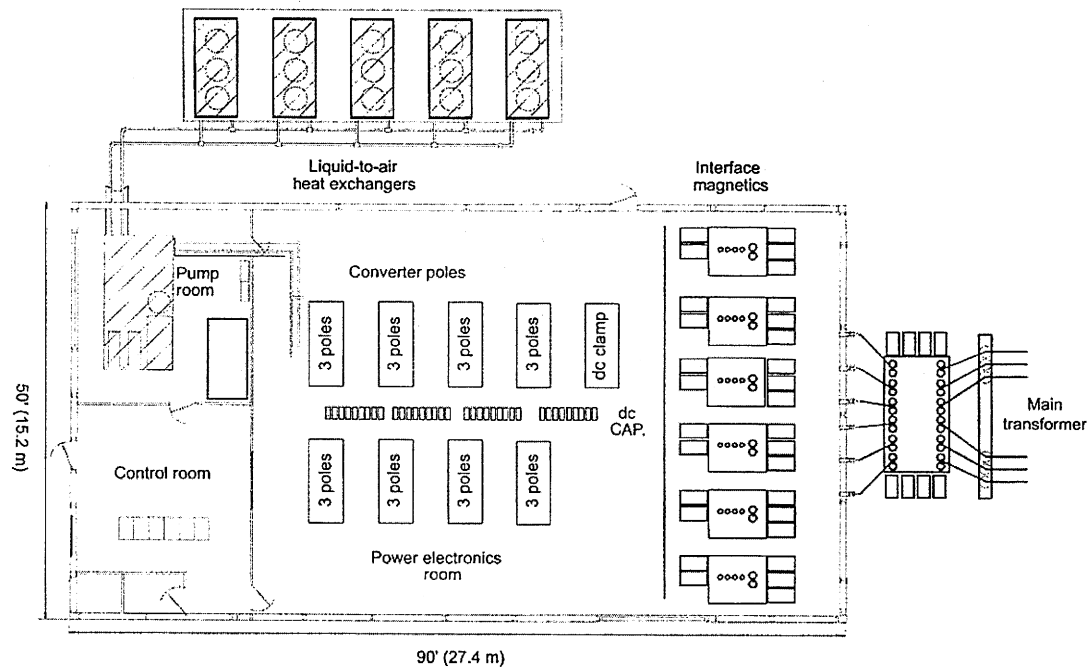


Figure 7-2
Simplified Layout of the STATCOM Building with the Main STATCOM Components at Sullivan Station [1]

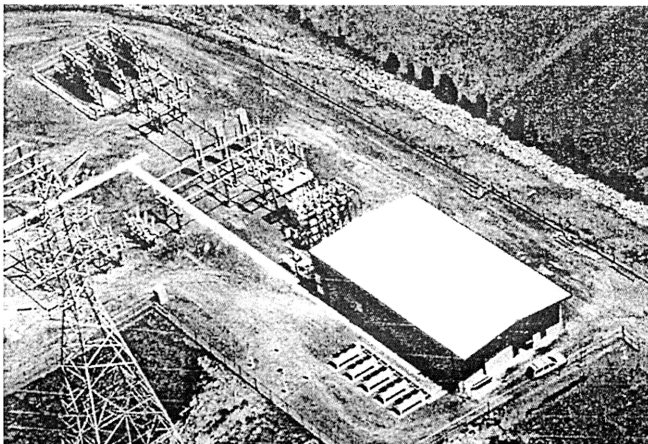


Figure 7-3
Aerial View of the FACTS Facility at Sullivan Station [1]

Operational Cases

There were four operational cases observed at Sullivan Station:

- Normal case, shunt inverter was on at normal load and voltage levels, capacitor bank was on.
- Gating was off, power supply of gating was also off ("off/off" case).

- Gating was off, power supply of gating was on (“off/on” case).
- Worst case in terms of radio frequency (RF) noise: shunt inverter was on, voltage level was close to normal, capacitor bank was on, inverter absorbed high MVar flow (i.e., the STATCOM behaved like an inductance, absorbing reactive power -- it is considered to be negative at Sullivan, though the same case is considered to be positive at Inez).

Several sub-cases were also utilized for some of the measurements, pending on capacitor bank switching on or off conditions at Sullivan Station.

General Measurement Information

For the selection of so-called “hot spots” in the control room and at other locations in the station a portable EMI instrument (RF Sniffer) was used. Both frequency spectrum ranges (200-450 kHz and 2-11 MHz) were utilized for such measurements.

The frequency spectrum for all Ez, Bx, By measurements was from 9 kHz to 30 MHz.

The frequency spectrum for all RFCT measurements was from 9 kHz to 30 MHz.

The frequency spectrum for all PLC measurements was from about 70 kHz to 270 kHz (Bands 3 and 4).

For all test points of power line and ambient field measurements the following conditions were recorded (see Table 7-1):

- latitude, and longitude information, obtained by a GPS system
- temperature, pressure, and relative humidity of the ambient air.

In all cases the height of the antenna ground plane was 1 meter.

Control Room Measurements

Measured quantities were Ez, the vertical component of the electric field strength, and Bx and By, the two horizontal components of the magnetic flux density.

To define again the terminology, the term “parallel position” is used when the plane of the loop (of the loop antenna) was vertical and parallel to a well-defined facility, such as a panel, bus or a wall in the area of the measurement location. The term “perpendicular position” is used when the plane of the loop (of the loop antenna) was kept vertical but rotated by 90 degrees, and it became perpendicular to the same well-defined facility.

Figure 7-4 shows the layout of the Sullivan FACTS Station.

Table 7-1
Test Locations and Atmospheric Conditions at Sullivan Station

Test Location	Latitude (North) and Longitude (West) info.	Temp., Pressure, and Relative Humidity Info.
Sullivan–N. Bristol Line Location #1, 15 m laterally	N 36 deg 30' 47.9" W 82 deg 18' 29.3"	67 deg F, 28.63 inHg 48 % RH
Sullivan–N. Bristol Line Location #1, 45 m laterally	N 36 deg 30' 47.8" W 82 deg 18' 30.5"	same as above
Sullivan–N. Bristol Line Location #1, 90 m laterally	N 36 deg 30' 47.3" W 82 deg 18' 32.3"	same as above
Sullivan–N. Bristol Line Location #2	N 36 deg 33' 38.2" W 82 deg 16' 43.0"	Not taken
Sullivan–N. Bristol Line Location #3A	N 36 deg 35' 44.7" W 82 deg 15' 41.0"	Not taken
Sullivan–N. Bristol Line Location #3B	N 36 deg 35' 43.3" W 82 deg 15' 40.7"	Not taken
Sullivan–Broadford Line (500 kV)	N 36 deg 26' 30.1" W 82 deg 15' 10.2"	75 deg F, 28.60 inHg, 42 % RH
Test Location for Ambient Field Level	N 36 deg 31' 12.5" W 82 deg 15' 23.7"	Not taken

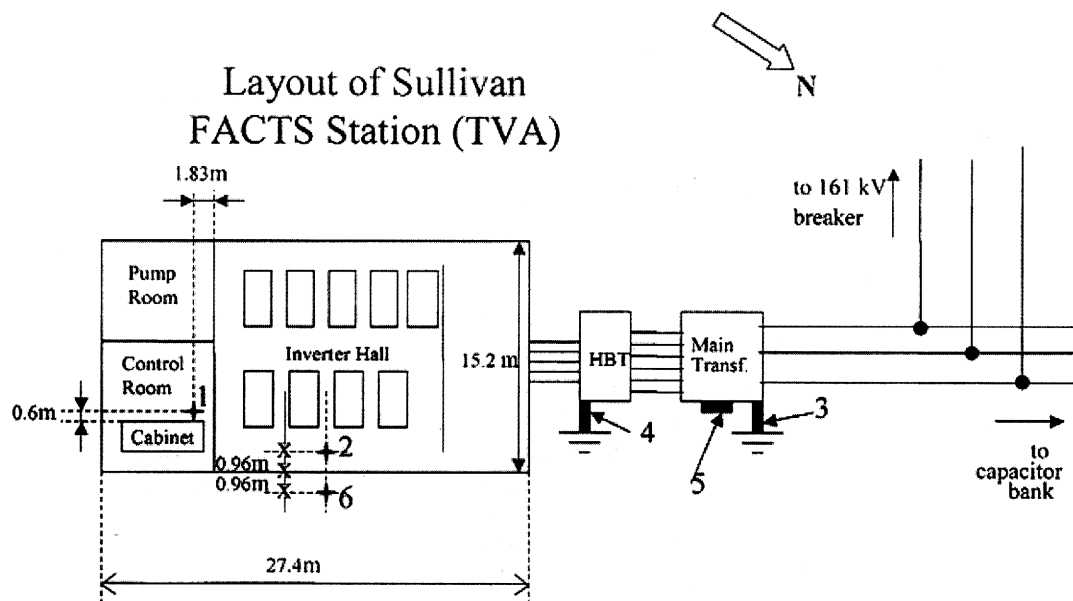


Figure 7-4
Layout of Sullivan FACTS Station with Measurement Locations 1-6
(HBT: Harmonic Blocking Transformer)

The control room location (Figure 7-4, marked by 1) was 1.83 m (6 ft) from the wall separating the control room and the inverter hall, 0.6 m (22 in) from the equipment cabinet. “Parallel” means that the plane of the loop was parallel to the equipment cabinet panels.

Measurements at the control room location were conducted for all four operational cases.

Figures 7-5 and 7-6 show the measured RF noise levels and the appropriate radiated susceptibility limit lines in the normal case. Both figures show the levels for the normal operational case, and for the “off/off” and “off/on” cases as well. However, it should be noted that in the “off/off” case the power for the control room equipment and for the computers there was still on.

Inverter Hall Measurements

Measured quantities were E_z , the vertical component of the electric field strength, and B_x and B_y , the two horizontal components of the magnetic flux density.

The “parallel” direction is defined as the plane of the loop (of the loop antenna) positioned parallel to the northeast (long) wall of the inverter hall. The “perpendicular” direction means that the plane of the loop was perpendicular to the same wall, after a 90 degree rotation.

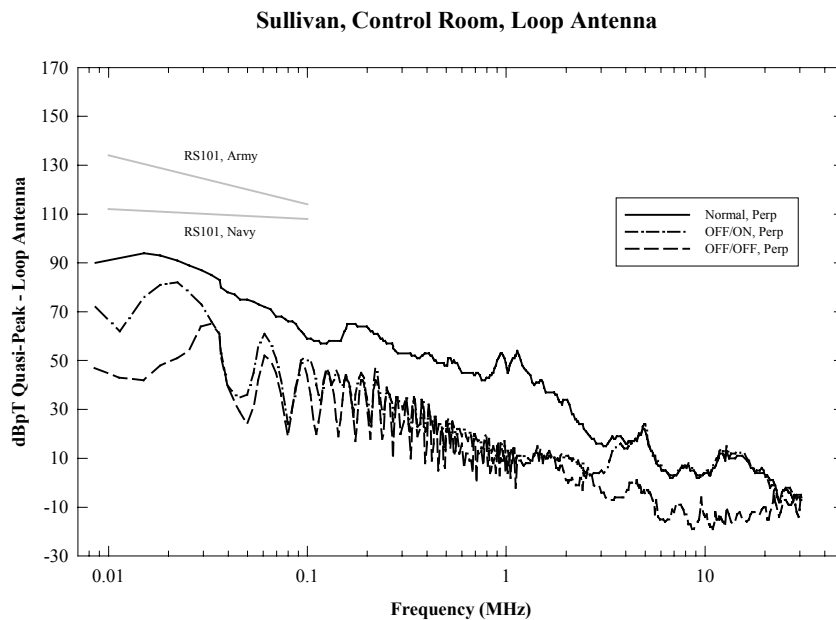


Figure 7-5
Sullivan, Control Room, Normal, Off/On and Off/Off Cases,
Loop Antenna Measurements and RS101 Limit Lines

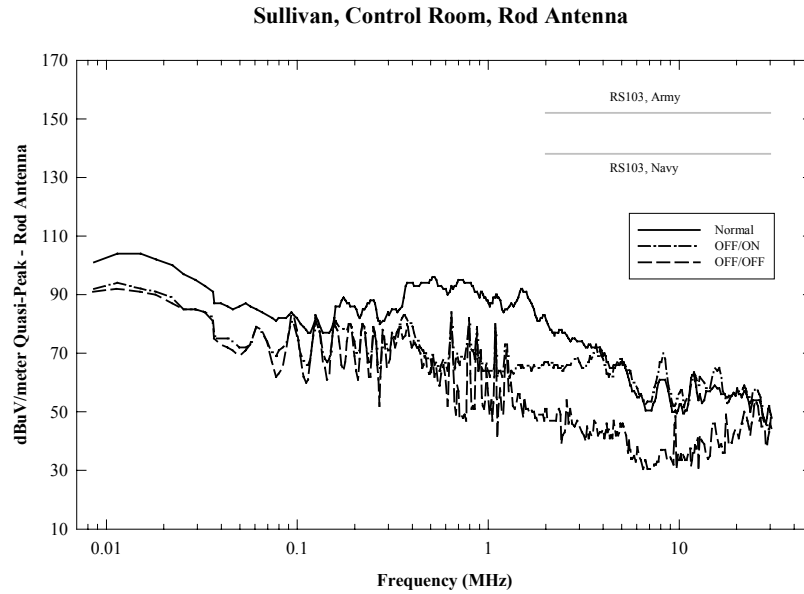


Figure 7-6
Sullivan, Control Room, Normal, Off/On and Off/Off Cases, Rod Antenna Measurements and RS103 Limit Lines

The inverter hall location selected (Figure 7-4, marked by 2) was half-way between poles D2 and D3, 0.96 m (38 in) from the wall.

Measurements at the inverter hall location were conducted only for the normal operational case.

Figures 7-7 and 7-8 show the measured noise levels and the appropriate radiated susceptibility limit lines.

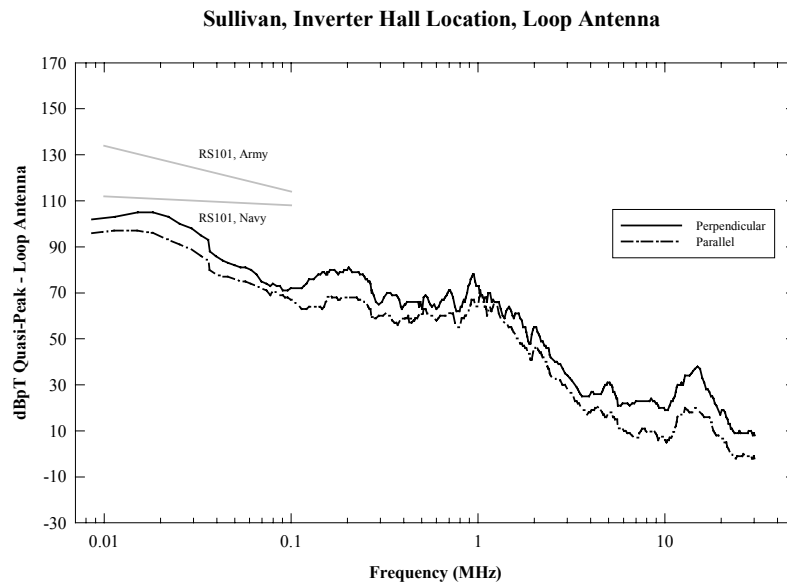


Figure 7-7
Sullivan, Inverter Hall, Normal Case, Loop Antenna Measurements and RS101 Limit Lines

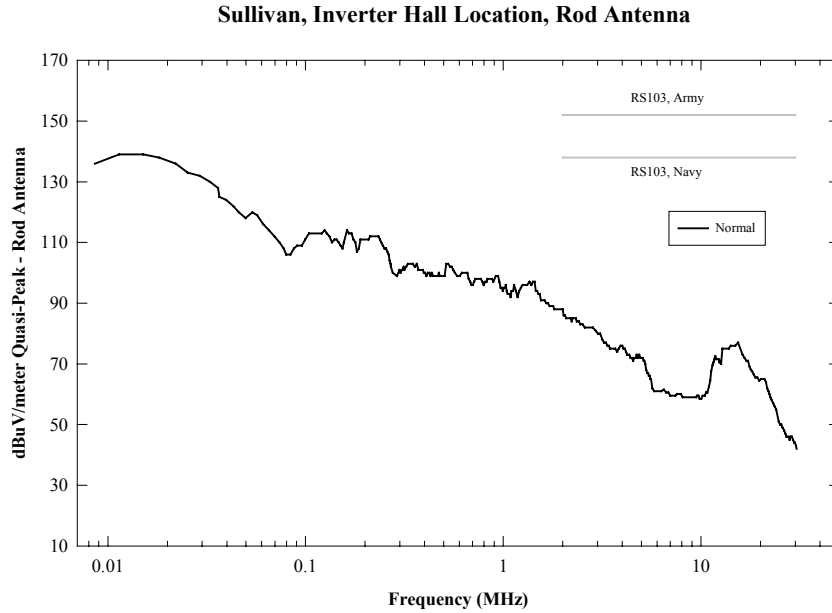


Figure 7-8
Sullivan, Inverter Hall, Normal Case, Rod Antenna Measurements
with RS103 Limit Lines

Measurements Outside the Inverter Hall

Measured quantities were E_z , the vertical component of the electric field strength, and B_x and B_y , the two horizontal components of the magnetic flux density.

The “parallel” direction is defined as the plane of the loop (of the loop antenna) positioned parallel to the northeast (long) wall of the inverter hall. The “perpendicular” direction means that the plane of the loop was perpendicular to the same wall, after a 90 degree rotation.

The measurement location selected (Figure 7-4, marked by 6) was half-way between poles D2 and D3, 0.96 m (38 in) from the wall, mirroring the test location (marked by 2) in the inverter hall.

Note that the “switchyard” measurement location at Sullivan was significantly away from the buses. At Inez, the “switchyard” location was right under the buses.

Measurements at this location were conducted only for the normal operational case.

Figures 7-9, 7-10 and 7-11 show the measured noise levels and the appropriate limit lines.

- for Figure 7-9, the RS101 lines (radiated susceptibility, magnetic field),
- for Figure 7-10, the RS103 lines (radiated susceptibility, electric field),
- for Figure 7-11, the NDGPS signal level lines.

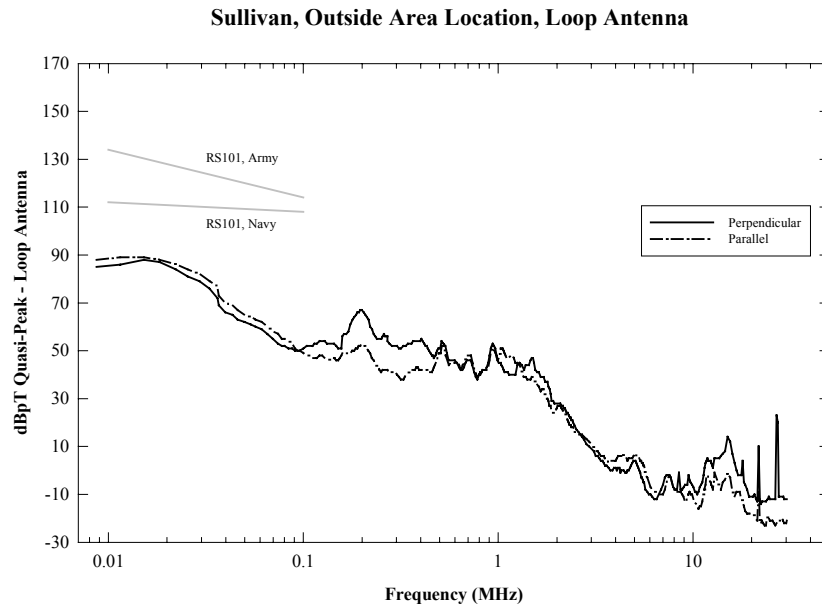


Figure 7-9
Sullivan, Outside Inverter Hall, Normal Case, Loop Antenna Measurements with RS101 Limit Lines

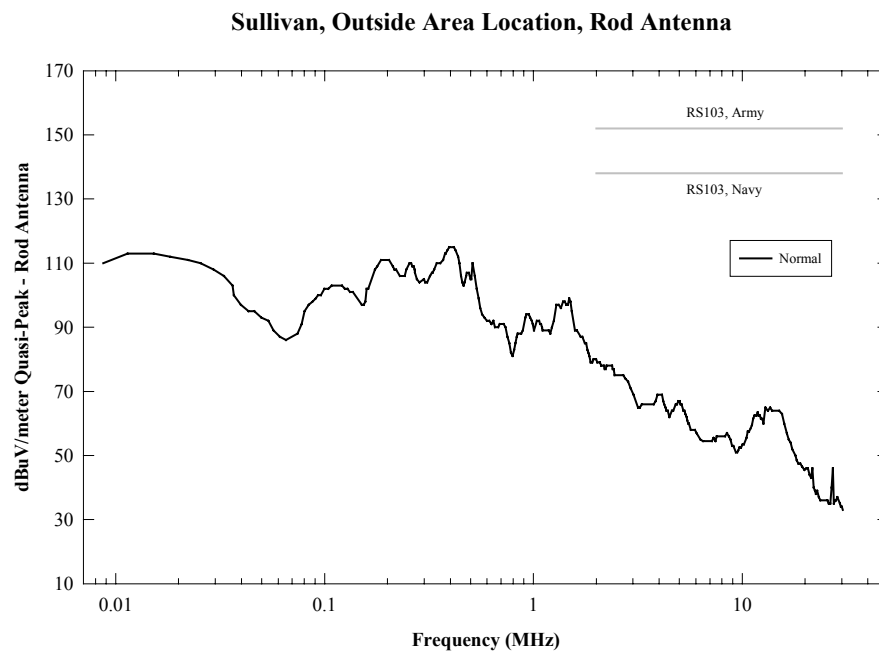


Figure 7-10
Sullivan, Outside Inverter Hall, Normal Case, Rod Antenna Measurements with RS103 Limit Lines

Sullivan, Outside Area Location, Rod Antenna

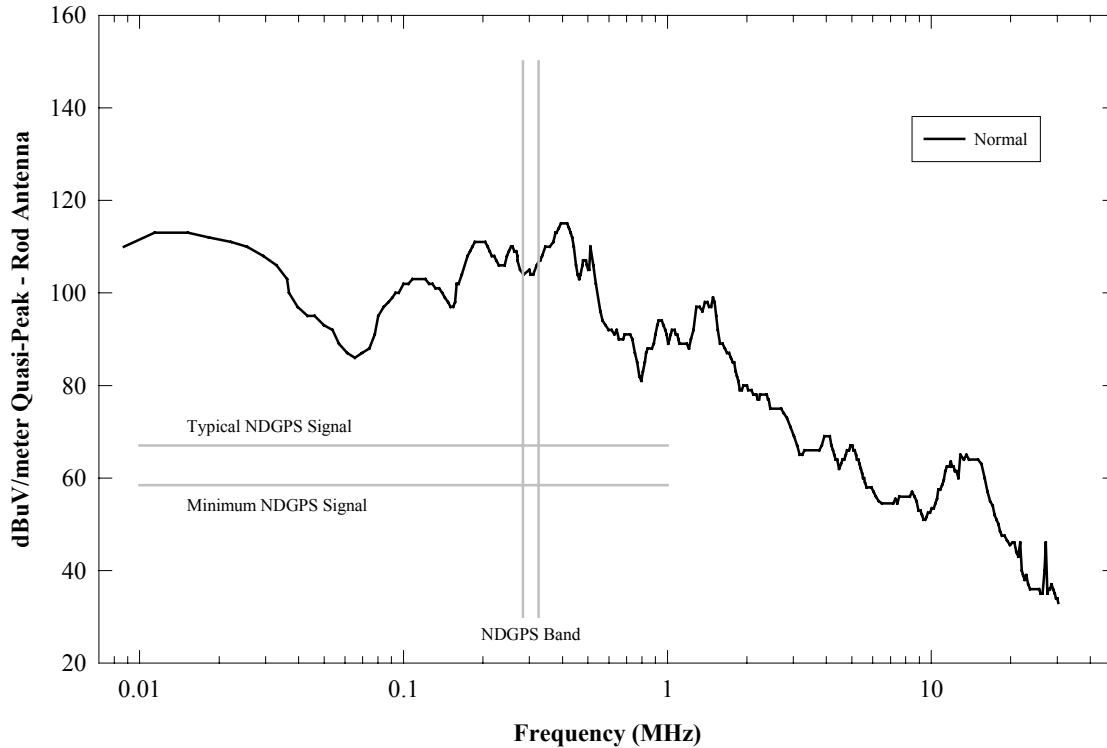


Figure 7-11
Sullivan, Outside Inverter Hall, Normal Case, Rod Antenna Measurements with NDGPS
Signal Levels Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

Conducted Noise Measurements with RFCT

The output of the Electro-Metrics RFCT was monitored at three structure grounding locations in the switchyard:

- the grounding of the main (No.2) transformer of the STATCOM (Figure 7-4, marked by 3)
- the grounding of a bus support at the harmonic blocker (Figure 7-4, marked by 4)
- and at one of the radiator interconnection bar of the main transformer (Figure 7-4, marked by 5).

Measurements at these three locations were conducted only for the normal operational case.

Figure 7-12 shows the measured structure current levels and the appropriate CS109 (conducted susceptibility, structure current) limit lines.

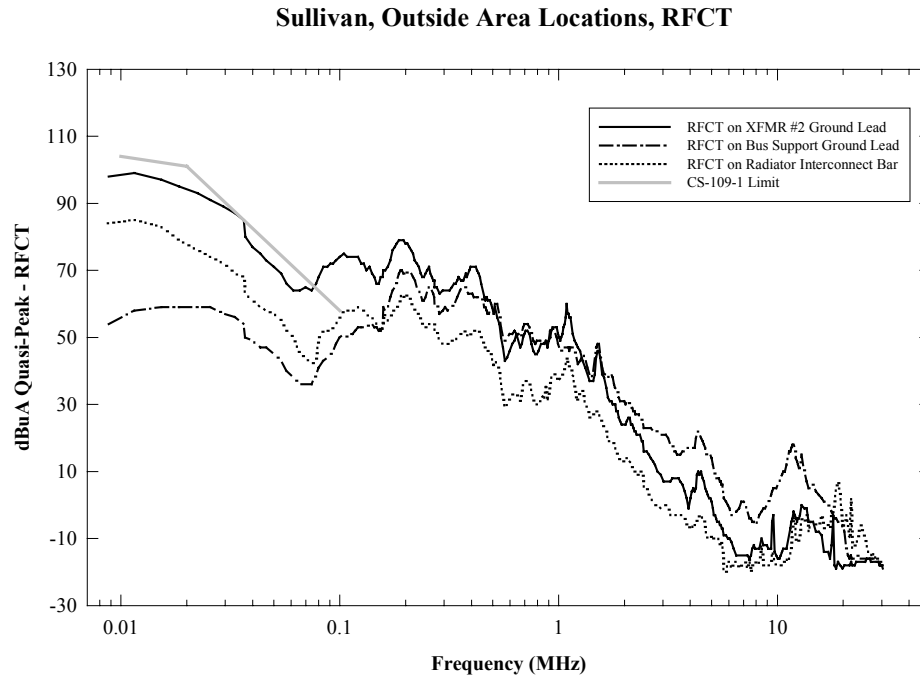


Figure 7-12
Sullivan, Switchyard, RFCT Measurements with CS109 Limit Lines

Power Line Measurements

161 kV Line

Power line: Sullivan–North Bristol, 161 kVrms line-to-line voltage, with horizontal arrangement of the three-phase conductors over the test section.

Measured quantity was Bx, i.e., B component perpendicular to the power line direction, at 1 m height above ground. The plane of the loop (of the loop antenna) was parallel with the power line conductors.

Phasing: All line measurements were conducted on the side of Phase A (or 1).

Distances of the measurement locations from Sullivan were

- at Location 1: 8,453 m (5.25 mi),
- at Location 2: 14,336 m (8.91 mi), and
- at Location 3: 19,772 m (12.29 mi).

At Location 1, the lateral distances of test points from the outside conductors were 15, 45, and 135 meters.

At the other locations, lateral distances were 15 meters only.

At Location 3, 15 meter distance from Phase A was not possible due to dense shrubbery. Therefore, a test point on the other side of the line, 15 m from Phase C was used. (Location #3B).

Conductor elevations above ground were in the range of 9-10 meters.

Figures 7-13, 7-14 and 7-15 show the 161 kV power line measurement locations.

At Location 1, Bx measurements were performed for the 4 operational cases above. At all other locations, tests were made only for the normal case.

Figure 7-16 shows the comparison of RMS and QP (CISPR) readings at Location 1, at 15 m distance, for normal case, measured by the loop antenna.

The average difference between the RMS and QP (CISPR) reading is about 5 dB. In other words,
 $dB\ RMS = dB\ QP - 5\ dB$

Note the signatures of the PLC along the line at about 85 kHz, and the AM radio stations (0.5-1.6 MHz) and shortwave radio stations as well (6-30 MHz).

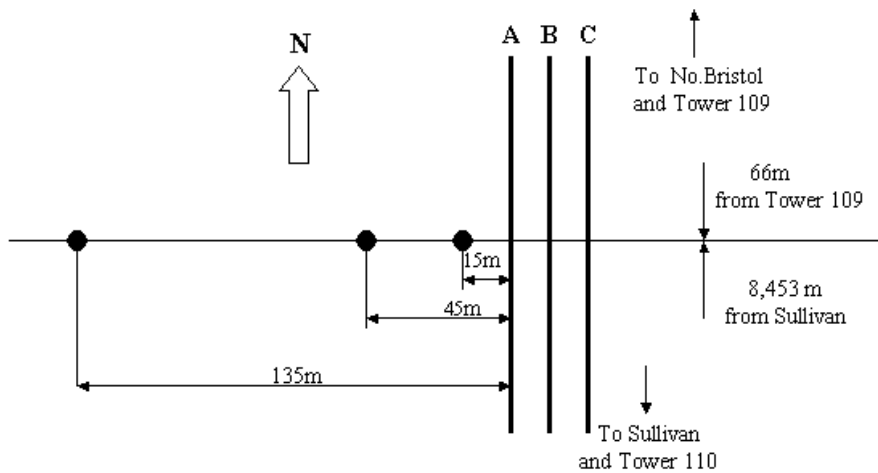


Figure 7-13
Sullivan-North Bristol Line, Location 1

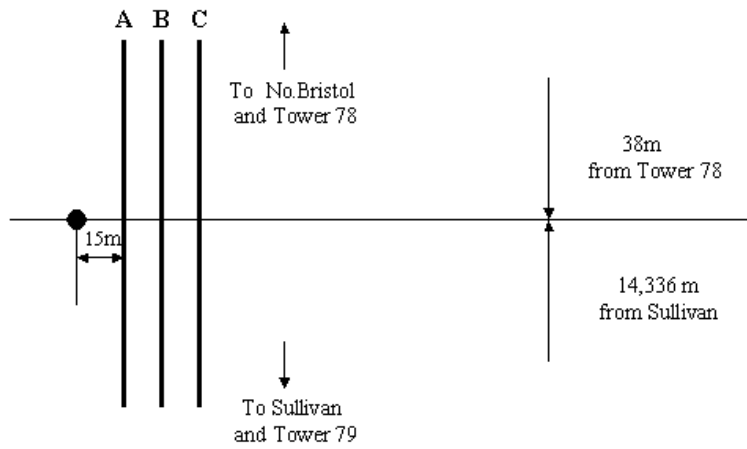


Figure 7-14
Sullivan–North Bristol Line, Location 2

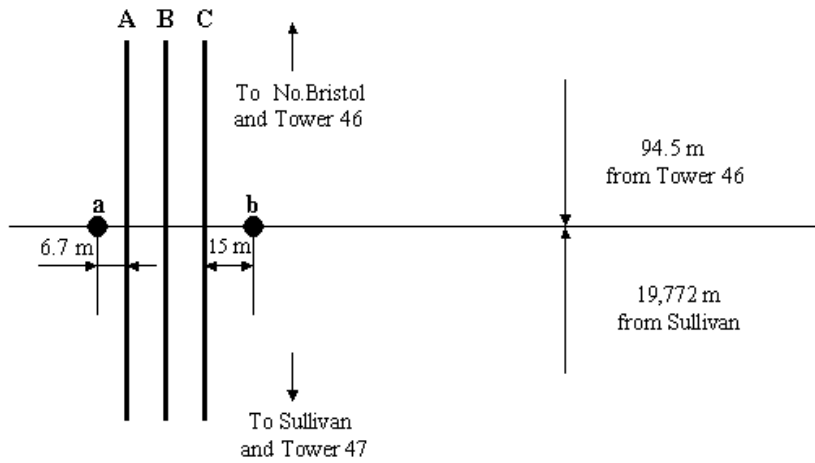


Figure 7-15
Sullivan–North Bristol Line, Location 3

Sullivan, Line Location #1, 15 meter distance, Loop Antenna

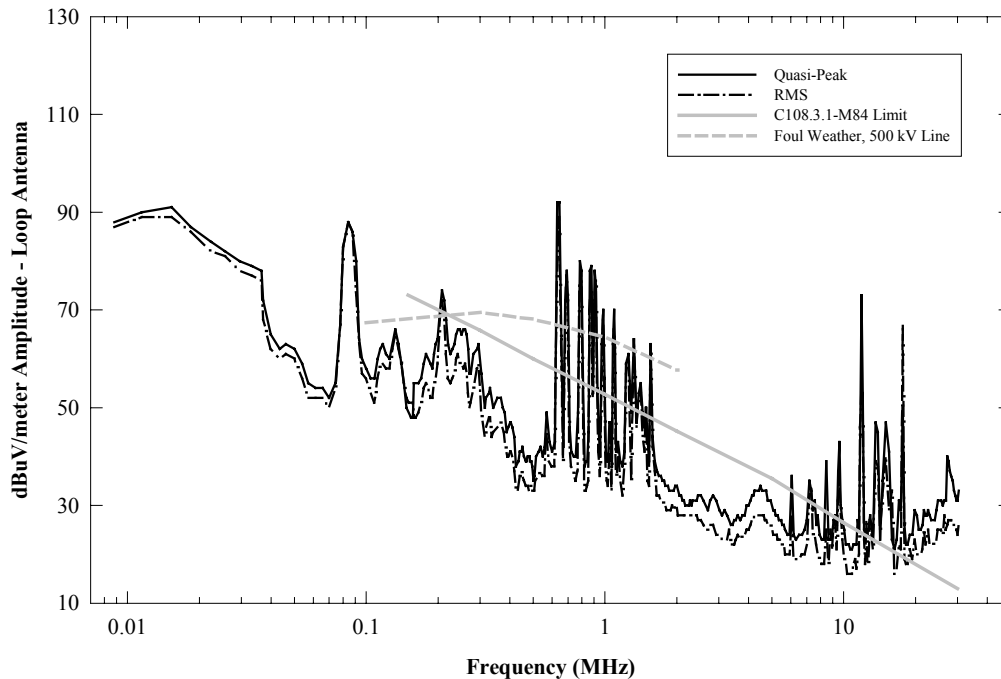


Figure 7-16
Sullivan–North Bristol Line, Location 1, 15 m Distance, Normal Case,
Loop Antenna Measurements, Comparison of RMS and QP (CISPR) Readings

Figure 7-17 shows Bx levels at Location 1, at 15 m distance, for the normal case and for the case when gating was off and power supply of gating was also off (“off/off” case). The loop antenna readings at the remote ambient location, and two limit lines (Canadian standard for fair weather, and foul weather radio noise prediction levels) are also shown.

Please see Chapter 9 (Conclusions) for more discussion and analysis.

Figure 7-18 shows the same Bx levels at Location 1, at 15 m distance, for the normal case and for the “off/off” case. The loop antenna readings at the remote ambient location, and NDGPS signal level lines are also shown.

An airport non-directional beacon (TR) was detected during the Sullivan remote ambient measurements. Its frequency is 299 kHz. It is a beacon for the nearby Johnson City/Bristol/Kingsport area airport, listed as “Mocca.” The beacon location is at

- N 36 deg 33’ 19.670”
- W 82 deg 19’ 04.501”

Figures 7-19 and 7-20 may give some information related to attenuation. Limit lines are also shown.

More measurement details are shown in Appendix B (see Figures B-1 to B-5).

Sullivan, Line Location #1, 15 meter distance, Loop Antenna

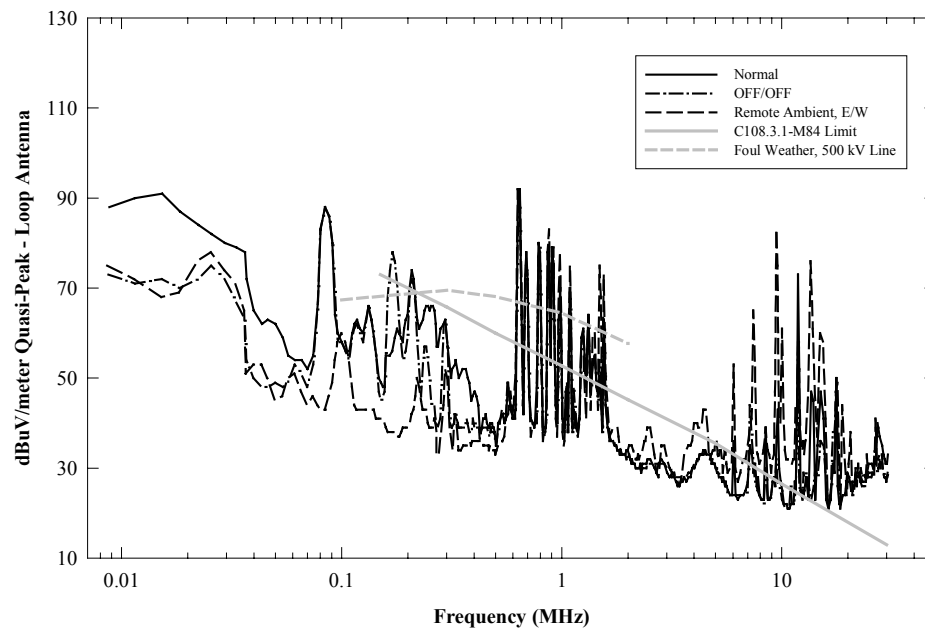


Figure 7-17
Sullivan–North Bristol Line, Location 1, 15 m Distance, Loop Antenna Measurements with Limit Lines

Sullivan, Line Location #1, 15 meter distance, Loop Antenna

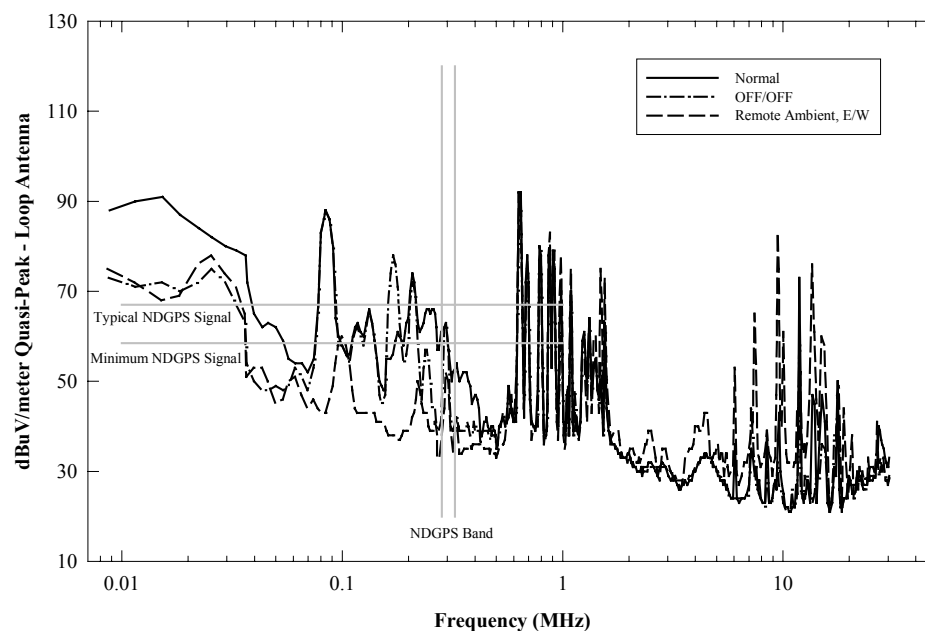


Figure 7-18
Sullivan–North Bristol Line, Location 1, 15 m Distance, Loop Antenna Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

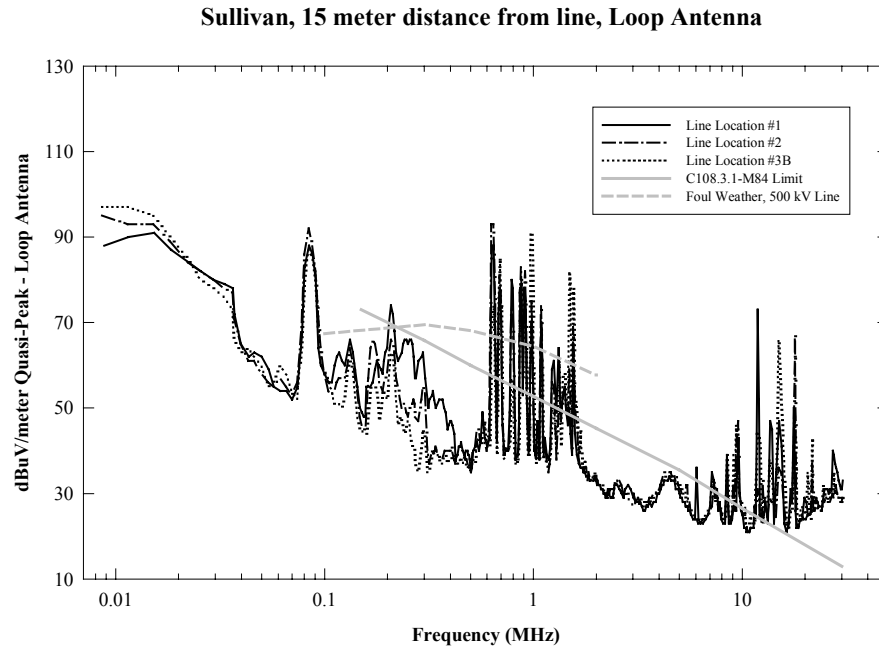


Figure 7-19
Sullivan–North Bristol Line, Locations 1-2-3B, 15 m Distance, Loop Antenna
Measurements with Limit Lines

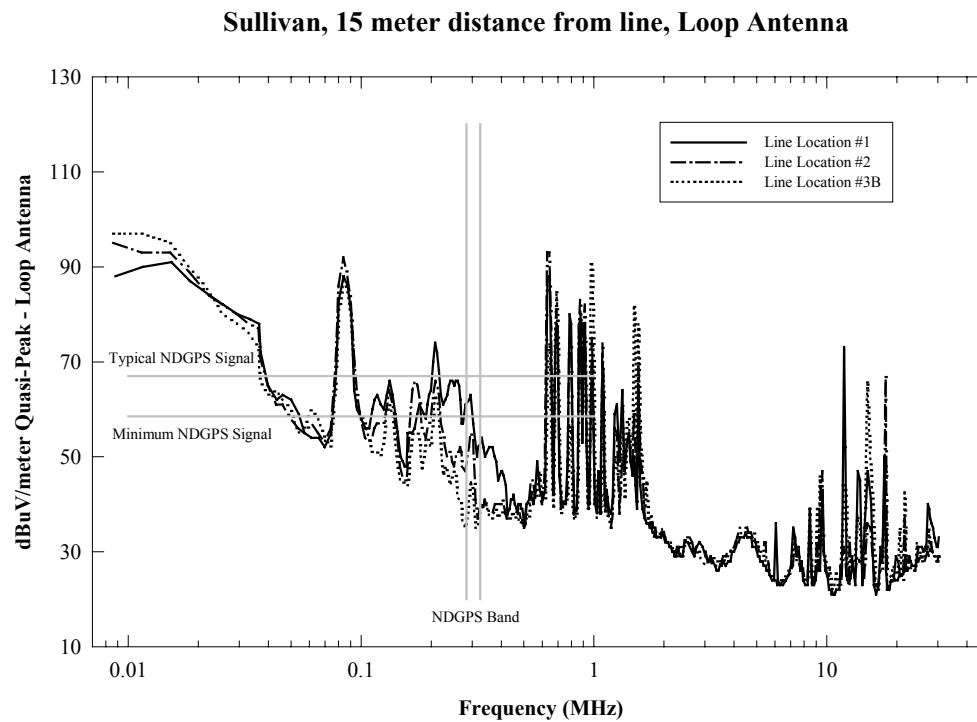


Figure 7-20
Sullivan–North Bristol Line, Locations 1-2-3B, 15 m Distance, Loop Antenna
Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR)
Noise Measurements (see page 5-8)

500 kV Line

Power line: Sullivan–Broadford, 500 kVrms line-to-line voltage, with horizontal arrangement of the three-phase conductor bundles. There are three subconductors per phase.

Measured quantity was B_x, i.e., B component perpendicular to the power line direction, at 1 m height above ground. The plane of the loop (of the loop antenna) was parallel with the power line conductors.

Phasing: All line measurements were conducted on the side of Phase A (or 1).

Distance of the measurement location from Sullivan (Location 4) was about 2,781 m (1.73 mi).

The lateral distance of the test point from the outside subconductors was 15 meters.

Conductor elevation above ground was about 13 meters.

Figure 7-21 shows the 500 kV power line measurement location (Location 4).

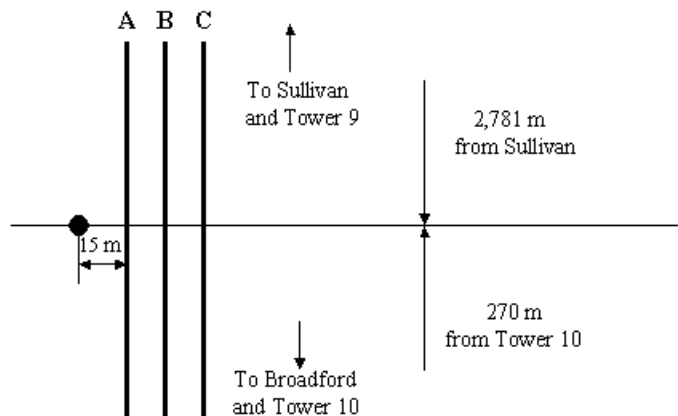


Figure 7-21
Sullivan–Broadford 500 kV Line, Location 4

Figure 7-22 and 7-23 show B_x levels at Location 4, at 15 m distance, for the normal case. The loop antenna readings at the remote ambient location, and appropriate limit lines are also shown.

Sullivan, Line Location #4, 15 meter distance, Loop Antenna

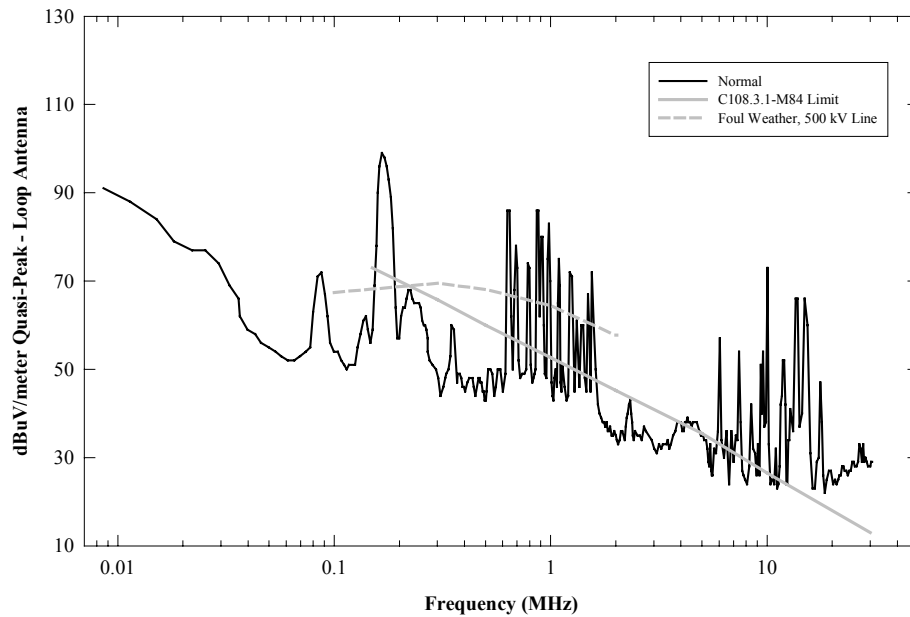


Figure 7-22
Sullivan–Broadford 500 kV Line, Location 4, 15 m Distance, Normal Case,
Loop Antenna Measurements with Limit Lines

Sullivan, Line Location #4, 15 meter distance, Loop Antenna

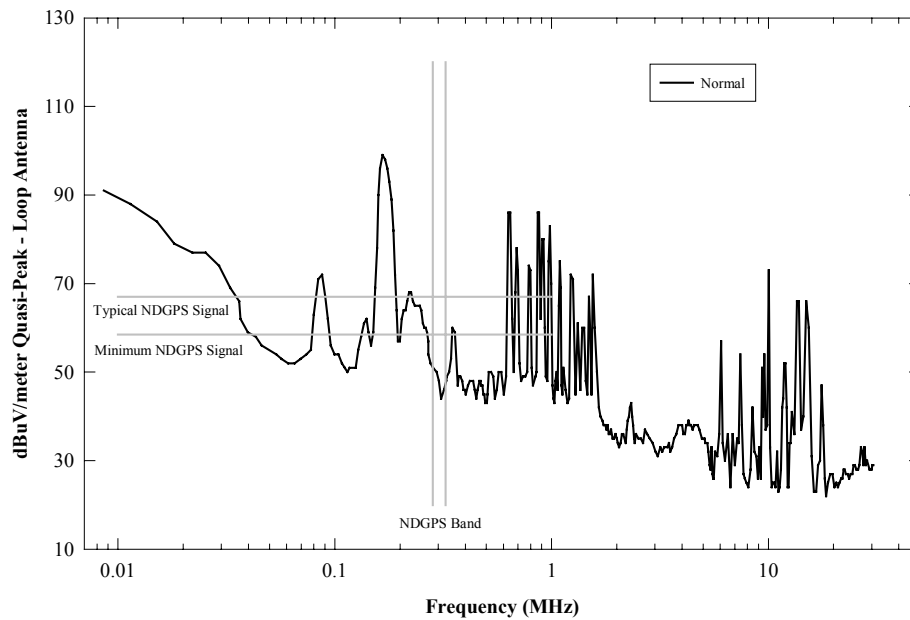


Figure 7-23
Sullivan–Broadford 500 kV Line, Location 4, 15 m Distance, Normal Case,
Loop Antenna Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW
(CISPR) Noise Measurements (see page 5-8)

PLC Measurements

The power line protection at Sullivan utilizes the directional comparison blocking scheme, using power line carrier (PLC).

PLC measurements were conducted at Sullivan, with the Signalcrafters 70 device on the Sullivan–North Bristol 161 kV line, for the same four operational cases listed above, in the “Forward” and “Reverse” test cases, with capacitor banks at Sullivan switched on or off.

Similar measurements were conducted at the North Bristol Station, with the Signalcrafters 70 device on the Sullivan–North Bristol line, only for the normal operational case, in the “Forward” and “Reverse” test cases, with the capacitor bank at Sullivan switched on or off.

Two measurements were conducted for each operational case. They are called in the report “Forward” and “Reverse,” following the names of the test connections and the toggle switch positions of the Signalcrafter 70 device.

Figures 7-24 shows the forward and reverse measurement results at North Bristol for the normal operational case, with the capacitor bank at Sullivan switched on. The carrier frequency (82-85 kHz) appears to be untouched. The differences between the “Forward” and “Reverse” test cases at the carrier frequency are a bit larger than 30 dB. (The horizontal lines mean the noise floor of the instrumentation.)

Figure 7-24 also shows the comparison of RMS and QP (CISPR) readings of the PLC measurements. The average difference between the RMS and QP (CISPR) reading at the carrier frequency appears to be less than 5 dB.

More measurement details are shown in Appendix B (see Figures B-7-B-13).

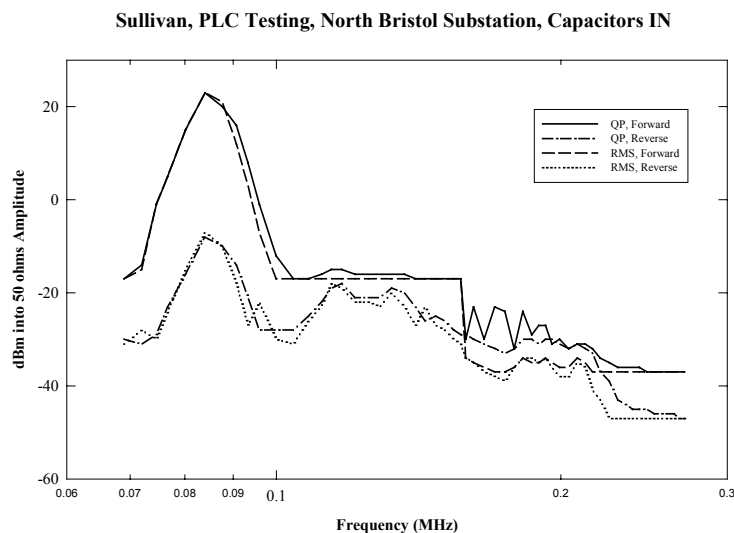


Figure 7-24
PLC Testing at North Bristol, Normal Case, Forward and Reverse Test Cases,
Comparison of RMS and QP (CISPR) Readings

Ambient Noise Level Measurements

Measured quantities were E_z , the vertical component of the electric field strength, and B_x and B_y , the two horizontal components of the magnetic flux density.

The ambient noise levels were measured at a reasonably remote location, close to 6:00 PM on May 16, 2002. The weather was fair and sunny; there were no storms in the area.

Figure B-6 of Appendix B shows the measured noise levels. Figure B-6 also shows the presence of strong AM and short wave radio broadcast signals. There is a stronger signal at about 100 kHz, not identified yet, and at about 300 kHz, a nearby airport beacon signal.

Summary

The method of application of limits, and the reasons for the limits applied are described and discussed in Chapter 5.

The main characteristics of the RF noise performance of the Sullivan Station can be summarized as follows:

Radiated Susceptibility Limit, Magnetic Field (RS101) Limit:

- Figure 7-7 shows that the RF noise magnitudes in the inverter hall in the normal case are close to the RS101 susceptibility limit levels around 20 kHz.
- Figures 7-5 and 7-9: actual RF noise levels do not exceed the RS101 susceptibility limit levels at the control room and outside inverter hall measurement locations.

Radiated Susceptibility Limit, Electric Field (RS103) Limit:

- Figures 7-6, 7-8, 7-10 show that the actual RF noise levels do not exceed the RS103 susceptibility limit levels at the control room, inverter hall, and outside area locations.

Conducted Susceptibility (Structure Current, CS109) Limit:

- Figure 7-12 shows that two of the three measured structure current magnitudes (normal condition) exceed the CS109 limit above a specific frequency. For Location 3 (see Figure 7-4), it is about 80 kHz, for Location 4, it is about 100 kHz. For Location 3, the measured structure current value reaches the CS109 limit in the vicinity of about 40 kHz.

Canadian Standard for Fair Weather:

- Figures 7-17 and 7-22 show that the measured RF noise levels at Line Locations 1 and 4, 15 m distance (normal condition), remain under the fair weather related limit line except two frequencies close to 200 kHz. The PLC, and the AM and short wave radio broadcast frequencies are above the noise levels. Note that Locations 1-3 were along a 161 kV power line, but Location 4 was at a 500 kV power line.

Foul Weather Radio Noise Prediction Levels:

- Figures 7-17 and 7-22 also show that the measured RF noise levels (in fair weather) at Line Locations 1 and 4, 15 m distance (normal condition), remain under the foul weather related limit line except the same two frequencies close to 200 kHz. The PLC, and the AM and short wave radio broadcast frequencies again are above the noise levels.

NDGPS Signal Levels:

- Figure 7-11 shows that the RF noise level in and close to the switchyard exceeds the typical NDGPS signal level.
- Figures 7-18, and Figures B-3 and B-5 of Appendix B show that the RF noise level at Line Location 1, 15 m distance (normal condition), is close to the minimum NDGPS signal level after the corrections discussed in Chapter 5.

PLC:

- Figure 7-24 shows that during the measurements taken, the carrier frequency appears to be untouched.
- Figure 7-24 also shows the PLC signal-to-noise ratio; it is about 30 dB.

RF noise features along the Sullivan–North Bristol 161 kV power line:

- Attenuation of the radiated RF noise laterally from the Sullivan–North Bristol power line is shown in Figures B-4 and B-5 in Appendix B.
- Slight attenuation of the conducted RF noise along the Sullivan–North Bristol power line is shown in Figures 7-19 and 7-20.

Comparison of RMS and QP (CISPR) readings:

For pulse repetition frequencies greater than 20-30 kHz, the QP value is approximately the same as the peak value. For sinusoidal signals the QP value is approximately $\sqrt{2}$ times the RMS value [8].

However, for the zero-mean Gaussian amplitude noise distribution the RMS value is estimated as about 1/4 times the peak value [8]. It is assumed that the impulsive type noise shows a similar distribution.

Therefore, for impulsive type noise the calculated difference of the QP and RMS values is assumed to be: $10 \log_{10} 4 = 10 \times 0.6 = 6 \text{ dB}$.

- Figures 7-16, 7-24, and Figure B-15 of Appendix B show the measurement results related to the use of RMS and QP (CISPR) detector circuits.
- The average difference between the RMS and QP (CISPR) power line noise readings is about 5 dB. In other words, $\text{dB RMS} = \text{dB QP} - 5 \text{ dB}$. That is reasonably close to the calculated difference of 6 dB shown above.

- The average difference between the RMS and QP (CISPR) readings at carrier frequencies is smaller than 5 dB.

These characteristics of the RF noise performance of the Sullivan Station can be extended to cover conditions other than the normal—please review the additional measurement related figures in Appendix B.

8

COMPARISONS

Comparisons Related to the Measurements at Inez Station

There were two control room locations at Inez where noise measurements were conducted.

Figure 8-1 shows the noise levels at both locations measured by the same loop antenna during normal load conditions, together with the RS101 limit lines. At both locations the “perpendicular” orientation readings were larger than the readings at the “parallel” orientation. (The reader is asked to review Chapter 6 for antenna locations and orientations.) Figure 8-2 shows the noise levels at both locations measured by the same rod antenna during normal load conditions, together with the RS103 limit lines. Comparing the noise levels at Locations 1 and 2 in the Inez Control Room at normal load conditions, the noise levels at Location 2 exceed those of at Location 1 at most (but not all) of the frequencies.

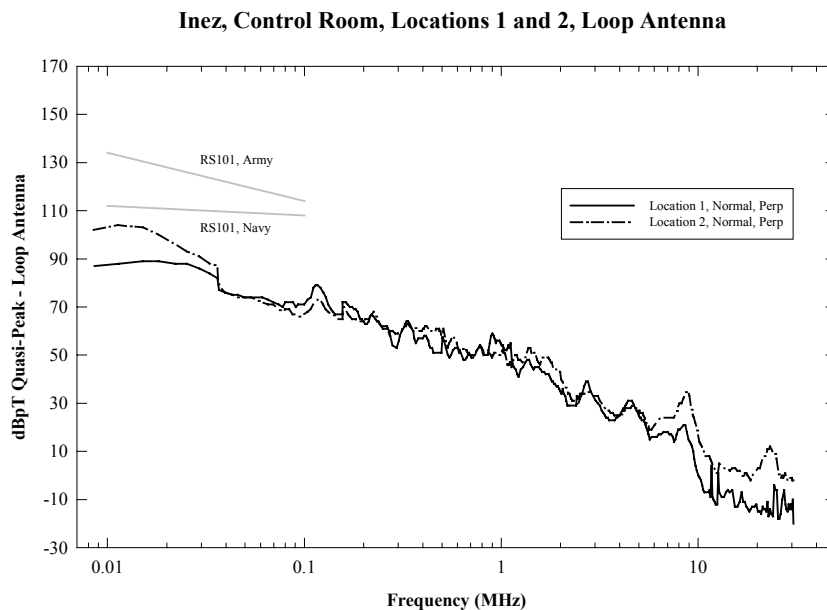


Figure 8-1
Inez, Two Control Room Locations, Normal Case, Loop Antenna Measurements and RS101 Limits

Figure 8-3 shows the noise levels at both locations measured by the same loop antenna during “off/off” load conditions, together with the RS101 limit lines. At Location 1 the “perpendicular” orientation readings were larger than the readings at the “parallel” orientation; however, at

Location 2, the “parallel” orientation meant the higher reading. Figure 8-4 shows the noise levels at both locations measured by the same rod antenna during “off/off” load conditions, together with the RS103 limit lines. Comparing the noise levels at Locations 1 and 2 in the Inez Control Room at “off/off” load conditions, the noise levels at Location 2 again exceed those of at Location 1 at most (but not all) of the frequencies.

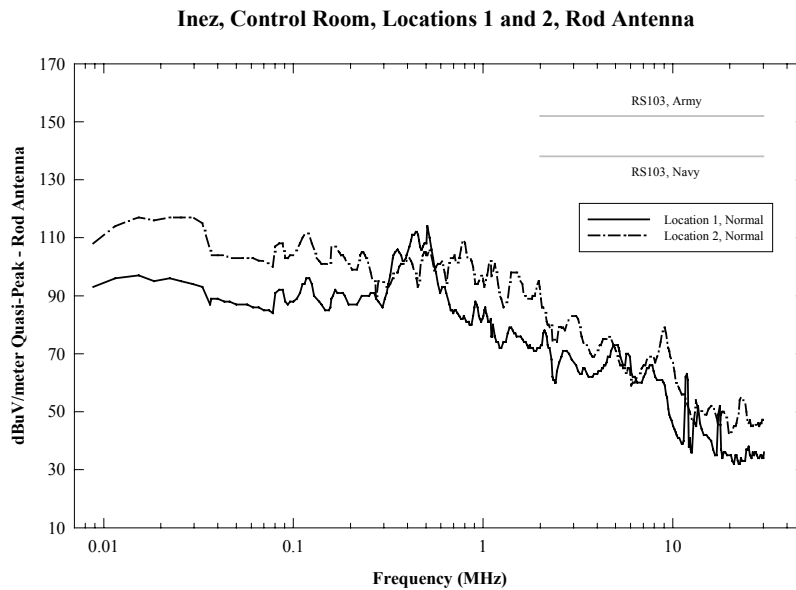


Figure 8-2
Inez, Two Control Room Locations, Normal Case, Rod Antenna Measurements and RS103 Limits

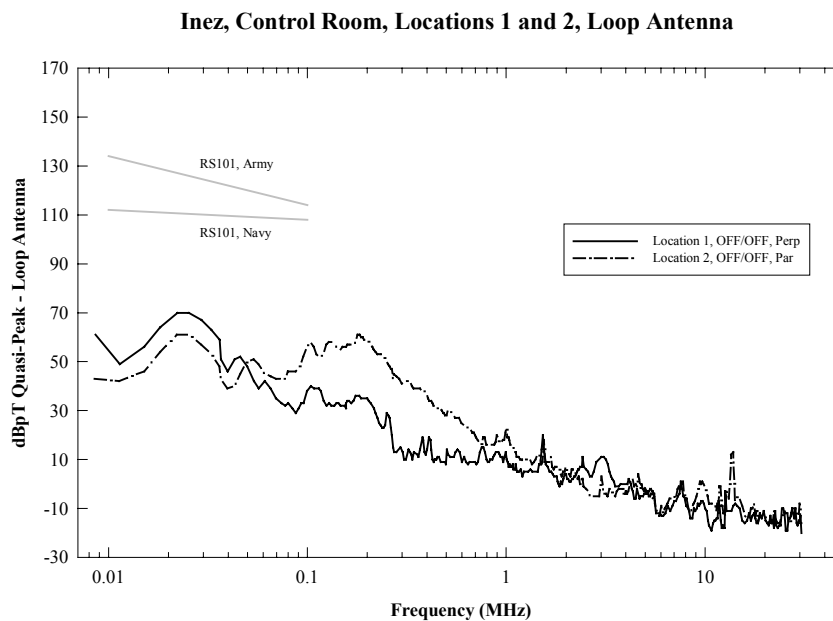


Figure 8-3
Inez, Two Control Room Locations, Off/Off Case, Loop Antenna Measurements and RS101 Limits

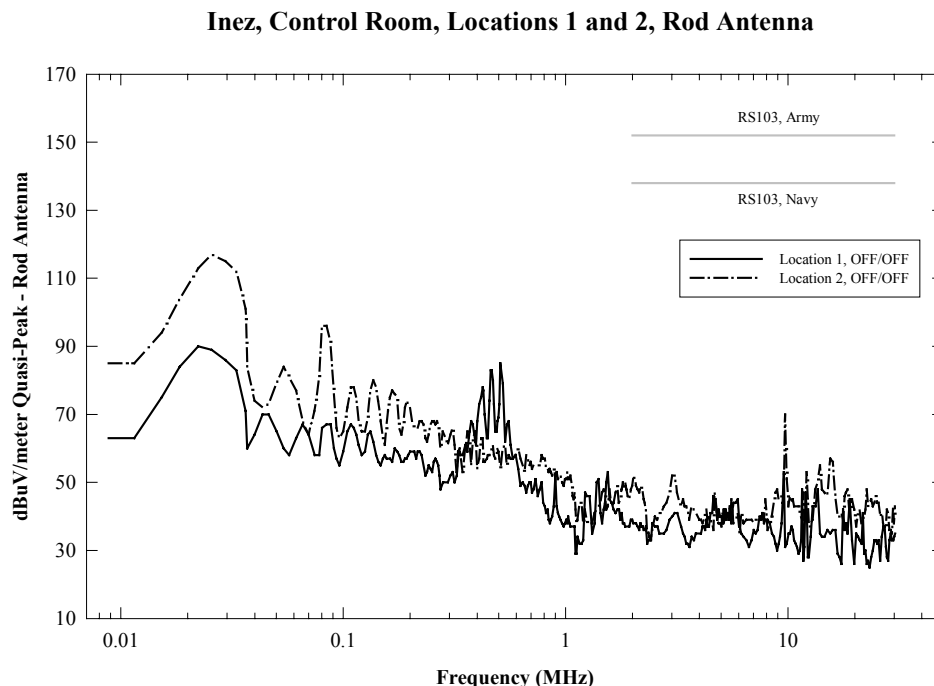


Figure 8-4
Inez, Two Control Room Locations, Off/Off Case, Rod Antenna Measurements
and RS103 Limits

Naturally, there are significant noise level differences, at most of the frequencies 30 to 40 dB, between the normal and “off/off” load conditions; compare Figures 8-1 and 8-3 for loop antenna readings, and Figure 8-2 and 8-4 for rod antenna readings

There were several “outside” locations at Inez where noise measurements were conducted. Readings taken at some of those locations can be compared. The test points considered here are the shunt and series areas outside the inverter hall, the closest power line measurement point (Location 1) at 15 m lateral distance, and the remote ambient level.

Figure 8-5 shows the noise levels at those locations measured by the same loop antenna during normal load conditions, together with the power line related limit lines. Figure 8-6 shows exactly the same noise measurements but together with the NDGPS signal level lines.

Comparing the noise levels at the switchyard locations at normal load conditions, the noise levels at the shunt and series areas are not too far from each other. At some frequencies the noise level in the shunt area exceeds that in the series area. At some other frequencies the opposite happens. The noise level at the closest power line measurement point (Line Location 1) is significantly lower than the switchyard levels, mostly because of larger distances between the energized components and the test point with the loop antenna, i.e., because of the conductor or bus elevation at the test location.

Inez, Outside Test Locations, Loop Antenna

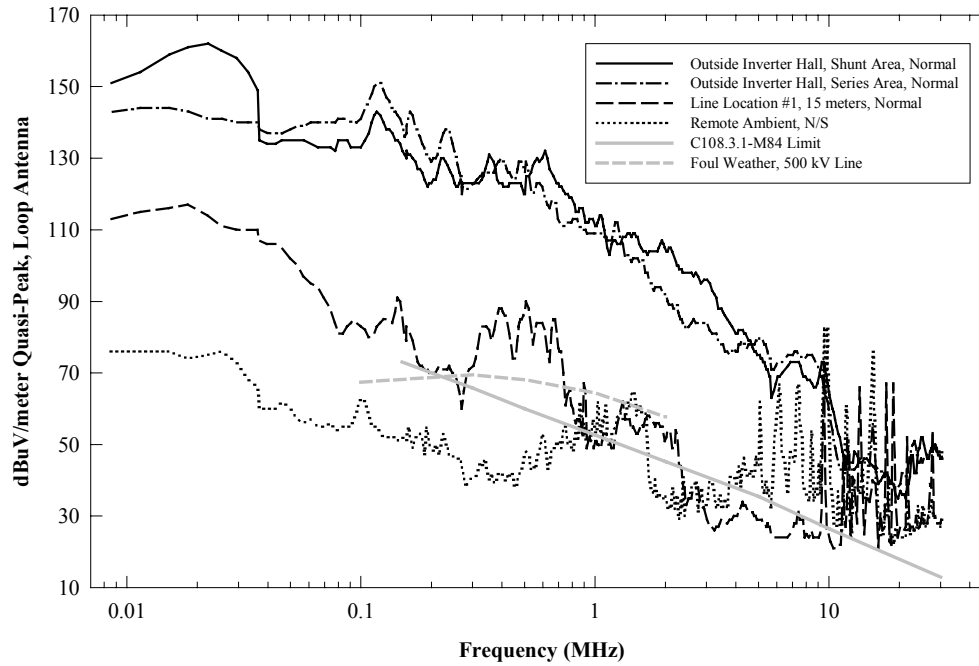


Figure 8-5
Inez, Outside Test Locations, Normal Case, Loop Antenna Measurements with Limit Lines

Inez, Outside Test Locations, Loop Antenna

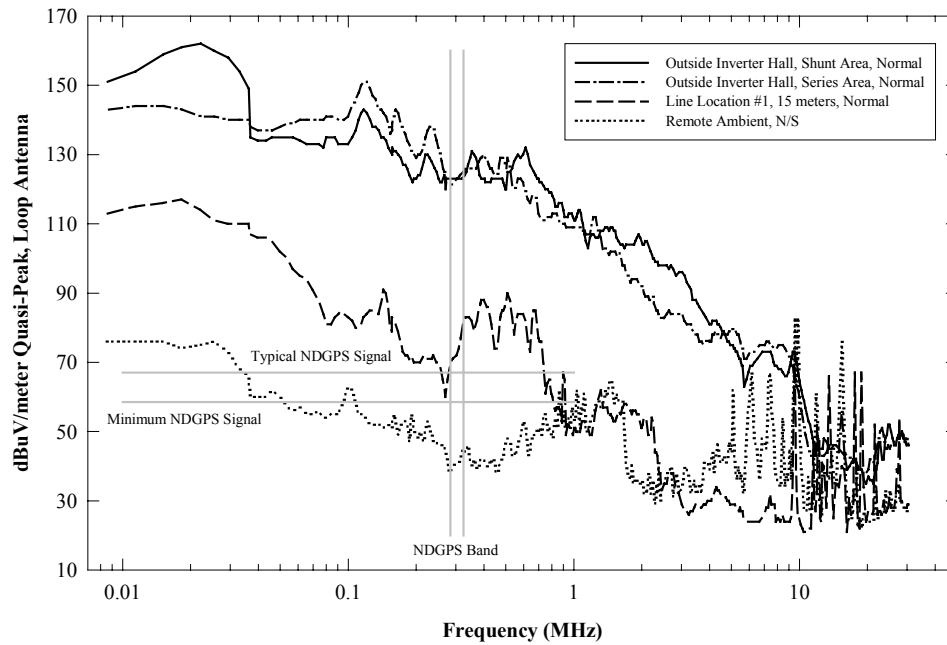


Figure 8-6
Inez, Outside Test Locations, Normal Case, Loop Antenna Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

Comparisons Related to the Measurements at Sullivan Station

There were several “outside” locations at Sullivan where noise measurements were conducted. Readings taken at some of those locations can be compared. The test points considered here are the area outside the inverter hall, the closest 161 kV power line measurement point (Location 1) and the 500 kV power line measurement point, both at 15 m lateral distance, and the remote ambient level.

Figure 8-7 shows the noise levels at those locations measured by the same loop antenna during normal load conditions, together with the power line related limit lines. Figure 8-8 shows exactly the same noise measurements but together with the NDGPS signal level lines.

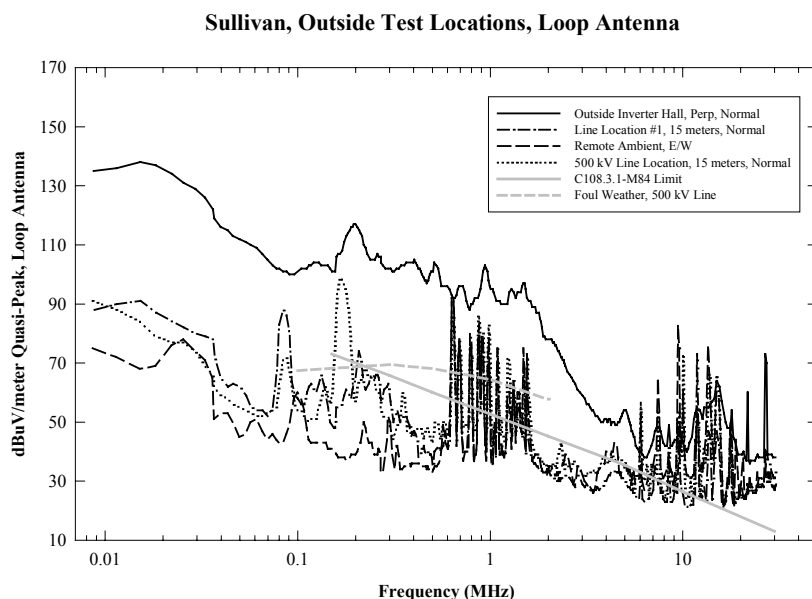


Figure 8-7
Sullivan, Outside Test Locations, Normal Case, Loop Antenna Measurements
with Limit Lines

Comparing the noise levels at the 161 kV (Location 1) and 500 kV (Location 4) line locations at normal load conditions, the noise levels (not counting the presence of the carrier frequencies) are close to each other. At some frequencies the noise level at the 161 kV line exceeds that of at the 500 kV line. Distances between the test locations and Sullivan Station were close. The transformer impedances (driving point and transfer impedances as well) are functions of the frequency. Therefore, the additional 161/500 kV transformation introduces a frequency dependent impedance in the path of the conducted RF noise.

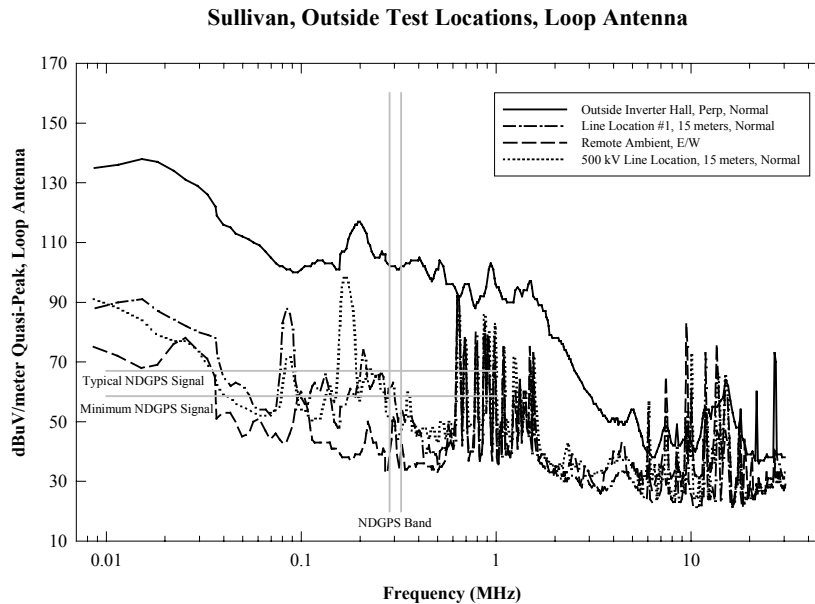


Figure 8-8
Sullivan, Outside Test Locations, Normal Case, Loop Antenna Measurements with NDGPS
Signal Levels Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

Comparisons Related to the Measurements at Inez and Sullivan Stations

Noise measurements conducted in the control rooms at Inez and at Sullivan are compared first.

Figure 8-9 shows the noise levels at both locations measured by the same loop antenna during normal load conditions, together with the RS101 limit lines. At both locations the “perpendicular” orientation meant the larger readings. (The reader is asked to review Chapters 6 and 7 for antenna locations and orientations.) Figure 8-10 shows the noise levels at both locations measured by the same rod antenna during normal load conditions, together with the RS103 limit lines. Comparing the noise levels at Location 2 in the Inez Control Room and the control room test location at Sullivan at normal load conditions, the noise levels at Location 2 of Inez exceed those of at Sullivan at practically all (with a few exceptions) of the frequencies. The typical average noise level difference appears to be about 10 dB.

Figures 8-11 and 8-12 show the noise levels at the same locations but at “off/off” conditions. The noise levels are much lower compared to those of the normal load conditions. Some noise originating from various items of auxiliary equipment in the FACTS stations is still picked up by the antennas. The presence of standing waves can also be seen in Figures 8-11 and 8-12.

Inez and Sullivan, Control Rooms, Loop Antenna

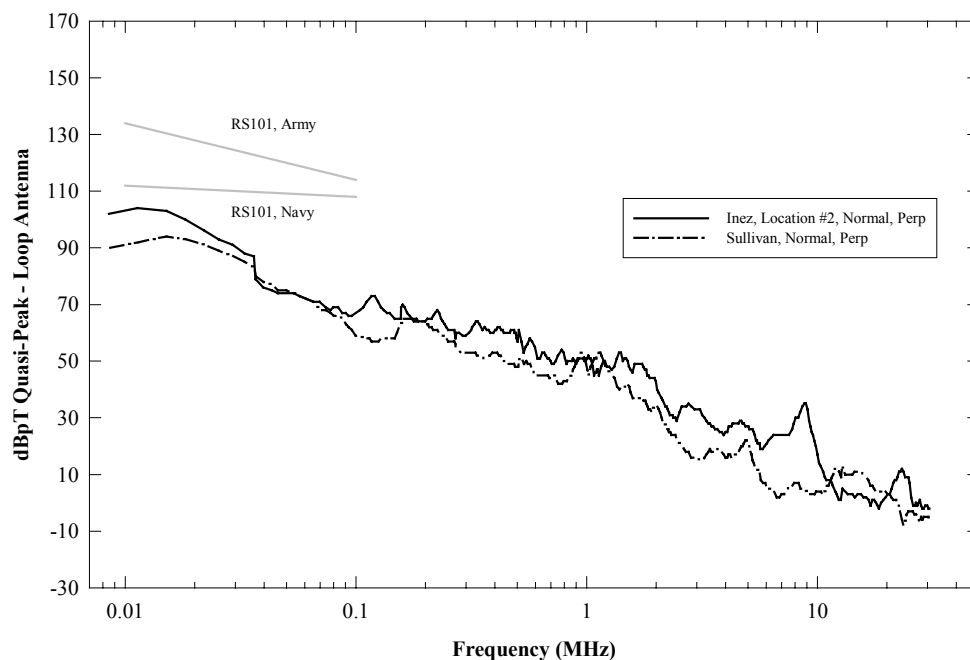


Figure 8-9
Inez and Sullivan, Control Room Locations, Normal Case, Loop Antenna Measurements and RS101 Limits

Inez and Sullivan, Control Rooms, Rod Antenna

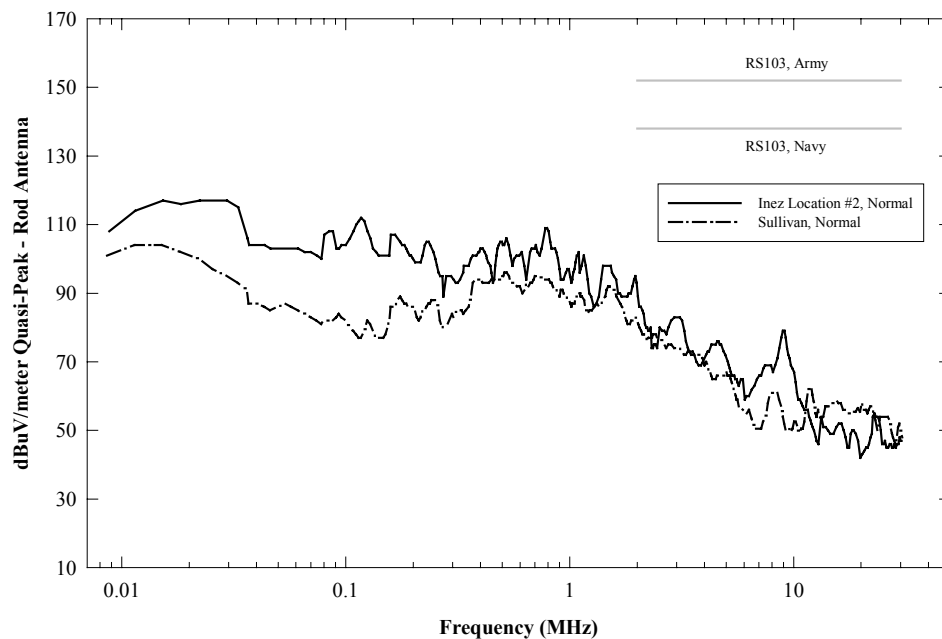


Figure 8-10
Inez and Sullivan, Control Room Locations, Normal Case, Rod Antenna Measurements and RS103 Limits

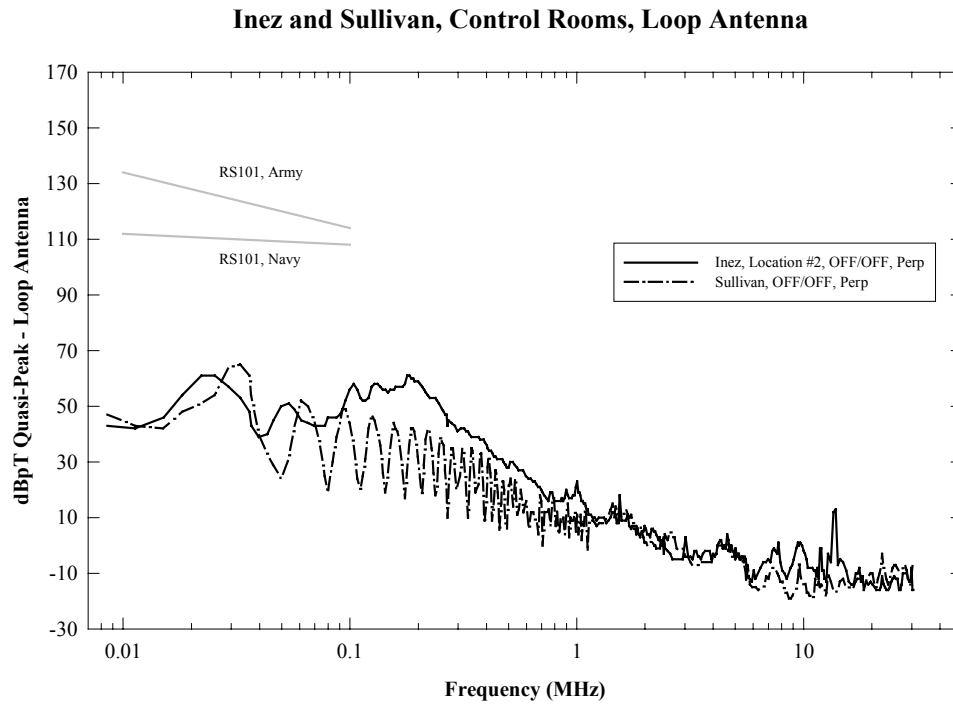


Figure 8-11
Inez and Sullivan, Control Room Locations, Off/Off Case, Loop Antenna Measurements and RS101 Limits

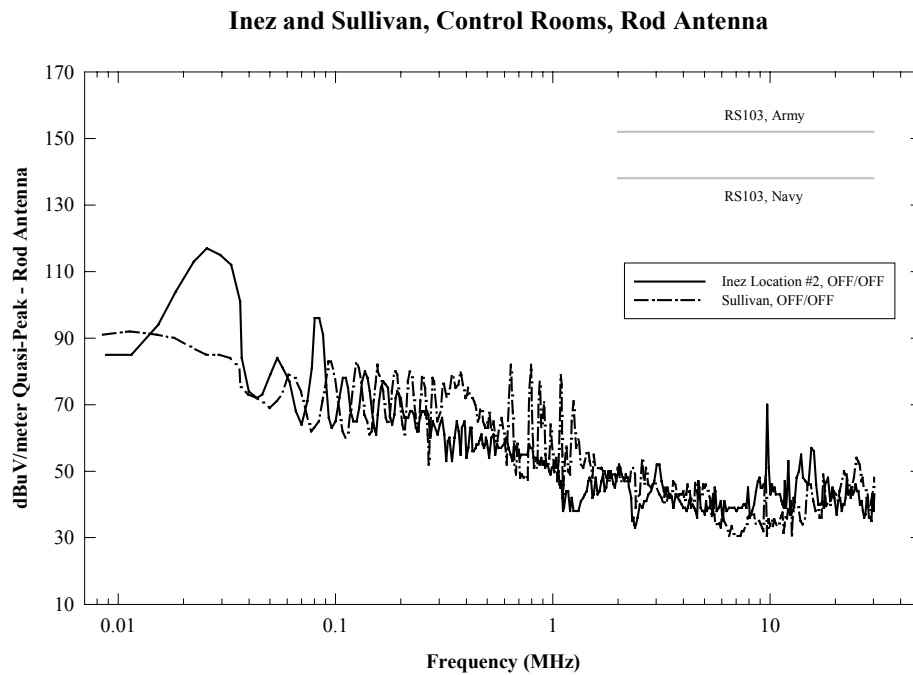


Figure 8-12
Inez and Sullivan, Control Room Locations, Off/Off Case, Rod Antenna Measurements and RS103 Limits

Then, noise measurements conducted in the inverter halls at Inez and at Sullivan are compared. Noise levels taken at Inez are represented by the shunt and series area readings. In general, noise levels in the inverter halls are close to each other. Levels at Sullivan appear to be a bit lower than at Inez, though only at some frequency ranges. (See Figures 8-13 and 8-14.)

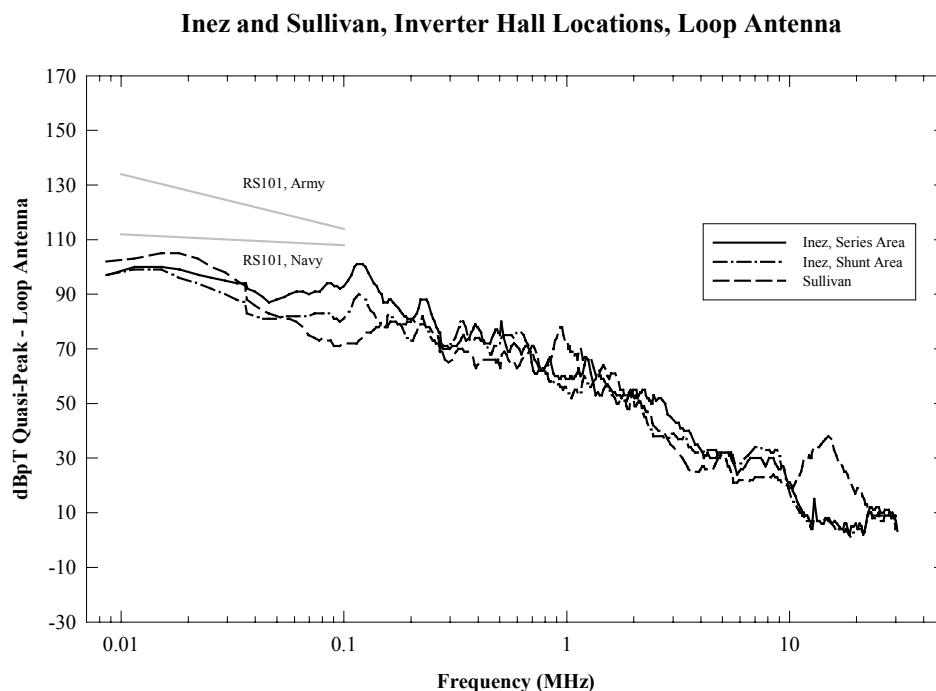


Figure 8-13
Inez and Sullivan, Inverter Hall Locations, Normal Case, Loop Antenna Measurements and RS101 Limits

Figure 8-15 shows that there is a definite difference between the highest RFCT levels at Inez, and at Sullivan, respectively. The CS109 limit lines are also shown. Levels measured are higher at Inez than at Sullivan. The lower levels at Sullivan are probably due to the application of the harmonic blocking transformer outside and inductors in the inverter building at Sullivan.

Note that the “switchyard” measurement location at Sullivan was away from the buses. At Inez, the “switchyard” location was right under the buses.

Noise levels measured at Location 1 (at 15 m distance) along the Inez - Johns Creek 138 kV line and along the Sullivan - North Bristol 161 kV line are compared in Figures 8-16 and 8-17. Limit lines are also shown.

Finally, there appear to be some differences between the remote ambient noise level readings in the vicinity of Inez, and Sullivan, respectively. Figures 8-18 and 8-19 show readings taken with the loop antenna (the orientation resulting in higher readings is indicated), including limit lines.

Figures 8-20 and 8-21 show readings taken with the rod antenna.

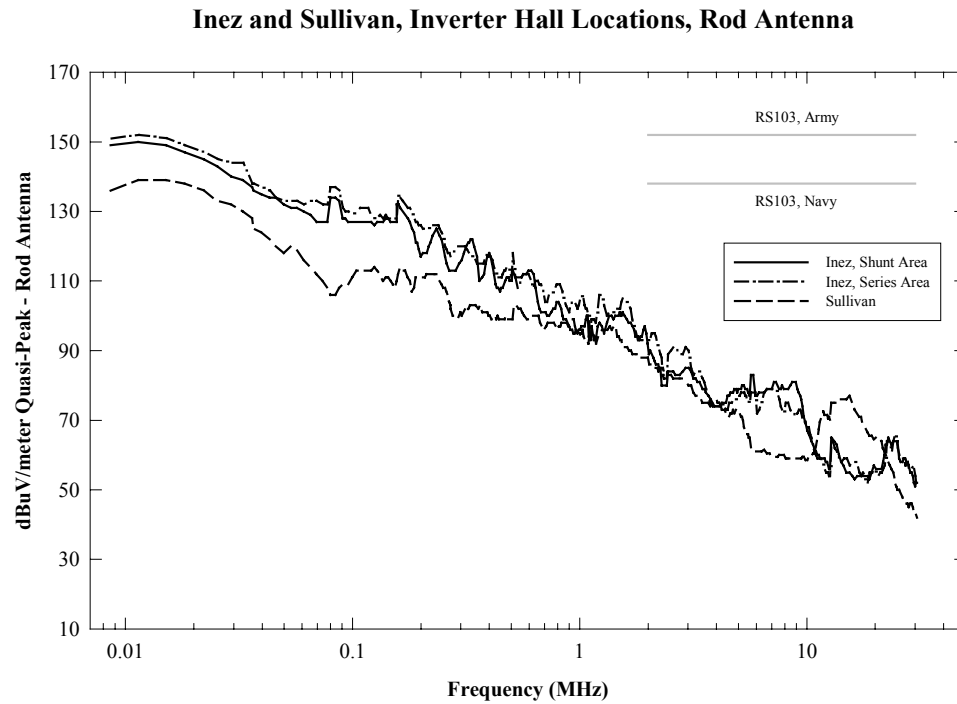


Figure 8-14
Inez and Sullivan, Inverter Hall Locations, Normal Case, Rod Antenna Measurements and RS103 Limits

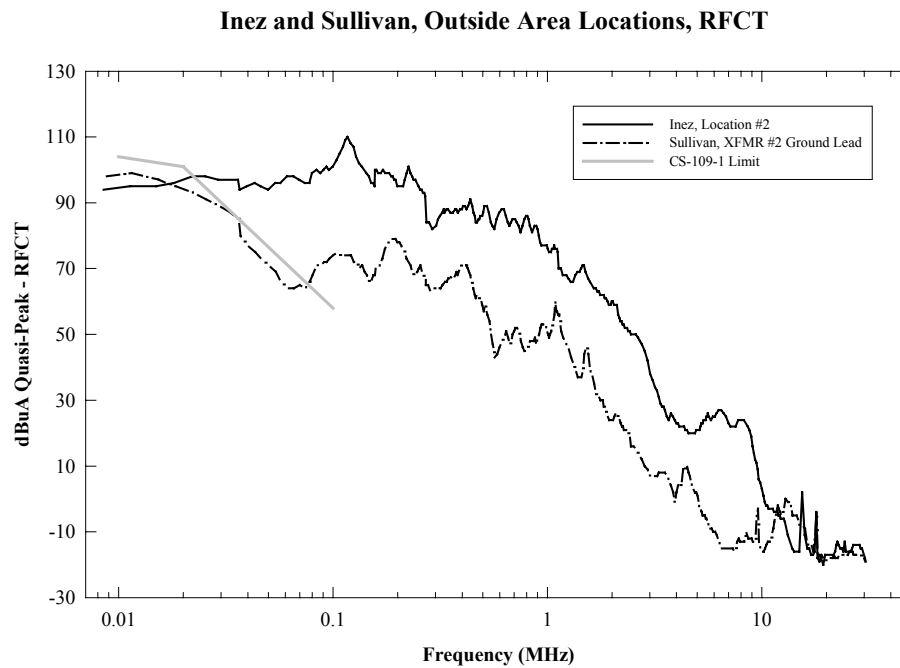


Figure 8-15
Inez and Sullivan, Switchyard Locations, Normal Case, RFCT Measurements with CS109 Limit Lines

Inez and Sullivan, Line Locations #1, 15 meter distance, Loop Antenna

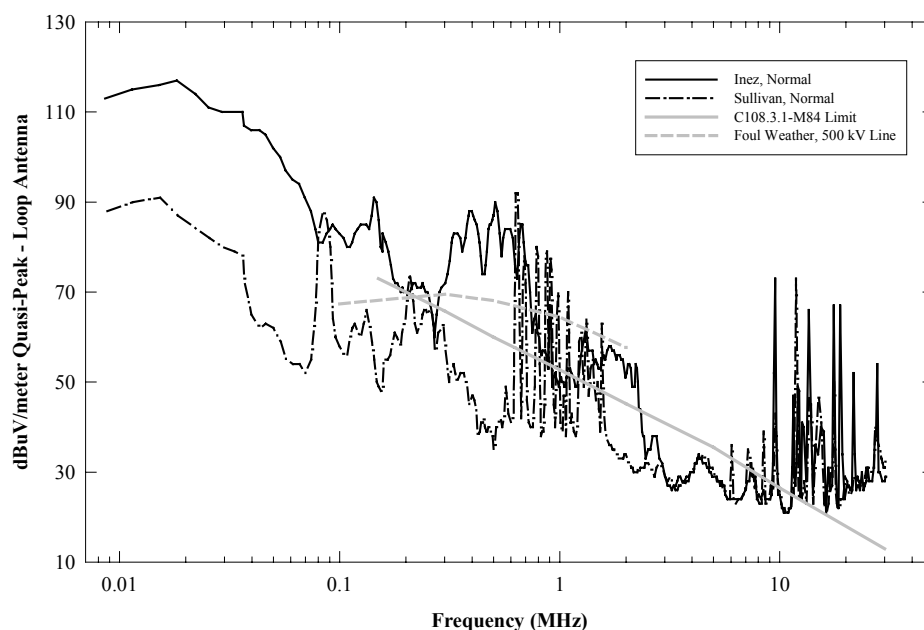


Figure 8-16
Inez and Sullivan, Line Locations 1, 15 m Distance, Normal Case, Loop Antenna
Measurements with Limit Lines

Inez and Sullivan, Line Locations #1, 15 meter distance, Loop Antenna

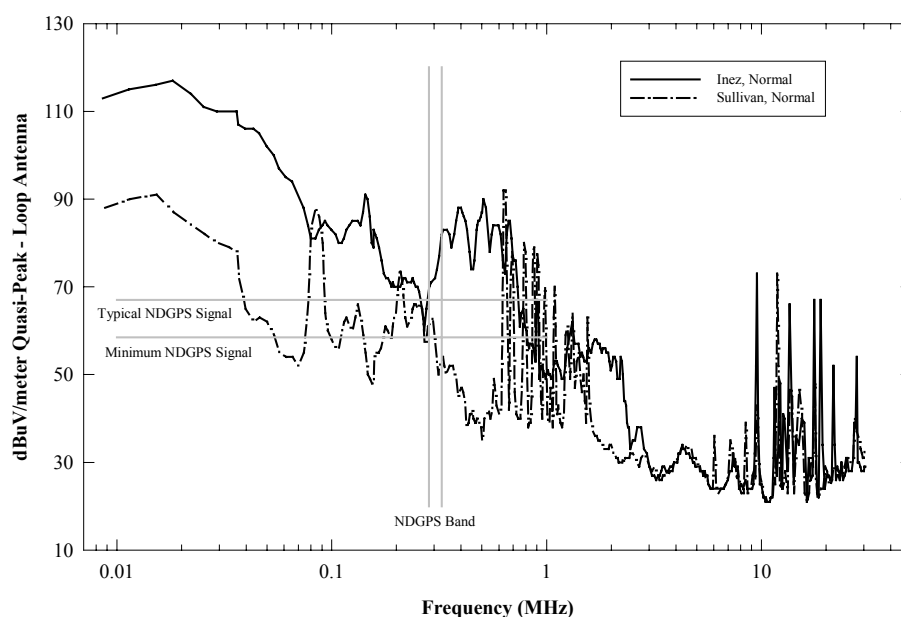


Figure 8-17
Inez and Sullivan, Line Locations 1, 15 m Distance, Normal Case, Loop Antenna
Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR)
Noise Measurements (see page 5-8)

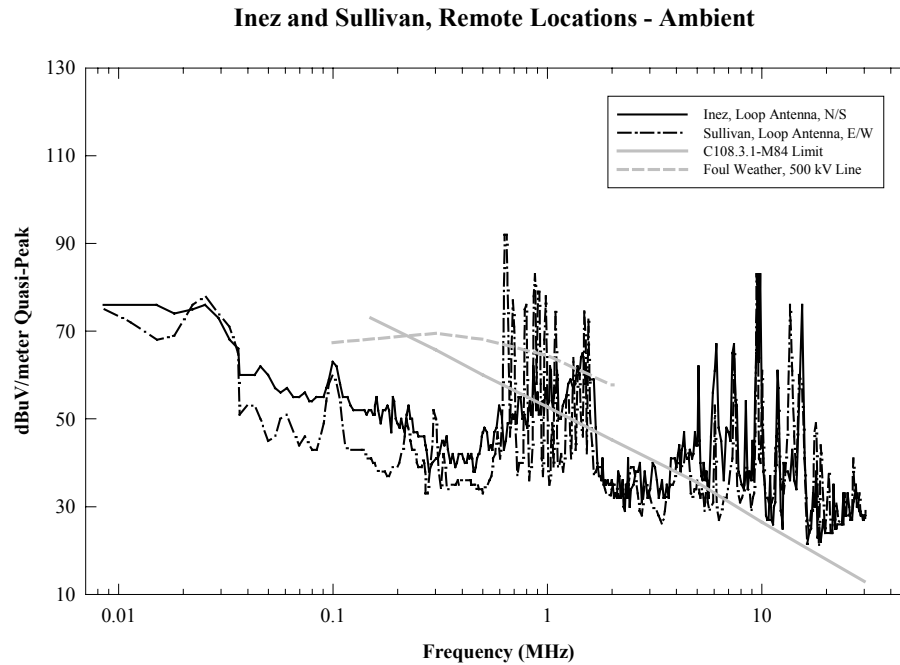


Figure 8-18
Inez and Sullivan, Remote Locations, Ambient Noise Level, Loop Antenna Measurements with Limit Lines

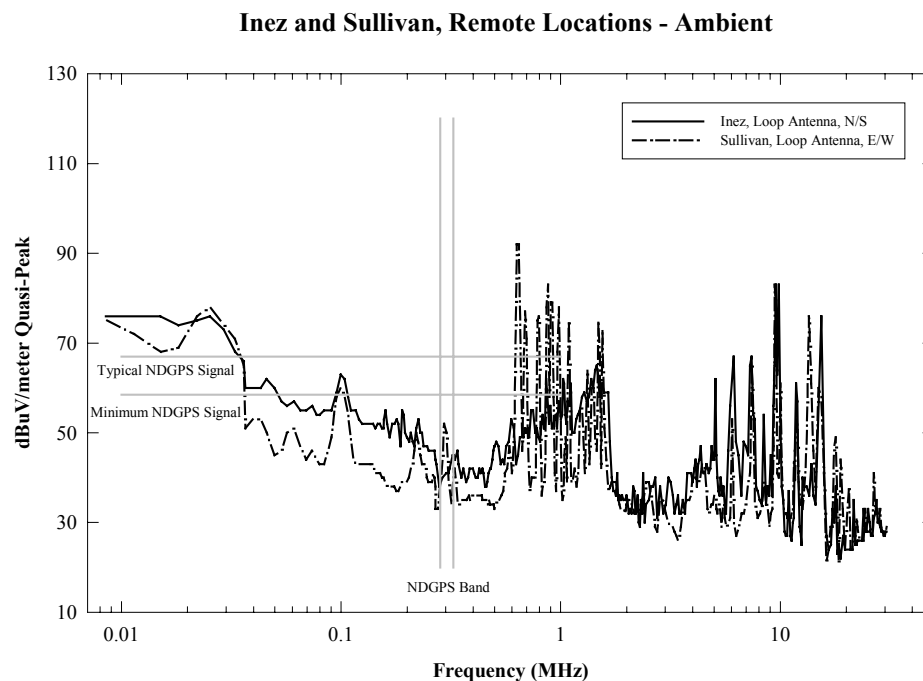


Figure 8-19
Inez and Sullivan, Remote Locations, Ambient Noise Level, Loop Antenna Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

Inez and Sullivan, Remote Locations - Ambient

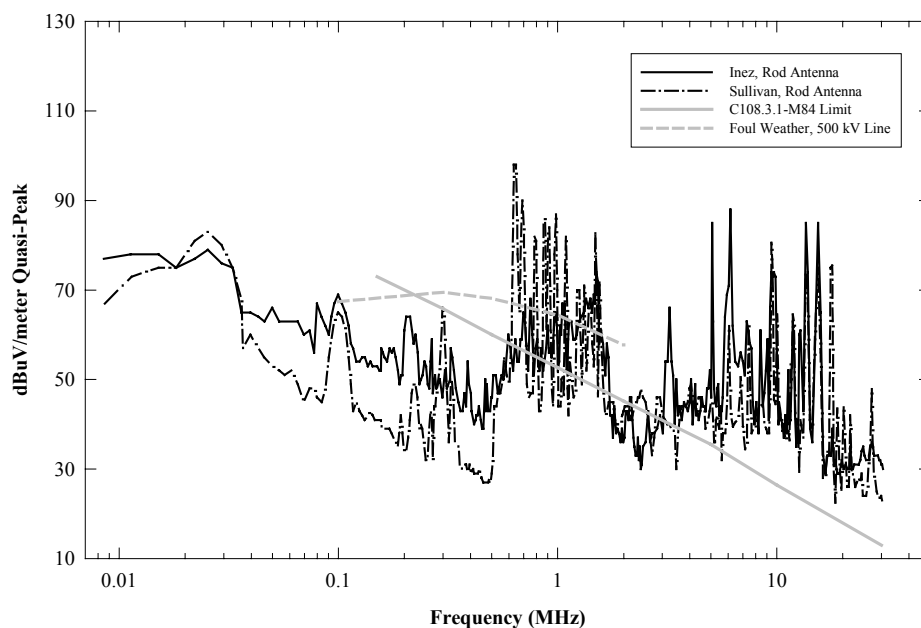


Figure 8-20
Inez and Sullivan, Remote Locations, Ambient Noise Level, Rod Antenna Measurements with Limit Lines

Inez and Sullivan, Remote Locations - Ambient

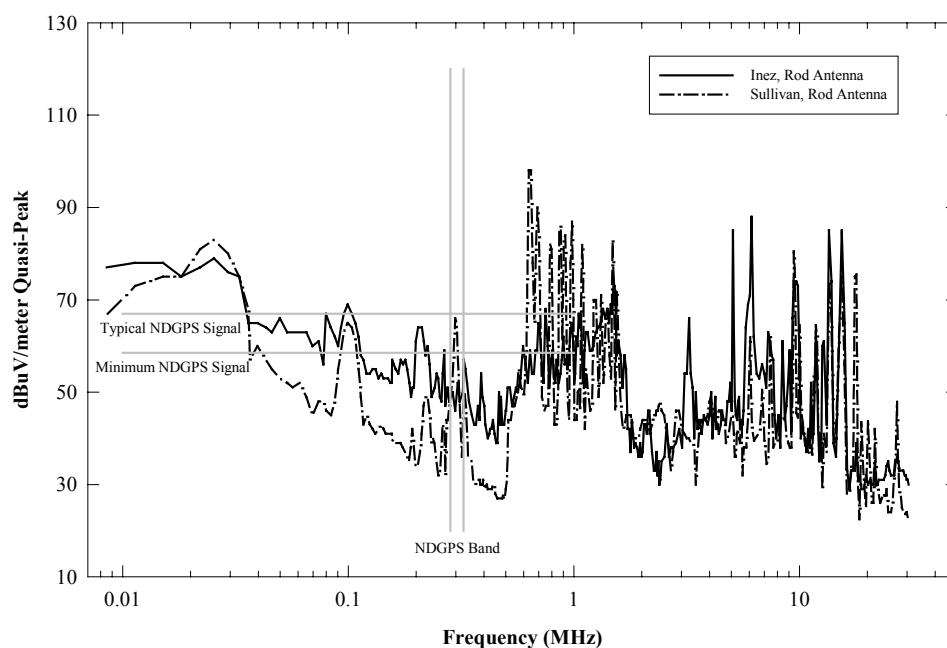


Figure 8-21
Inez and Sullivan, Remote Locations, Ambient Noise Level, Rod Antenna Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

9

CONCLUSIONS, FUTURE WORK

Introduction

One of the goals of this report is to provide information to FACTS users and vendors relating design and operating characteristics of FACTS devices to the RF noise spectra that results. These relationships are not easy to resolve. However, likely explanations and possible options can be listed. Also, a future test plan can be developed outlining how the uncertainties might be resolved, and how mitigation options could be tested.

There are five environments in a typical FACTS station:

- control room
- inverter hall
- switchyard
- power lines
- Power Line Carrier (PLC) system.

Discussions related to these environments are necessary and helpful—they may help readers to stay focused on the problems or potential problems related to FACTS stations.

General Conclusions Related to FACTS Stations

Comparison of the RF noise levels originating from FACTS stations with the foul weather RF noise levels shows that the Inez RF noise levels exceeded the foul weather related limit up to about 900 kHz. This could be a concern if interference with licensed services (e.g., AM broadcast stations) would be reported. (Note that GPS receivers are not licensed services.)

A requirement to desist under 47CFR15 (Code of Federal Regulations) may apply if FACTS devices are located close to metropolitan areas. At Inez, it appeared that the low band AM radio stations in operation were distant and not nearby stations. Companies operating or planning to operate FACTS equipment should be aware of these problems in order to avoid siting issues.

Manufacturers of control equipment are currently required to meet the “IEC Basic Standard for EMC Immunity and Emissions” for CE marked products sold in Europe. Additionally, they are faced with placing their equipment into environments that are described in MIL-STD 461E, methods of RS101, CS109, and CS114. Currently these threats are not simulated by equipment

vendors, nor is testing according to MIL-STD 461E is required by the users of power system equipment.

It is interesting to mention that during the project measurements QP (CISPR) RF noise detection methods were used. However, after potential threats were identified, the report utilizes MIL-STD formats as well.

Conclusions Related to the Three FACTS Stations Where RF Noise Was Measured

It is important to note that control equipment at the FACTS stations where RF noise was measured is currently being exposed to threats that it was not tested to withstand.

Participants of this project want to be careful to avoid the impression that the standards cited in this report should be applied to the locations of the measurements and the conditions during the measurements. The equipment at the three FACTS stations has not been tested to these standards. So, the fact that levels in these standards cited are not exceeded is no guarantee that the equipment will work correctly.

The main characteristics of the RF noise performance at the Inez and Sullivan FACTS stations can be summarized as follows:

Comparing the noise levels at Inez at the switchyard locations at normal load conditions, the noise levels at the shunt and series areas are close to each other. At some frequencies the noise level in the shunt area exceeds that of in the series area. At some other frequencies the opposite happens.

The noise level at Inez at the closest power line measurement point (Line Location 1) is significantly lower than the switchyard levels, mostly because of larger distances between the energized components and the test point with the loop antenna, i.e., mostly because of the geometry (conductor or bus elevation) at the test location.

Comparing the noise levels at Sullivan at the 161 and 500 kV power line locations at normal load conditions, the noise levels (not counting the presence of the carrier frequencies) are close to each other. At some frequencies the noise level at the 161 kV power line exceeds that of at the 500 kV power line. Distances between the test locations and Sullivan Station were close. The additional 161/500 kV transformation also introduces a frequency dependent ratio of the input and output quantities.

Comparing the noise levels at the hot spots in the Inez and Sullivan control rooms at normal load conditions, the noise levels at Inez exceed those of at Sullivan at practically all (with a few exceptions) of the frequencies. The typical average noise level difference appears to be about 10 dB. Reasons for this will be summarized and presented after the analysis of the test results related to Marcy.

Comparing the noise levels at the same locations but at “off/off” conditions, the noise levels are much lower compared to those of the normal load conditions. Some noise originating from various items of auxiliary equipment in the FACTS stations is still picked up by the antennas.

In general, noise levels in the inverter halls are close to each other. Levels at Sullivan appear to be a bit lower than at Inez, though only at some frequency ranges.

There is a definite difference between the highest RFCT levels at Inez, and at Sullivan, respectively. Levels measured are higher at Inez than at Sullivan. The lower levels at Sullivan are probably due to the application of the harmonic blocking transformer outside and inductors in the inverter building at Sullivan.

Conclusions Related to FACTS Stations – Specific Comments

For more details, see the “Summary” sections of Chapter 6 (Inez) and Chapter 7 (Sullivan).

Items related to limits set by standards are as follows:

Radiated Susceptibility Limit, Magnetic Field (RS101) Limit:

- At Inez the magnitude of the actual RF noise in the switchyard (shunt area, normal condition) due to the FACTS device slightly exceeds the RS101 susceptibility limit line (limit level) at about 20 kHz.
- At Inez the RF noise magnitudes in the control room (Location 2, normal condition, when the loop antenna is in the “perpendicular” direction) and in the inverter hall (both series and shunt areas, normal condition, when the loop antenna is in the “perpendicular” direction) are close to the RS101 susceptibility limit levels.
- At Sullivan the RF noise magnitudes in the inverter hall in the normal case are close to the RS101 susceptibility limit levels at around 20 kHz.

Radiated Susceptibility Limit, Electric Field (RS103) Limit: Measurements at Inez and Sullivan show that the actual RF noise levels do not exceed the RS103 susceptibility limit levels at the control room, inverter hall, and outside area (switchyard) locations.

Conducted Susceptibility (Structure Current, CS109) Limit:

At Inez the three measured structure current magnitudes (normal condition) exceed the CS109 limit above a specific frequency. For instance, at Location 2 the limit is exceeded over 25 kHz.

At Sullivan two of the three measured structure current magnitudes (normal condition) exceed the CS109 limit above a specific frequency. For Location 3, it is about 80 kHz, for Location 4, it is about 100 kHz. For Location 3, the measured structure current value reaches the CS109 limit in the vicinity of about 40 kHz.

Canadian Standard for Fair Weather:

- At Inez the measured RF noise levels at Line Location 1, at 15 m lateral distance from the outermost conductor (normal condition), due to the FACTS device exceed the limit line in a broad frequency range.
- At Sullivan the measured RF noise levels at Line Location 1 (161 kV line) and Line Location 4 (500 kV line), at 15 m lateral distance from the outermost conductor (normal condition), remain under the fair weather related limit line except two frequencies close to 200 kHz. The PLC, and the AM as well as the short wave radio broadcast frequencies are above the noise levels.

Foul Weather Radio Noise Prediction Levels:

- At Inez the measured RF noise levels (in fair weather) at Line Location 1, at 15 m lateral distance from the outermost conductor (normal condition), due to the FACTS device exceed the foul weather related limit line up to about 0.9 MHz.
- At Sullivan the measured RF noise levels again at Line Locations 1 and 4, at 15 m lateral distance from the outermost conductor (normal condition), remain under the foul weather related limit line except the same two frequencies close to 200 kHz. The PLC, and the AM as well as the short wave radio broadcast frequencies are above the noise levels.

NDGPS Signal Levels:

- Both at Inez and at Sullivan the RF noise level in the switchyard greatly exceeds the typical NDGPS signal level.
- Both at Inez and at Sullivan the RF noise level at Line Location 1, at 15 m lateral distance from the outermost conductor (normal condition), is close to the typical NDGPS signal level after the corrections discussed in Chapter 5.
- Figure 6-19 is a good example for the demonstration of a calculation on how close one can be to a power line with the FACTS noise on it and still operate a NDGPS receiver. Assume, based on the figure, that the FACTS noise is 9 to 19 dB above the typical and minimum NDGPS signals, after correcting for the narrower bandwidth of a NDGPS receiver. Given the need for at least 7 dB signal-to-noise ratio, the noise must decay by 16-26 dB by moving further from the line. If we assume $1/r^2$ decay in the noise, then this will mean somewhere between 35 and 70 meters of additional distance from the power line. The NDGPS receiver might not work if the user is closer to the line than these additional distances.

With more details: if the average height of the line conductors at the measurement site is 13 m, the distance of the “original” test point (assumed to be at 1 m height) from the outermost conductor can be calculated as $\sqrt{(12^2 + 1^2)} = 12.04$ m. Then the noise level at 12.04 m from the outermost conductor (i.e., at the “original” point) and the same at x or y meter additional lateral distance from it (i.e., at the “additional” point) can be calculated. With the differences between the noise levels at these two locations given as 16 dB at “x” additional distance, and 26 dB at “y” additional distance, these additional distances are calculated as approximately 35 and 70 m from the line. These additional lateral distances are to be added to the original lateral distance, 15 m.

PLC:

- Measurements both at Inez and at Sullivan show that during the measurements taken the carrier frequency appeared to be untouched.
- Of all cases measured at Inez, the smallest PLC signal-to-noise ratio was 22 dB. Measurements at Sullivan showed that the smallest signal-to-noise ratio was about 30 dB.

RF noise features along the 138–161 kV power lines originating from Inez and Sullivan, respectively:

- The lateral attenuation of the radiated RF noise is quite clear.
- The attenuation of the conducted RF noise along the power line is relatively slight.

Comparison of RMS and QP (CISPR) readings:

For pulse repetition frequencies greater than 20-30 kHz, the QP value is approximately the same as the peak value. For sinusoidal signals the QP value is approximately $\sqrt{2}$ times the RMS value [8].

However, for the zero-mean Gaussian amplitude noise distribution the RMS value is estimated as about 1/4 times the peak value [8]. It is assumed that the impulsive type noise shows a similar distribution.

Therefore, for impulsive type noise the calculated difference of the QP and RMS values is assumed to be: $10 \log_{10} 4 = 10 \times 0.6 = 6 \text{ dB}$.

- Measurements at Sullivan showed that the average difference between the RMS and QP (CISPR) reading is about 5 dB. In other words, $\text{dB RMS} = \text{dB QP} - 5 \text{ dB}$.
- The average difference between the RMS and QP (CISPR) reading at carrier frequencies is smaller than 5 dB.

Future Work

More measurements are recommended at the following facilities:

- Essex Station (Vermont Electric Company, VELCO)—the FACTS facility has been manufactured by another vendor, not the one which manufactured the FACTS devices at Inez, Sullivan, and Marcy.
- Marcy Station (NYPA) in New York—after the FACTS facility will operate at full capacity.
- Eagle Pass (AEP) in Texas

Some measurements in the future, specifically, measurements in the control room, inverter hall, switchyard and PLC environments could use the Peak-RMS detection and 10 kHz bandwidth as required in MIL-STD 461E. However, the power line environment would require the use of the QP (CISPR) detector and 9 kHz bandwidth due to standards CAN3C108 and ANSI/IEEE 430-1986.

Additional studies to be performed:

- to measure and analyze the electromagnetic “footprint” a FACTS installation would leave
- to determine how close to metropolitan areas FACTS facilities could be built
- to determine how the degraded reception can be quantified
- to determine whether licensed services would be affected
- and to recommend what kind of mitigation would be appropriate.

10

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2. N. Mohan, T. M. Undeland and W. B. Robbins, Power Electronics, Converters, Applications, and design, Second Edition, J. Wiley, 1995.
3. ANSI/IEEE Std 430-1986, IEEE Standard Procedures for the Measurement of Radio Noise from Overhead Power Lines and Substations, IEEE, 1986.
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5. Limits and Measurement Methods of Electromagnetic Noise from AC Power Systems, 0.15 - 30 MHz, National Standard of Canada, CAN3-C108.3.1-M84, Canadian Standards Association, May 1984.
6. Transmission Line Reference Book, 345 kV and Above, Second Edition, EPRI, 1984.
7. S. D. Schennum and R. G. Olsen, "A Method for Calculating Wide Band Electromagnetic Interference from Power Line Corona," IEEE Trans. on Power Delivery, Vol. 10, pp.1535-1540, July 1995. (The method was applied to a typical 500 kV power line described in [6]).
8. P. Stenumgaard, "On Digital Radio Receiver Performance in EM Disturbance Environments," Radio Comm. Systems Lab, Dept. of Comm. Systems, Swedish Defence Research Agency, December 2000.
9. J. L. Blackburn, Protective Relaying, Dekker, 1987.

A

ADDITIONAL MEASUREMENT RESULTS AT INEZ

Appendix A contains additional information on the measurements at Inez.

Additional Noise Measurement Results

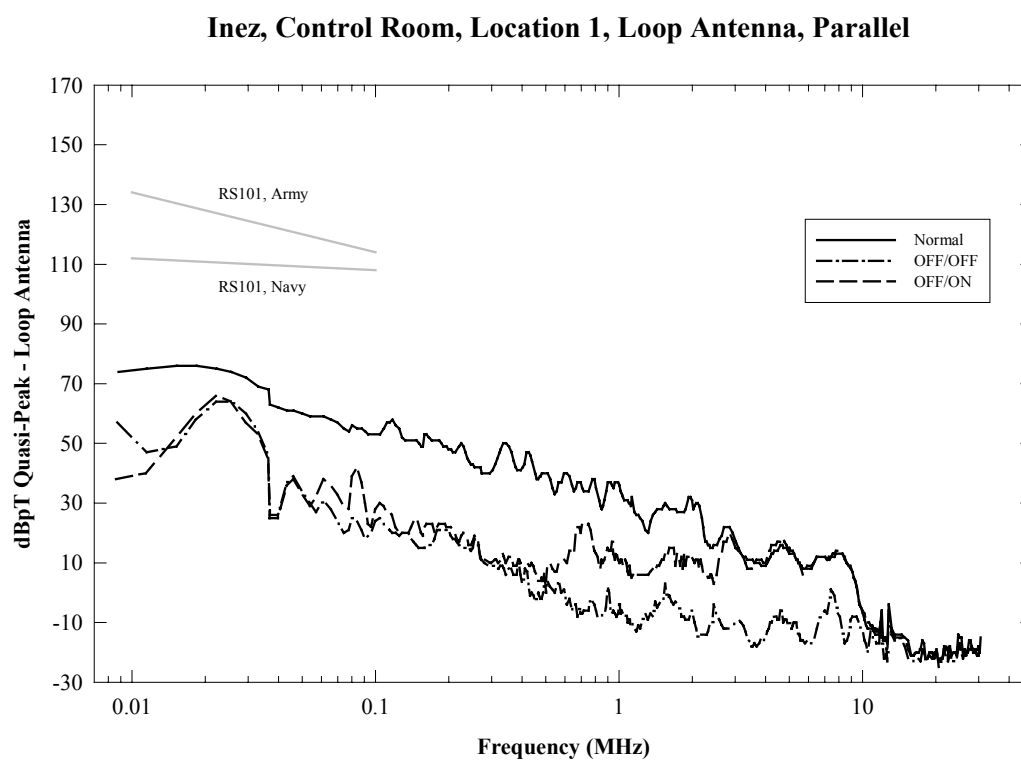


Figure A-1
Inez, Control Room, Location 1, Parallel Position, Loop Antenna Measurements and RS101 Limit Lines

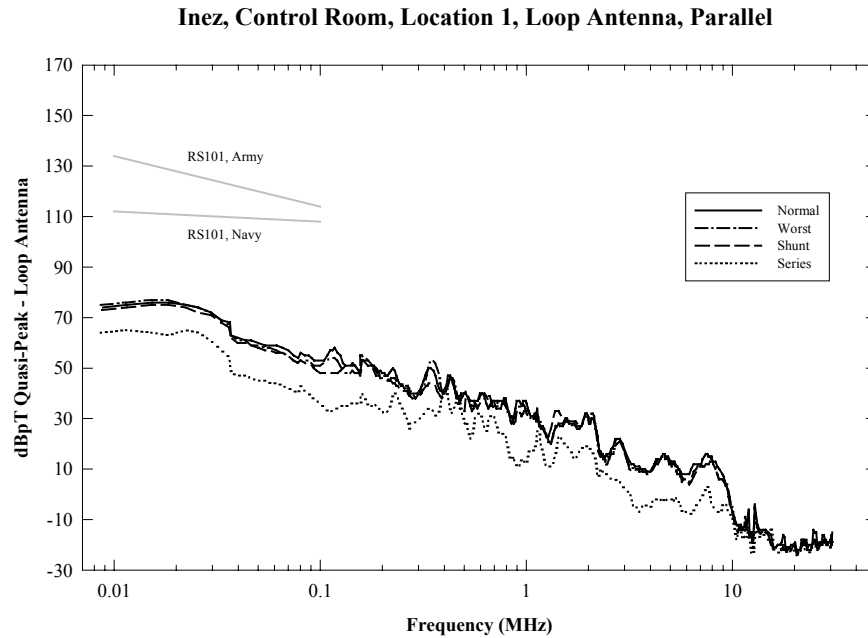


Figure A-2
Inez, Control Room, Location 1, Loop Antenna Measurements and RS101 Limit Lines

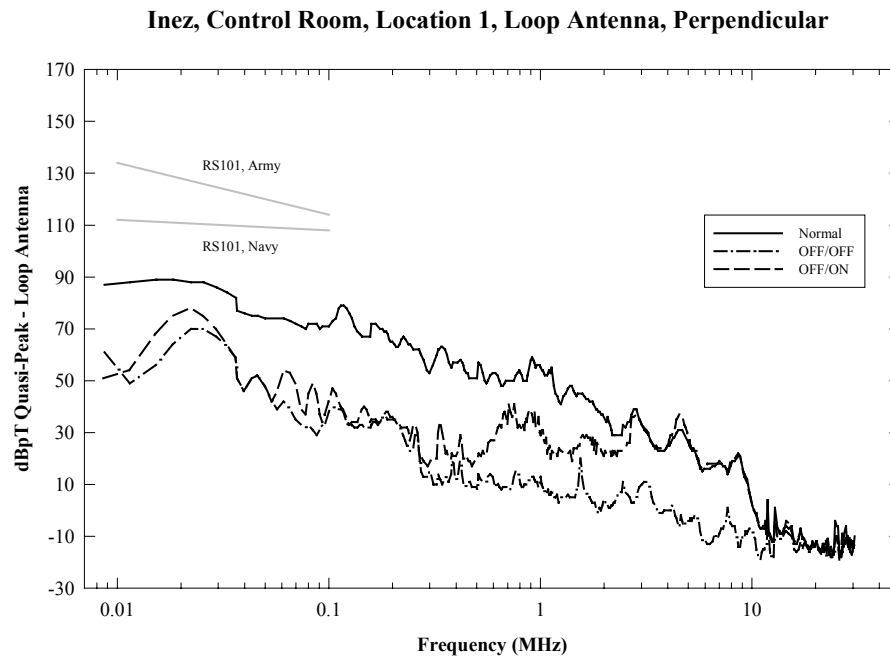


Figure A-3
Inez, Control Room, Location 1, Loop Antenna Measurements and RS101 Limit Lines

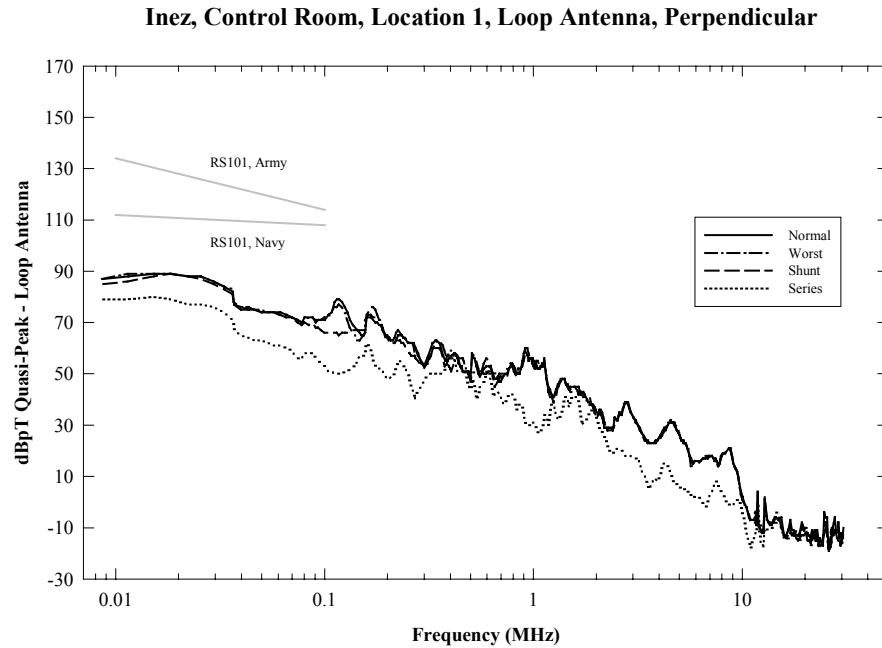


Figure A-4
Inez, Control Room, Location 1, Loop Antenna Measurements and RS101 Limit Lines

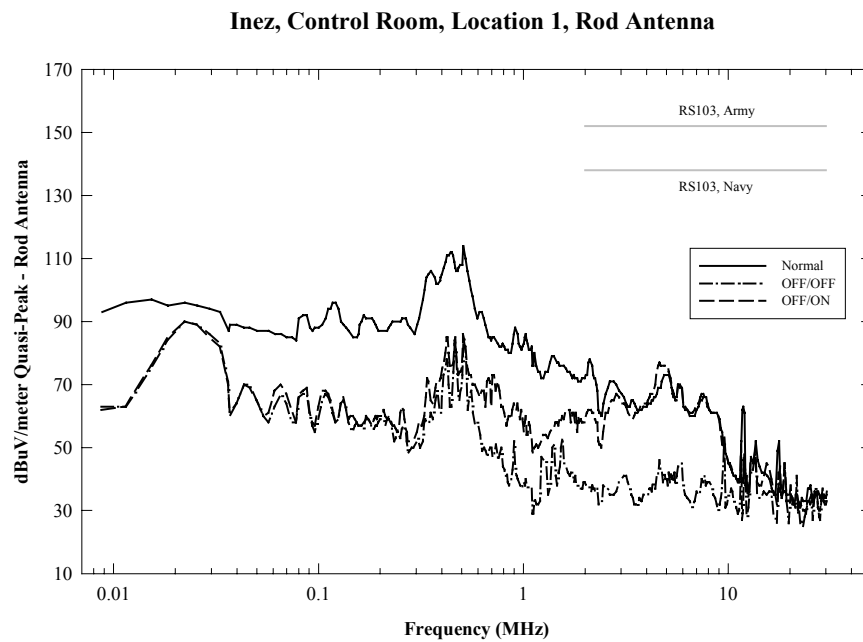


Figure A-5
Inez, Control Room, Location 1, Rod Antenna Measurements and RS103 Limit Lines

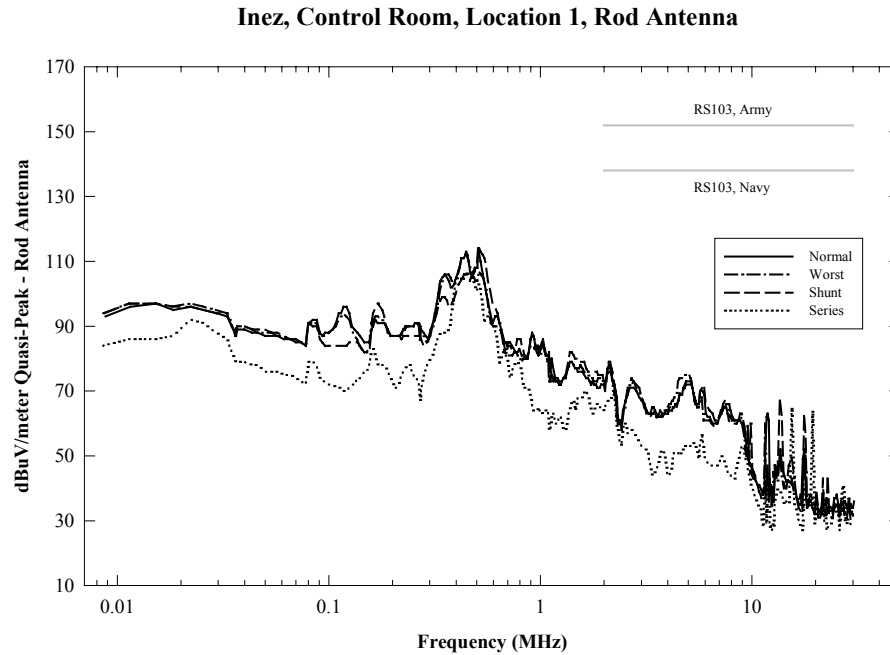


Figure A-6
Inez, Control Room, Location 1, Rod Antenna Measurements and RS103 Limit Lines

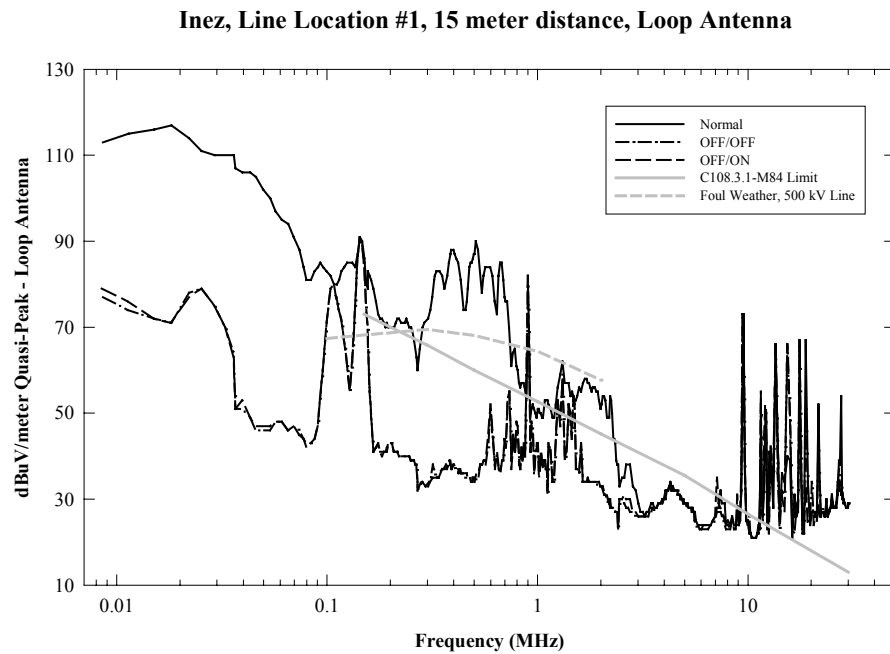


Figure A-7
Inez - Johns Creek Line, Location 1, 15 m Distance, Normal, Off/On and Off/Off Cases, Loop Antenna Measurements with Limit Lines

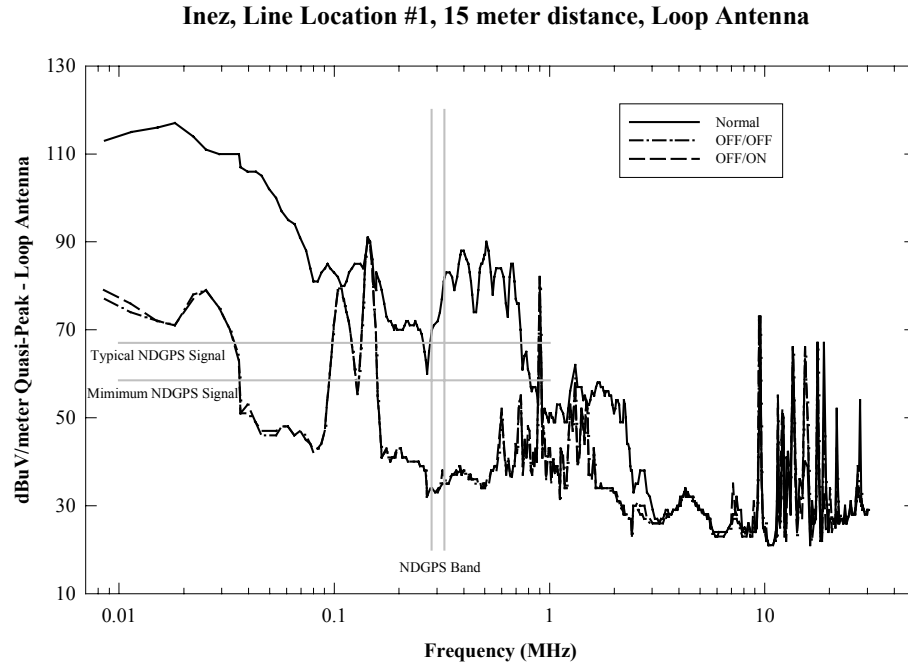


Figure A-8
Inez - Johns Creek Line, Location 1, 15 m Distance, Normal, Off/On and Off/Off Cases, Loop Antenna Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

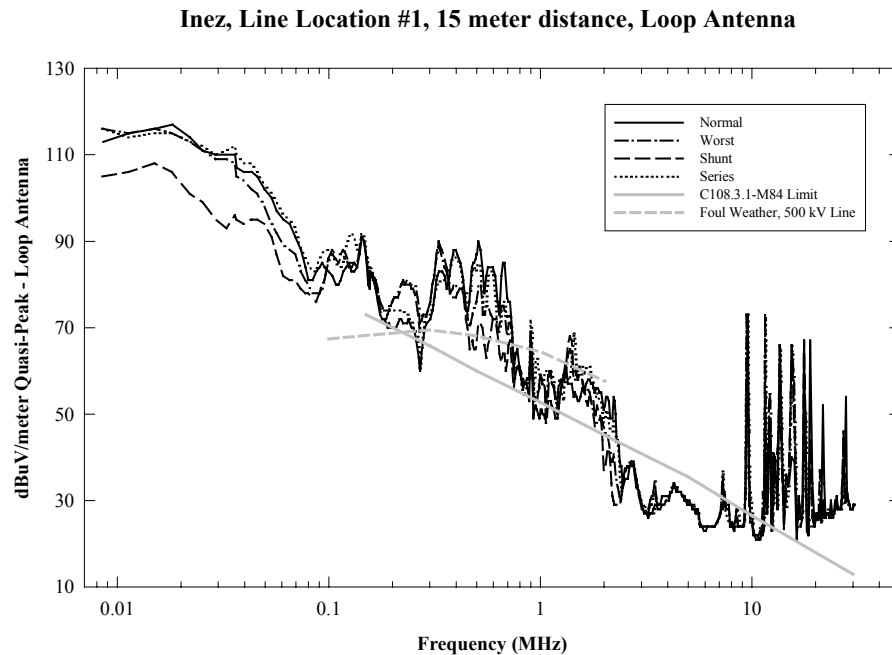


Figure A-9
Inez - Johns Creek Line, Location 1, 15 m Distance, Normal, Worst, Shunt and Series Cases, Loop Antenna Measurements with Limit Lines

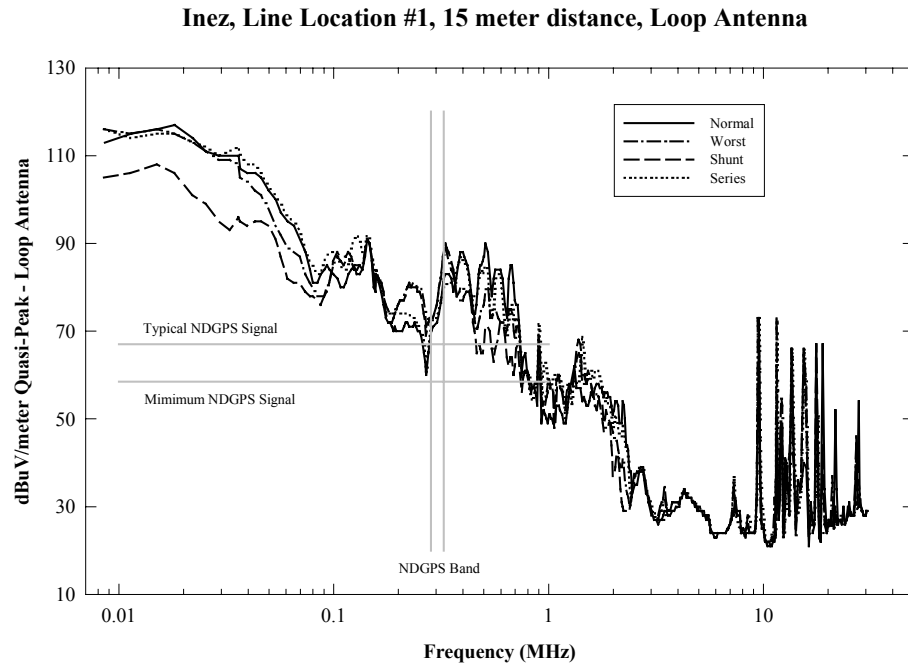


Figure A-10
Inez - Johns Creek Line, Location 1, 15 m Distance, Normal, Worst, Shunt and Series Cases, Loop Antenna Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

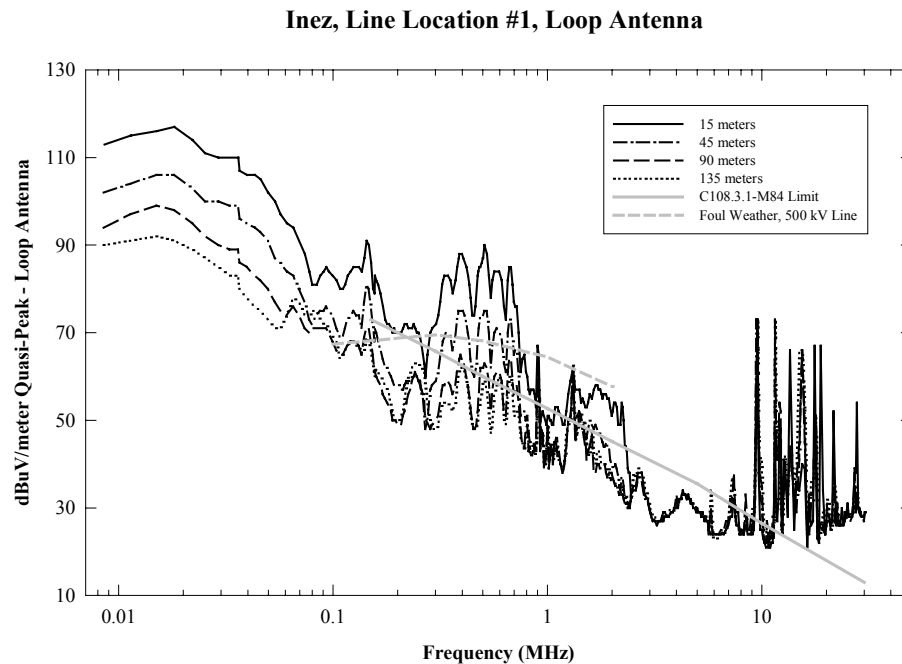


Figure A-11
Inez – Johns Creek Line, Location 1, 15-45-90-135 m Lateral Distances, Loop Antenna Measurements with Limit Lines

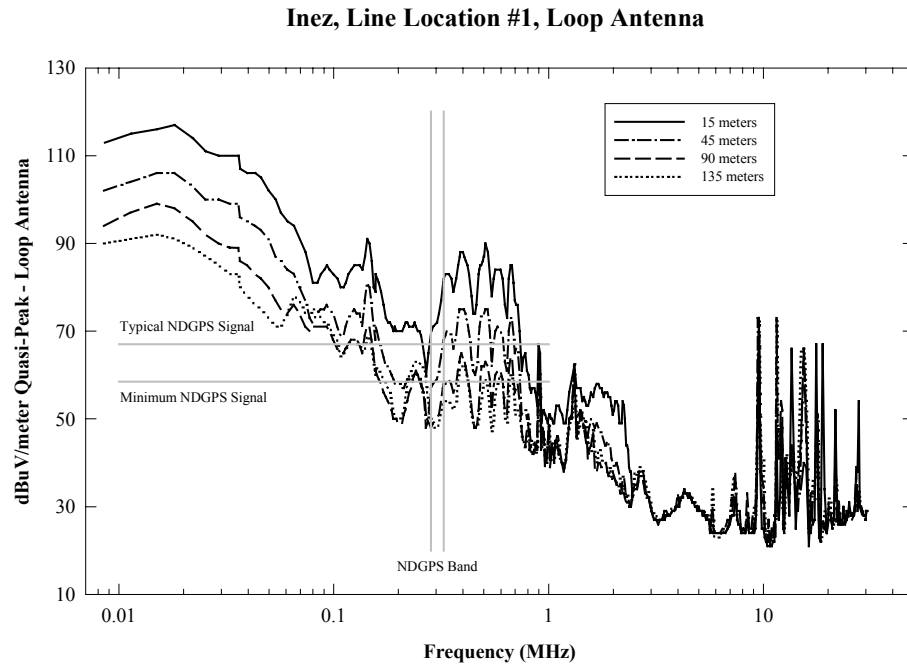


Figure A-12
Inez – Johns Creek Line, Location 1, 15-45-90-135 m Lateral Distances, Loop Antenna
Measurements with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR)
Noise Measurements (see page 5-8)

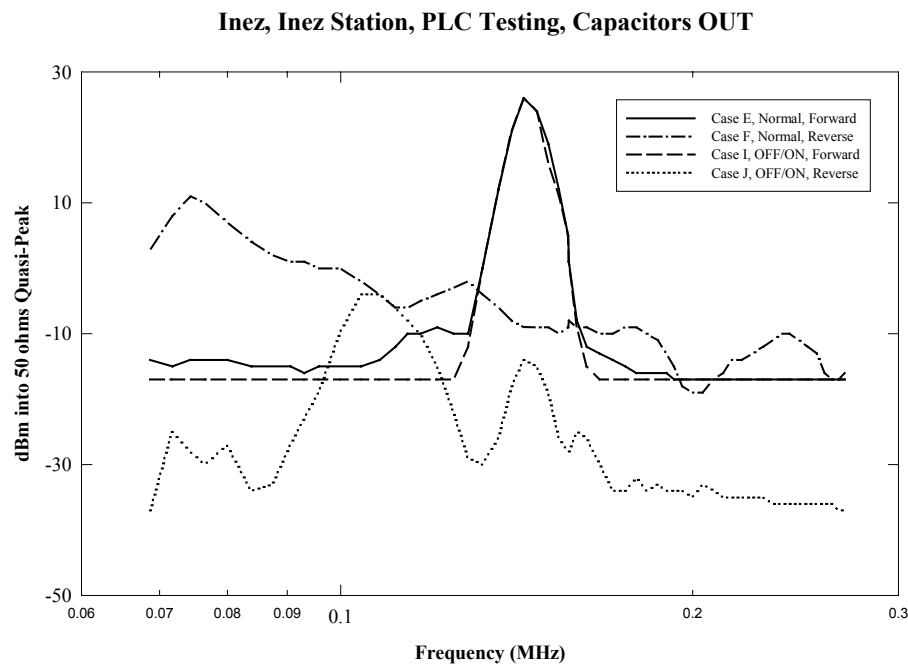


Figure A-13
PLC Testing at Inez, Normal and Off/On Cases, Capacitors Out, Forward and Reverse
Test Cases

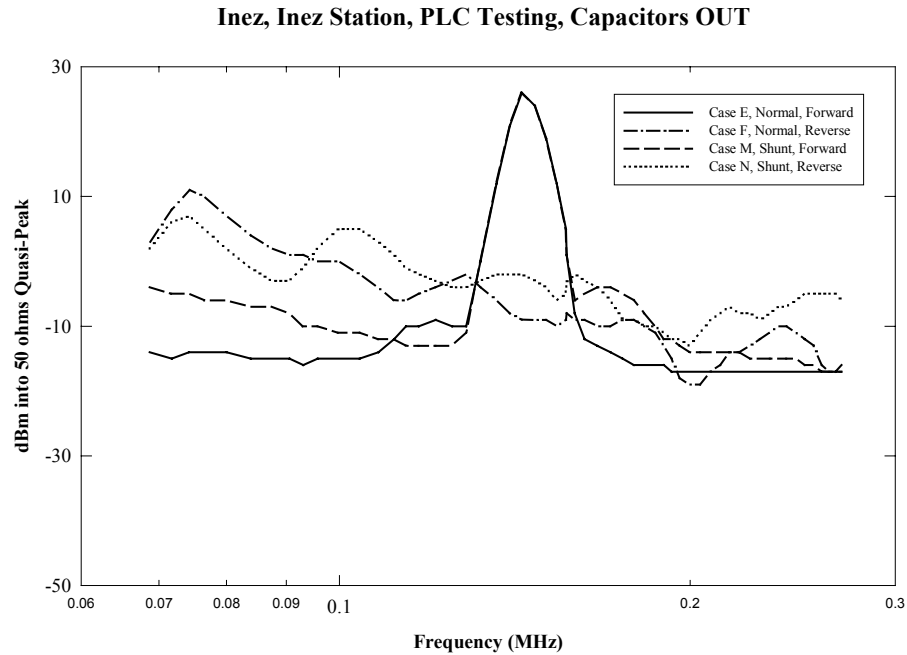


Figure A-14
PLC Testing at Inez, Normal and Shunt Cases, Capacitors Out, Forward and Reverse Test Cases

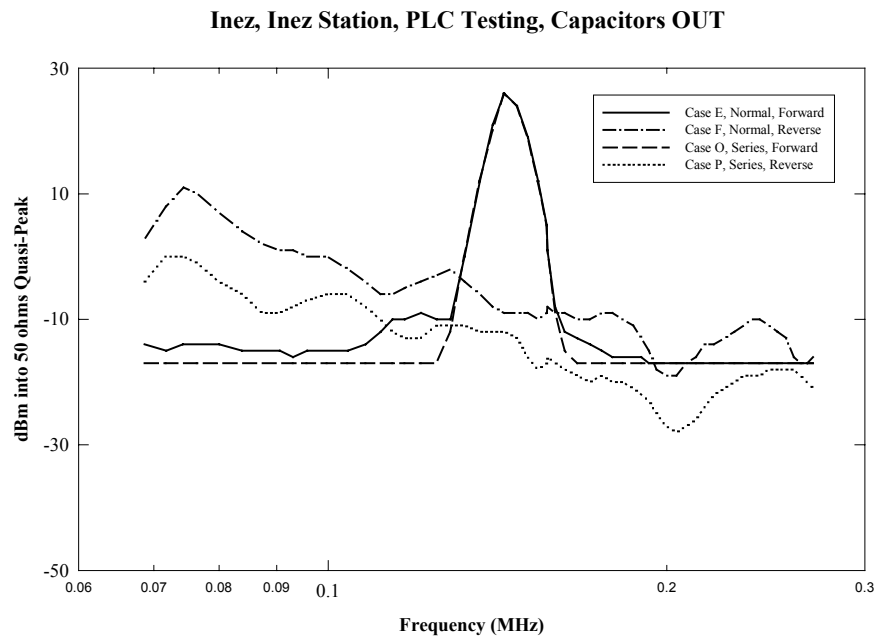


Figure A-15
PLC Testing at Inez, Normal and Series Cases, Capacitors Out, Forward and Reverse Test Cases

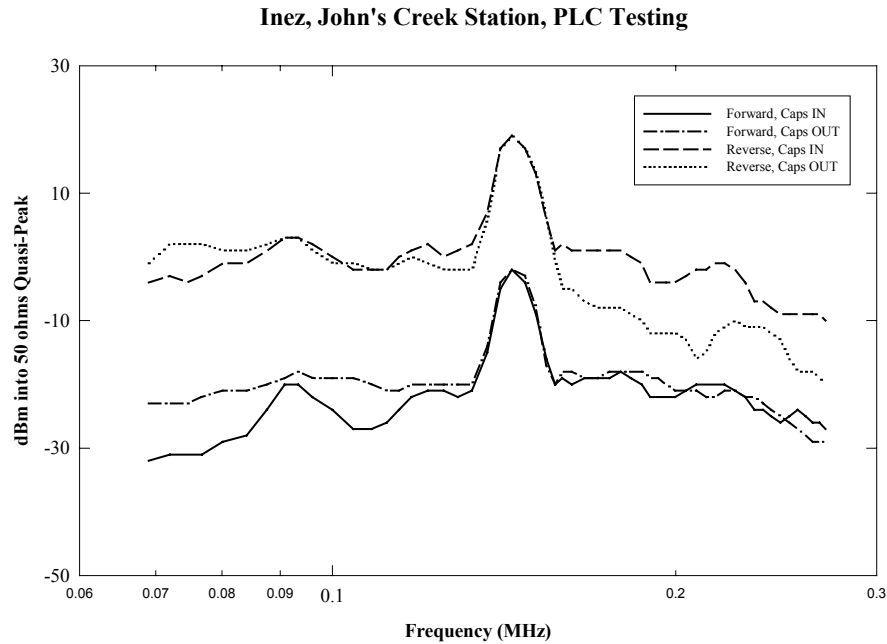


Figure A-16
PLC Testing at Johns Creek, Capacitors at Inez In/Out, Forward and Reverse Test Cases

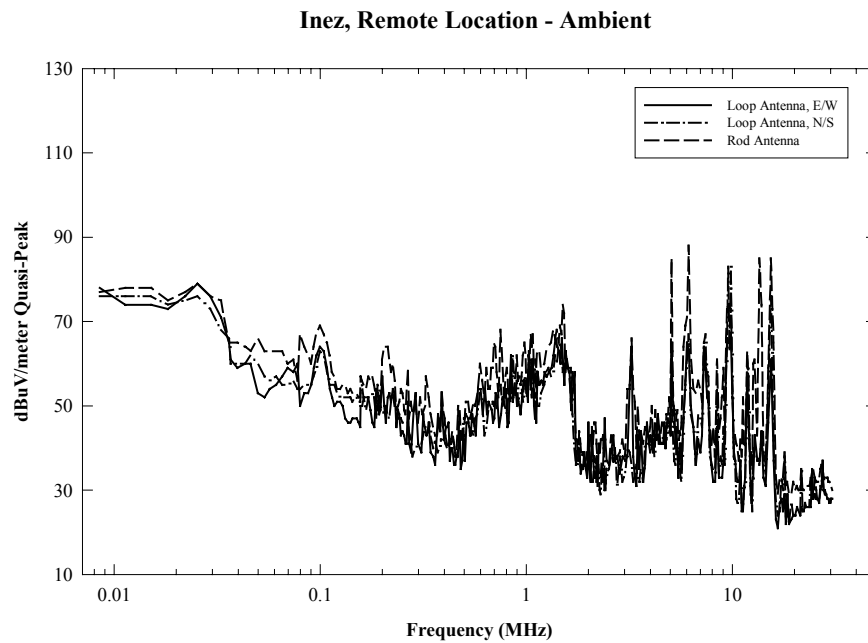


Figure A-17
Inez, Remote Location, Ambient Noise Levels

Summary of Load Levels

(Summary of load characteristics, load levels, and load ranges at Inez will be listed and grouped.)

B

ADDITIONAL MEASUREMENT RESULTS AT SULLIVAN

Appendix B contains additional information on the measurements at Sullivan.

Additional Noise Measurement Results

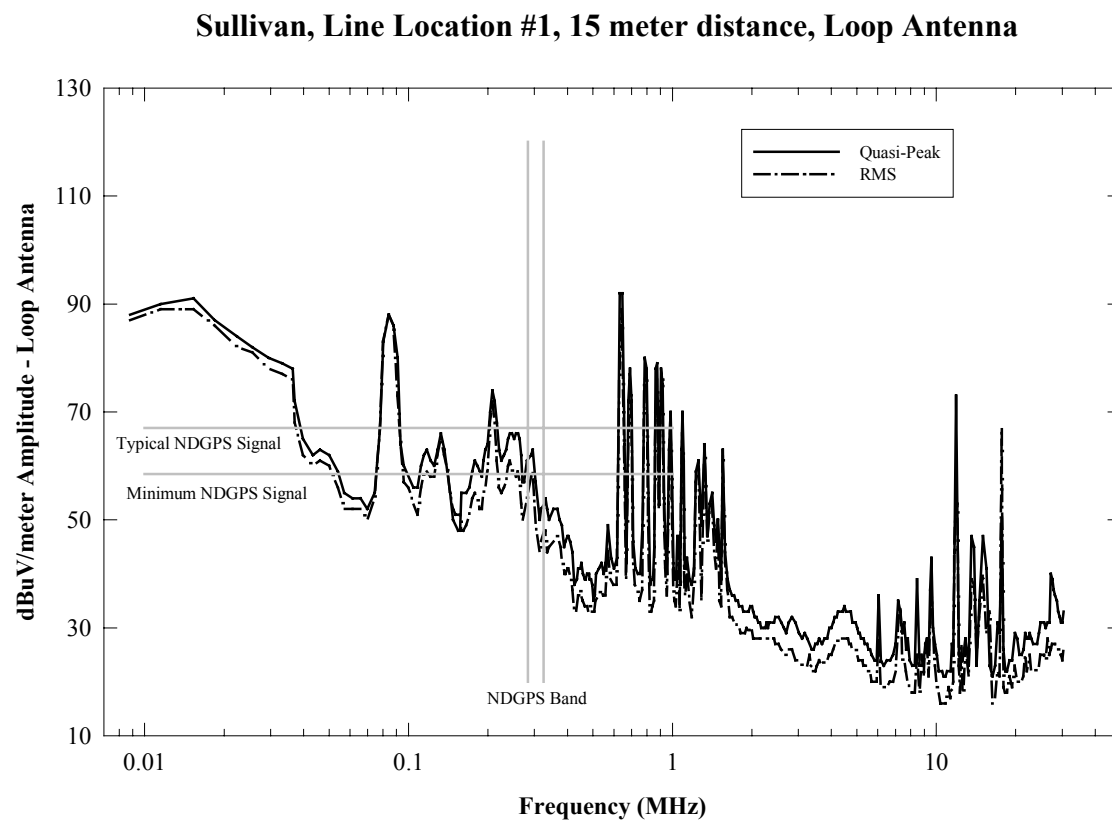


Figure B-1
Sullivan, Line Location 1, 15 m Distance, Loop Antenna Measurements,
Comparison of RMS and QP (CISPR) Readings with NDGPS Signal Levels Corrected
for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

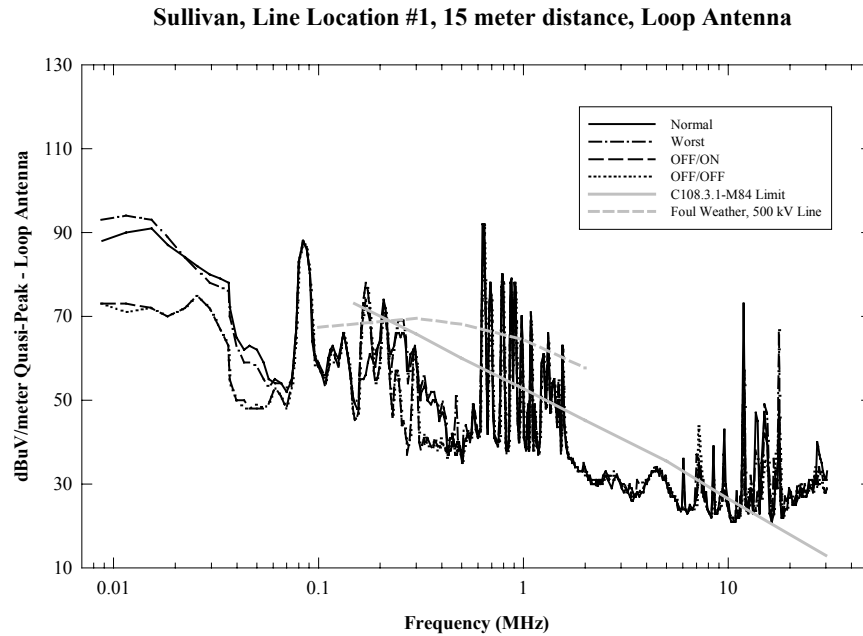


Figure B-2
Sullivan, Line Location 1, 15 m Distance, Loop Antenna Measurements,
Four Operational Cases, with Limit Lines

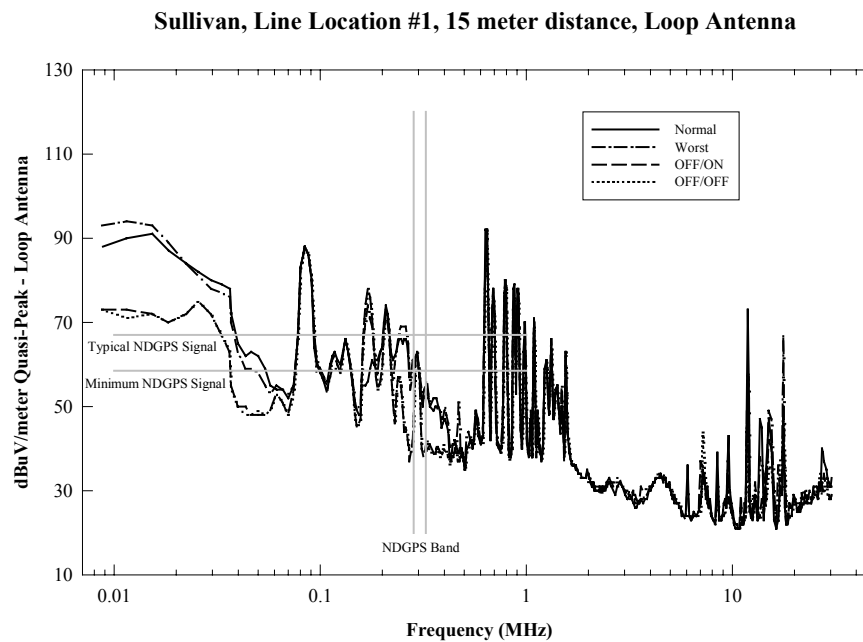


Figure B-3
Sullivan, Line Location 1, 15 m Distance, Loop Antenna Measurements,
Four Operational Cases, with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR)
Noise Measurements (see page 5-8)

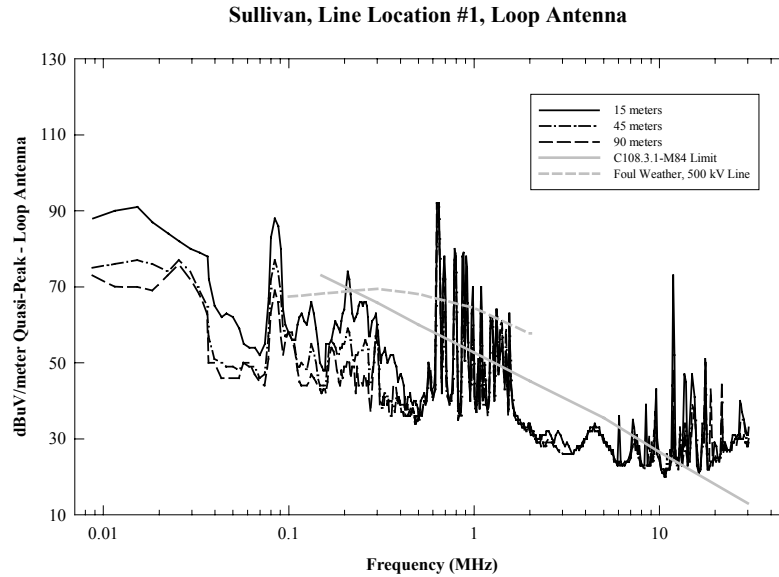


Figure B-4
Sullivan, Line Location 1, Loop Antenna Measurements, 15-45-90 m Lateral Distances, with Limit Lines

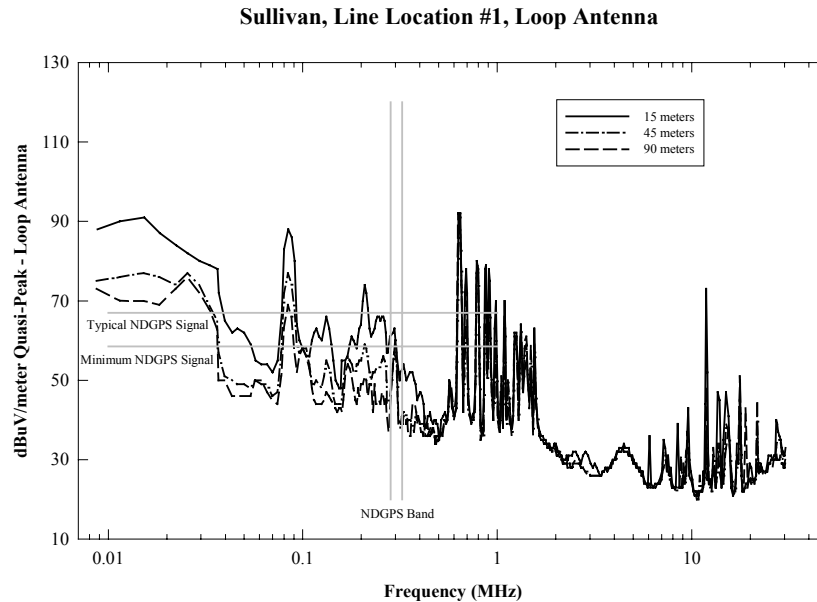


Figure B-5
Sullivan, Line Location 1, Loop Antenna Measurements, 15-45-90 m Lateral Distances, with NDGPS Signal Levels Corrected for QP 9kHz BW (CISPR) Noise Measurements (see page 5-8)

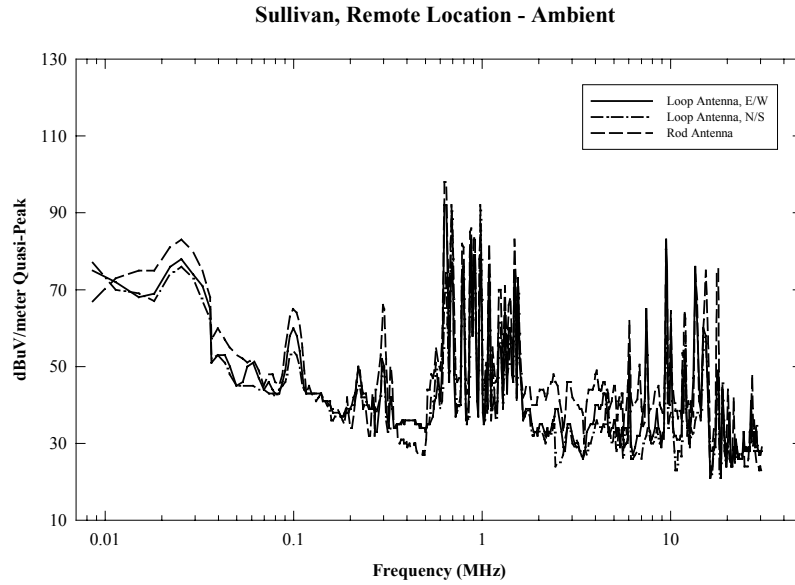


Figure B-6
Sullivan, Remote Location, Ambient Noise Levels

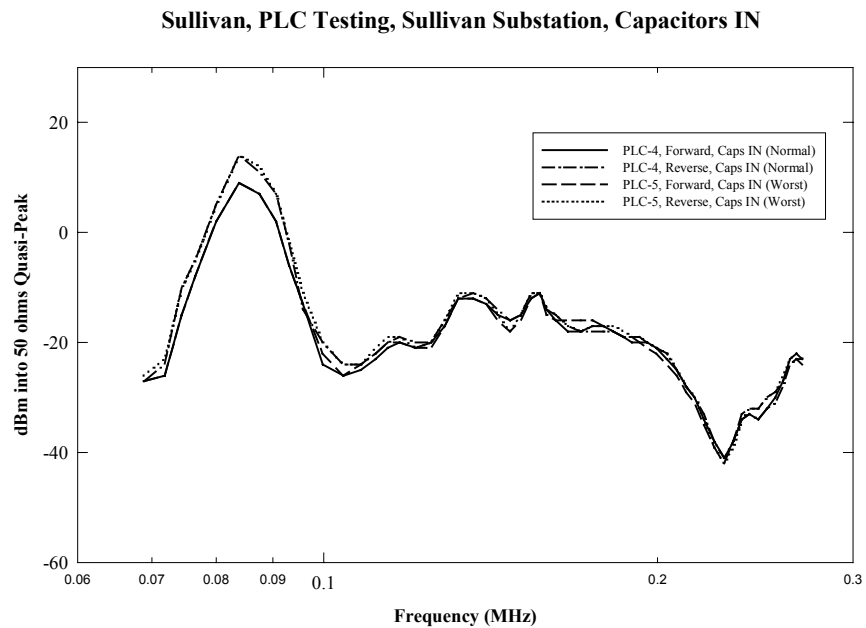


Figure B-7
PLC Testing in Sullivan, Normal and Worst Cases, Capacitors In, Forward and Reverse Test Cases

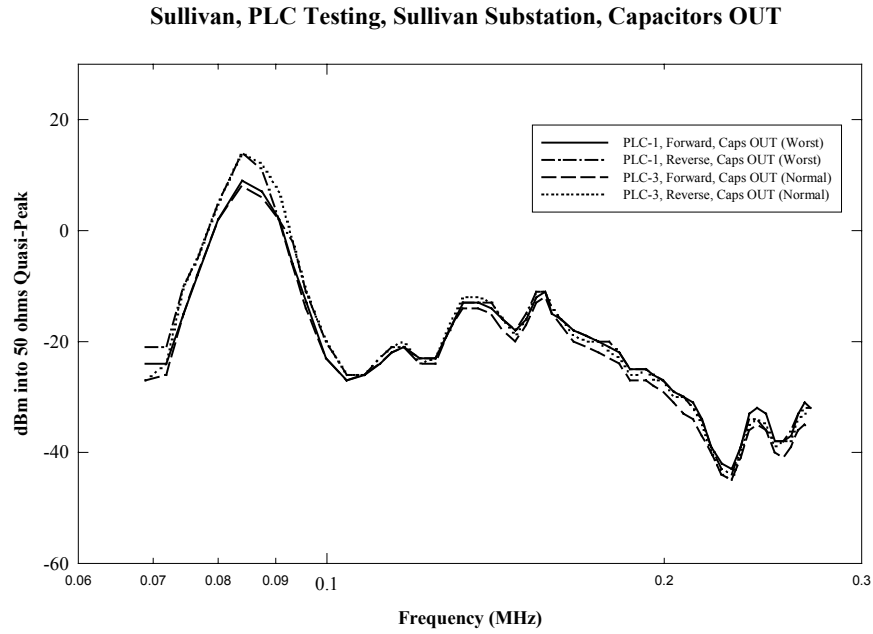


Figure B-8
PLC Testing in Sullivan, Normal and Worst Cases, Capacitors Out, Forward and Reverse Test Cases

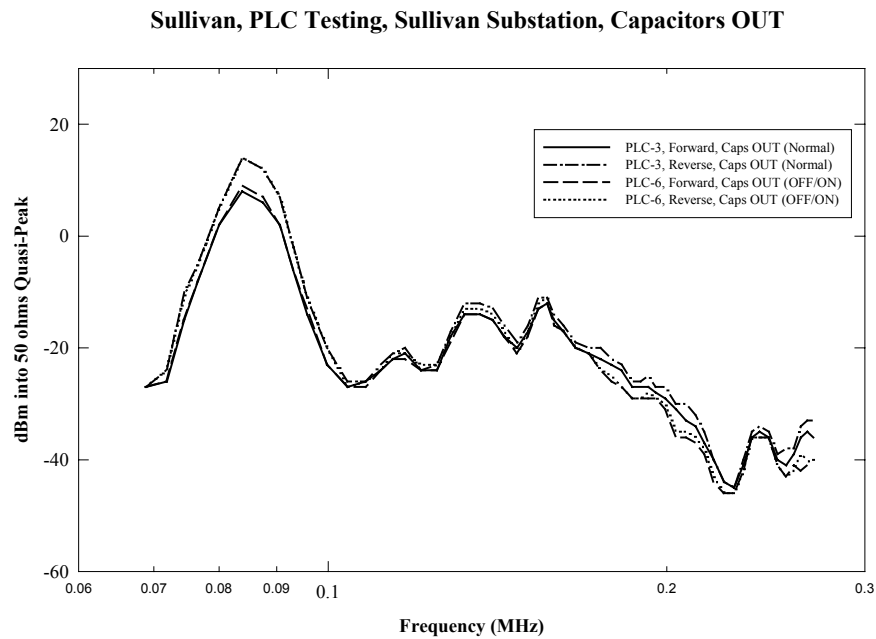


Figure B-9
PLC Testing in Sullivan, Normal and Off/On Cases, Capacitors Out, Forward and Reverse Test Cases

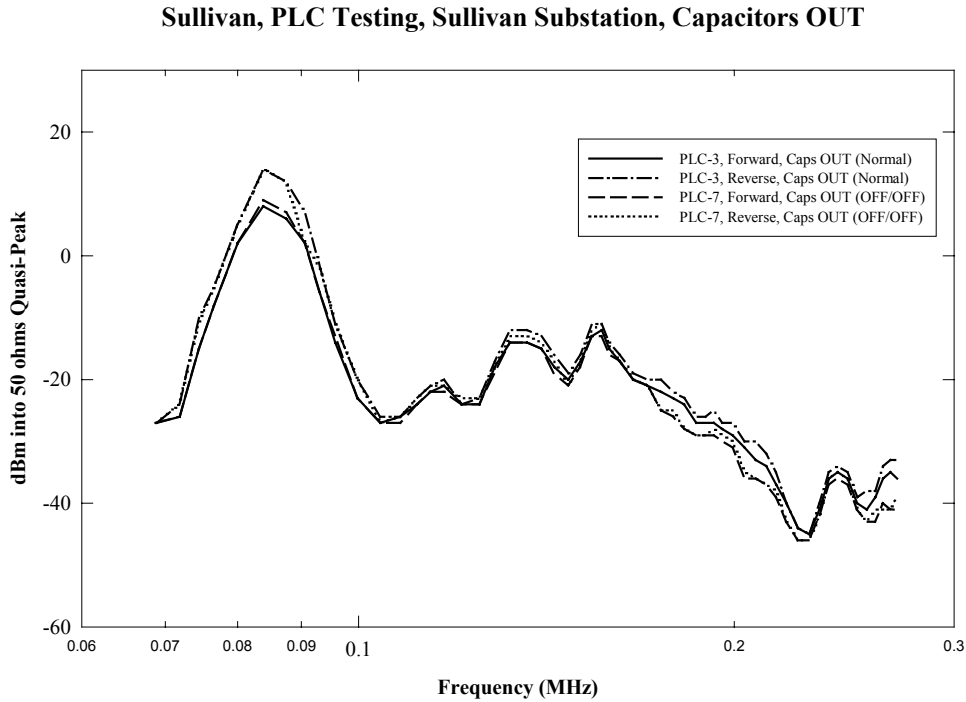


Figure B-10
PLC Testing in Sullivan, Normal and Off/Off Cases, Capacitors Out, Forward and Reverse Test Cases

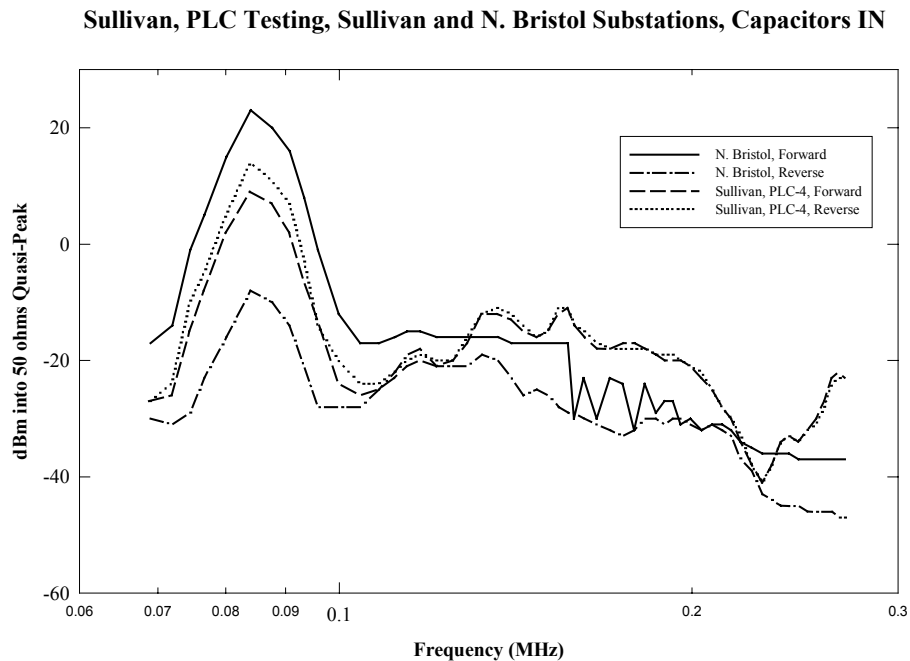


Figure B-11
PLC Testing in Sullivan and North Bristol, Capacitors In, Forward and Reverse Test Cases

Sullivan, PLC Testing, Sullivan and N. Bristol Substations, Capacitors OUT

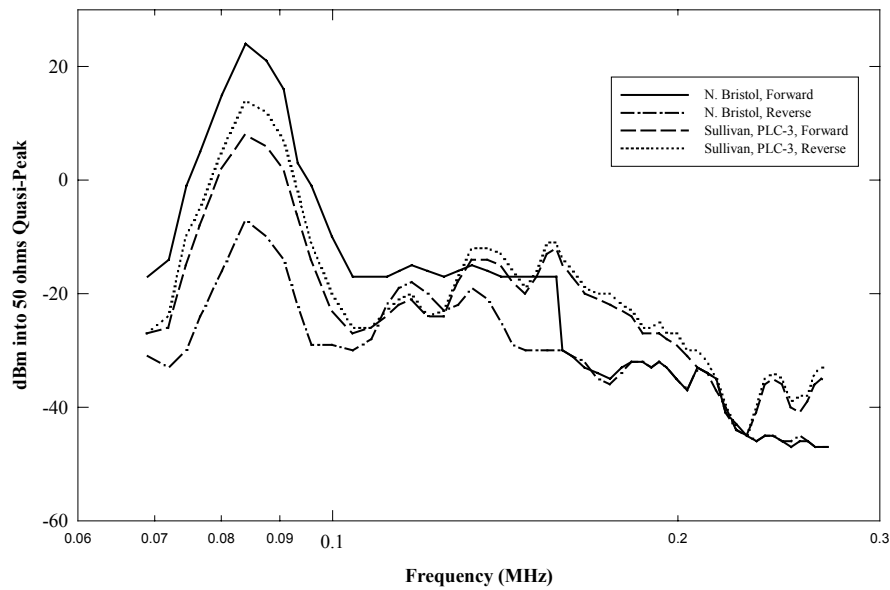


Figure B-12
PLC Testing in Sullivan and North Bristol, Capacitors Out, Forward and Reverse Test Cases

Sullivan, PLC Testing, North Bristol Substation, Capacitors OUT

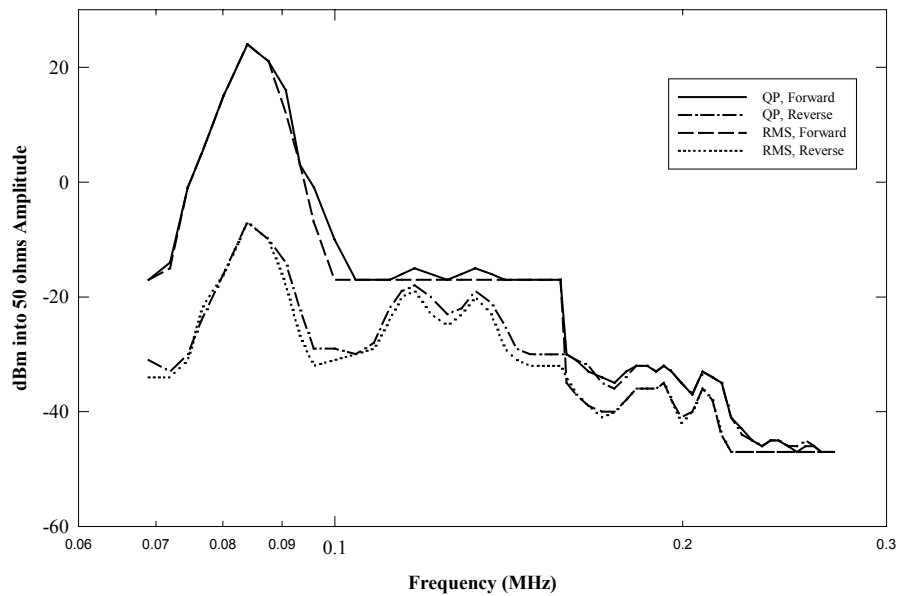


Figure B-13
PLC Testing in Sullivan and North Bristol, Capacitors Out, RMS and QP (CISPR) Readings, Forward and Reverse Test Cases

Summary of Load Levels

(Summary of load characteristics, load levels, and load ranges at Sullivan will be listed and grouped.)

C

PROTECTION INFORMATION

The protection systems applied at Inez, Sullivan, and Marcy Stations utilize power line carrier (PLC) channels. Figure C-1 shows the single line diagram of a line-to-ground PLC channel equipment [9].

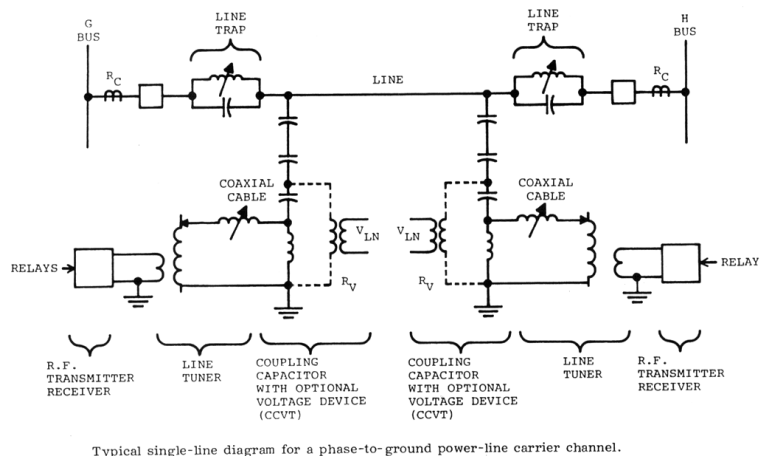


Figure C-1
Single Line Diagram of a Line-to-Ground PLC Channel Equipment [9]

The review below is based on [9].

The carrier frequency is between 30 and 300 kHz. It is connected to the power line. The connection is made through a coupling capacitor and a line tuner.

The coupling capacitor is often a voltage measuring device as well. If the coupling capacitor is built together with a voltage transformer, it is called a coupling capacitor voltage transformer (CCVT). The tuned inductance of the line tuner cancels the capacitance of the coupling capacitor. The result is a low-impedance resistive path for the radio frequency signals to and from the line section.

At the remote end there is a similar equipment.

The transmitter/receiver may be tuned to the same frequency, or to two different frequencies. The latter case may require a double frequency tuner.

A line trap is connected in series with the power line conductor at each terminal, just outside the radio frequency path. It is tuned to provide a high RF impedance. That minimizes signal loss into the substation. They are designed to carry the power frequency load current at very low loss.

There are several systems that can be applied. They are called

- directional comparison blocking or unblocking pilot systems
- directional comparison overreaching or underreaching transfer tripping trip pilot systems
- phase comparison systems
- remote tripping systems (transfer tripping, permissive transfer tripping).

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