North American SynchroPhasor Initiative (NASPI)
Performance & Standards Task Team

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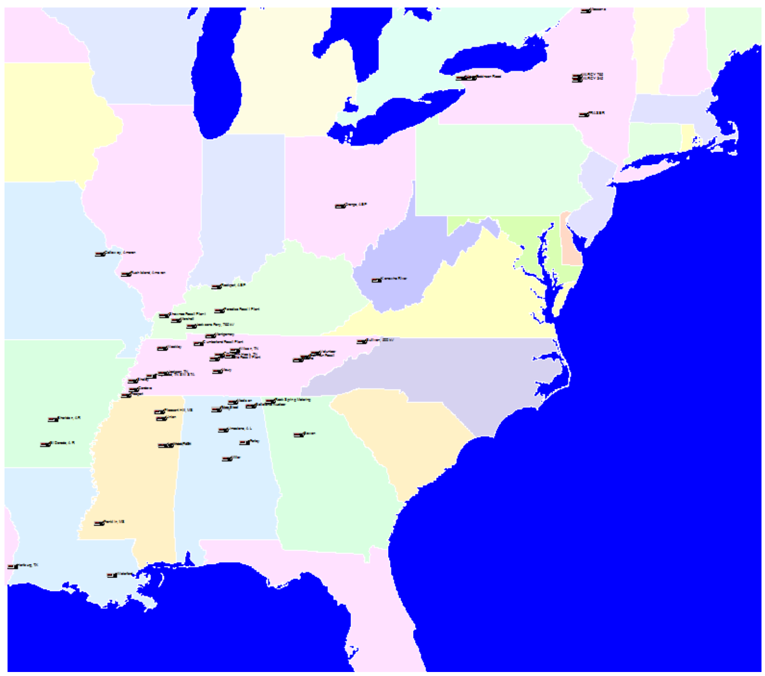
Synchrophasor Measurement Accuracy Characterization



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Revision History

Date	Rev. #	Description
11/30/07	1	Final version of PSTT

Disclaimer

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Data Accuracy Characterization

Scope: The scope of this effort is to characterize GPS-synchronized data in terms of their overall accuracy. Sources of error are: (a) instrumentation channel characteristics, (b) GPS-equipment characteristics and (c) system asymmetries. The characterization process is separated into two parts: (a) accuracy for power frequency data (fundamental frequency phasors) and (b) accuracy during transients.

An objective of this work is to define accuracy characterization tests to be performed on GPS-synchronized equipment that will provide users with the necessary information to make informed decisions as to the quality of data obtained with these units.

Another objective of this work is to allow users to determine the level of inaccuracy injected into the measurements from instrumentation channels and to provide methodologies to quantify this error.

Another objective is to discuss methodologies by which the overall accuracy can be improved.

The overall objective is to provide a document by which users can assess the overall accuracy of their selected instrument transformers and GPS-synchronized equipment.

Definitions

This section provides some useful definitions pertinent to GPS-synchronized devices, communication protocols and communications media.

DFR – Digital Fault Recorder

DDR – Dynamic Disturbance Recorder

SER – Sequence of Events Recorder

PMU – Phasor Measurement Unit. A device that samples analog voltage and current data in synchronism with a GPS-clock. The samples are used to compute the corresponding phasors. Phasors are computed based on an absolute time reference (UTC), typically derived from a built in GPS receiver.

PDC – Phasor Data Concentrator. A logical unit that collects phasor data, and discrete event data from PMU's and possibly from other PDC's, and transmits data to other applications. PDC's may buffer data for a short time period but do not store the data.

Relay – An electromechanical or electronic device applied to the purpose of power apparatus protection. A relay typically monitors voltages and currents associated with a certain power system device and may trip appropriate breakers when a potentially damaging condition is detected.

IED – Intelligent Electronic Device. A general term indicating a multipurpose electronic device typically associated with substation control and protection.

UTC – Coordinated Universal Time (initials order based on French). UTC represents the time-of-day at the Earth's prime meridian (0° longitude).

IRIG-B – Time transmission formats developed by the **Inter-Range Instrumentation Group** (IRIG). The most common version is IRIG-B, which transmits day of year, hour, minute, and second once per second, over a 1 kHz carrier signal.

GOES – Geostationary Operational Environmental Satellites. Operated by the National Oceanic and Atmospheric Agency (NOAA). Two GOES satellites broadcast a time code referenced to UTC. Clocks based on this transmission are accurate to 100 microseconds.

GPS – Global Positioning System. A satellite based system for providing position and time. The accuracy of GPS based clocks can be better than 1 microsecond.

pps – Pulse-Per-Second. A signal consisting of a train of square pulses occurring at a frequency of 1 Hz, with the rising edge synchronized with UTC seconds. This signal is typically generated by GPS receivers.

kpps – One thousand pulses per second. A signal consisting of a train of square pulses occurring at a frequency of 1 kHz, with the rising edge of synchronized with UTC milliseconds. This signal is typically generated by GPS receivers.

Sampling Rate – The number of samples (measurements) per second taken by an analog to digital converter system.

Navigation – The mode in which GPS receiver has locked onto signals from three or more satellites thus providing accurate time, as well as position.

COMTRADE-file format – COMTRADE file format is a standardized ASCII text or binary file (2 formats), originally designed for Digital Fault Recorders. It can be used to transfer locally recorded values from a PMU over to the central data storage. COMTRADE ASCII format is not efficient for long-term data storage but could be used for event file retrieval.

PhasorFile – A binary storage format that is used by PDC for long-term storage of SynchroPhasor data. Currently, this format is not standardized, and may be left in such a state as long as stored data is made available in an industry standard format (i.e. COMTRADE).

Communications Related Terms

Unicast – UDP transmission from one host to another (source/destination). When talking about a link on a network, typically a unicast link is inferred.

Broadcast – Data transmission from one host to many. The destinations will be all computers on a network, for example, all the computers in the office building. With broadcast, every computer on the network must be trusted.

Multicast – Data transmission from one host to many. Data is transmitted to a group IP address. Any member of the group can access the address to receive the data. Anybody can then join in this multicast group, and when a server sends to the group, everyone in the group will receive the data. The advantage is that it is very simple to set up groups.

WAN – Wide Area Network, stretching across large geographical distances. Latency's can be very large, up to many seconds.

LAN – Local Area Network, within a small building or office. Very low latency between endpoints on the network, often less then a couple ms.

VLAN – A simulated LAN that is spread across a LAN, but uses special IP addresses so that it appears a “physically” separate LAN.

Lossless data compression – Data stored in a lossless format can be retrieved *exactly* as it was created.

Lossy data compression – Data that is stored in a lossy format will have degraded accuracy when retrieved. However, more data can be stored in the same amount of space. Lossy data compression should be applied with caution and is not expected to play major role in synchrophasor data collection.

Communication Protocols Terms

IEEE 1344 – A highly efficient protocol for real time SynchroPhasor data. Typically data is streamed in this format over UDP/IP or across a serial link.

BPA/PDCStream – A variant of IEEE 1344, widely used by the BPA PDC and HMI software on the West Coast.

IEEE C37.118 – Related to IEEE 1344, but adds much needed capability. This protocol and its associated standard are intended to replace IEEE 1344 and the BPA/PDCStream protocols. Typically data is streamed in this format over UDP/IP or across a serial link.

OPC DA – (Open Process Control Data Access) OPC was created for industrial automation, for use within a factory, for example. It is designed to share simple data between computers running only Microsoft Windows®. There are 3 revisions that are commonly used. Different revisions are generally not compatible. This protocol is useful for simple data sharing between computers in a small LAN, but has serious security and performance issues when deployed across a WAN. OPC uses TCP/IP the underlying link.

OPC HAD – (Open Process Control Historical Data Access) an offshoot of OPC DA which allows a client to request stored data. This is a separate protocol, and different servers/clients must be developed.

OPC AE – (Open Process Control Alarms and Events) an offshoot of OPC DA, which allows clients to be notified on alarm conditions. As with OPC HAD, this is a separate protocol, and different servers/clients must be developed.

OPC XML DA – (Open Process Control XML Data Access) – An OPC DA protocol designed for use across a WAN. This protocol uses the standard Web Services structure, using SOAP and XML. This protocol is simple to work with and will allow PMU devices that don’t run Windows® as an operating system, to be an OPC server for providing data to any client. The OPC Foundation is creating a ‘Unified Architecture’ using the XML-based structure as the foundation for future development.

TCP/IP – TCP/IP is a low-level protocol for use mainly on Ethernet or related networks. Most of the higher-level protocols use TCP/IP to transport the data. TCP/IP provides a highly reliable connection over unreliable networks, using checksums, congestion control, and automatic resending of bad or missing data. TCP/IP requires time to handshake new connections and will block if missing data is being resent.

UDP/IP – UDP/IP is a low-level protocol that is typically unreliable. However it provides low-latency communication across Ethernet or related networks. UDP/IP does not provide any error-control or resending of missing or bad data. The Application will need to check data for correctness. UDP/IP however, does not require time for handshaking and will not block, making it ideal for *real-time* data communications.

HTTP – HTTP is a protocol made popular by the Internet and web pages. Web pages are transmitted using HTTP. It has also become the mechanism for the Web Services Paradigm using SOAP and XML. HTTP uses TCP/IP as the underlying protocol.

FTP – FTP is the file transfer protocol. It is a simple protocol where a client can connect and request a file to be downloaded. A separate data connection is automatically created where the data is then transferred across the network while the command connection becomes unavailable. FTP is commonly used to get recorded data from devices.

VPN – (Virtual Private Network). A communication network constructed by using public wires to connect nodes with procedures to ensure that only authorized users can access the network and that the data cannot be intercepted. These procedures typically use encryption and other security mechanisms.

1. Introduction

Digital data acquisition equipment with GPS synchronization adds another dimension to the utilization and application of the data. The technology is young and as such the performance of similar equipment from different manufacturers varies. Yet, for the smooth development of applications using this data in a multi-vendor environment, it is necessary to develop standards that will accommodate the rapid development and deployment of such applications. The purpose of this document is to define the desirable performance characteristics of GPS- synchronized devices. It is very common to refer to these devices as Phasor Measurement Units (or PMU), a term that was introduced by Jay Murphy of Macrodyne in January 1992 with the introduction of the first PMU device. It is also noted that Arun Phadke introduced the PMS device (Phasor Measurement System) and in the time period 1990-92 he installed several of the PMS's in AEP, NYPA and other utilities. The PMS while it used a GPS clock it was in general not very accurate since it had a low frequency antialiasing filter (analog) that introduced a relatively large phase error. The primary function of the first PMU device (Macrodyne 1620) was to provide the phasor of the positive sequence component with accuracy of 0.02 degrees at the fundamental, even though the Macrodyne PMU had the capability to measure low order harmonics as well. Today, it is not appropriate to use this term. Indeed these devices are simply data acquisition units with the capability to time tag the data with GPS time accuracy, i.e. better than one microsecond. The applications of utilizing this data go beyond the initial objective of computing the phasor of the positive sequence component.

An important issue is the knowledge of the data accuracy. Normally the GPS data represent the power level voltages and currents that are obtained by first transforming the power level voltages and currents to instrumentation level and then the GPS synchronized equipment digitize the reduced level voltages and currents. Assuming an ideal transfer function of the overall instrumentation channel, the power level voltages and currents are obtained. Unfortunately, the instrumentation channel does not have ideal characteristics. The objective of this document is characterize the overall error of the usual implementations of GPS synchronized data.

The chain of measurement tarts from the high voltage or current measurement point and it ends at the digital signal generated by the A/D converter. The devices in between are referred to as the *instrumentation channel*. Figure 1 illustrates the devices forming voltage and current channels typically found in electric power generating stations and substations.

The purpose of the instrumentation channel is to provide isolation from the high voltage power system and to reduce the voltages and currents to standard instrumentation level. Ideally, it is expected that the instrumentation channel will produce at the output a waveform that will be an exact replica of the high voltage or current and scaled by a constant factor. In reality, the instrumentation channel introduces an error. Specifically, each device in this chain, namely: Instrument Transformers, Control Cables, Burdens, Filters, and A/D converters, may contribute to some degree to signal degradation. Furthermore, the error introduced by one device may be affected by interactions with other devices of the channel. It is thus important to characterize the overall channel error.

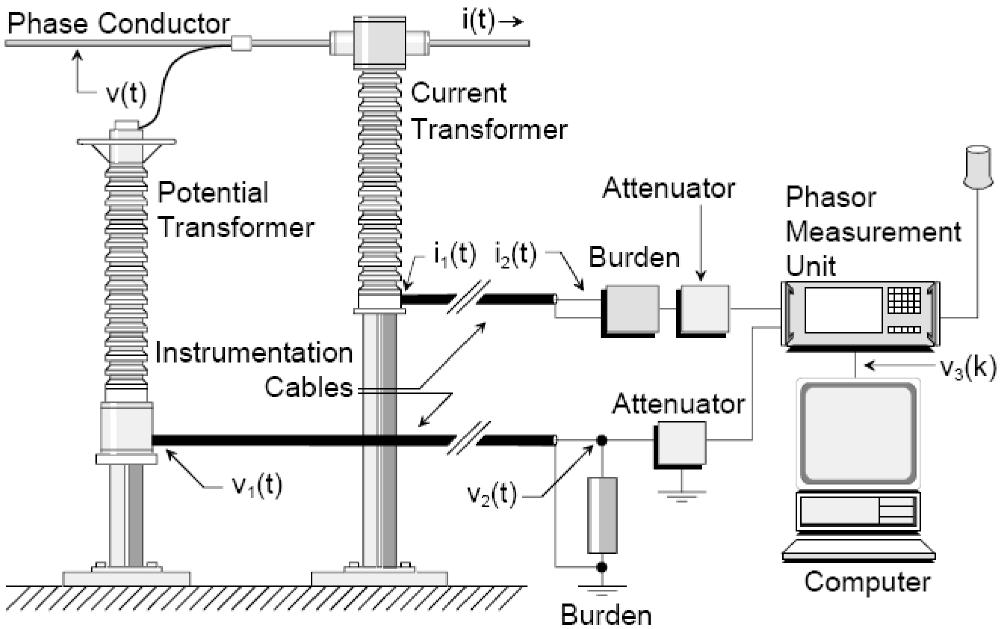

Figure 1: Typical potential and current instrumentation channels

The first link in the instrumentation channel equipment chain consists of voltage and current transformers, collectively called *instrument transformers*. These devices transform power system voltages and currents to levels appropriate for driving relays, fault recorders and other monitoring equipment. Several instrument transformer technologies are presently in use. The most common traditional technology devices are voltage and current transformers (PTs and CTs), which are based on magnetic core transformer technology. Another type of commonly used voltage transducers are capacitively coupled voltage transformers (CCVT's). These are based on a combination of capacitive voltage dividers and magnetic core transformers. Recently, voltage and current instrument transformers have been constructed based on the electro-optical and magneto-optical phenomena. These devices are known as EOVT's (Electro-Optical Voltage Transformers) and MOCT's (Magneto-Optical Current Transformers). While reference is made to these new type of instrument transformers, this report mainly focuses on PTs, CTs and CCVTs.

2. Data Accuracy

GPS-synchronized equipment has the capability to provide a data acquisition system with the following accuracy:

1. Time tagging with accuracy better than 1 microsecond (or equivalently 0.02 degrees of phase at 60 Hz).
2. Magnitude accuracy of 0.1% or better.

This accuracy is not available in all GPS-synchronized equipment. Even for the equipment that conform to this standard, this accuracy cannot be achieved for the overall system in any practical application, i.e. in the substation environment. In addition, depending on the implementation approach and equipment used, the accuracy of the collected data and the reliability of the data availability may differ. Typical GPS synchronized equipment (PMU's) are very accurate devices. However, the inputs to this equipment are scaled down voltages and current via instrument transformers, control cables, attenuators, etc. We collectively refer to it as the instrumentation channel. The instrumentation channel components are typically less accurate. Specifically, potential and current instrument transformers may introduce magnitude and phase errors that can be magnitudes of order higher than the typical PMU accuracy. Although, high accuracy laboratory grade instrument transformers are available, their application in substation environment is practically and economically infeasible.

Note that for most of the CTs, VTs, CCVTs, etc. in substations, the associated secondary circuit wiring (significant component of the instrumentation channel) is not normally "instrumentation class" wiring. In many cases, this wiring is control type cabling (non-twisted pairs) and is often unshielded. Often changes are made to these secondary circuits that affect the overall secondary circuit burden (for example, adding or replacing relays or other devices), without a detailed engineering analysis of the impact on high accuracy applications such as the PMU installation. The use of isolating switches, the application of grounds on these secondary circuits, and the presence of non-linear burdens) are a few of the items that can have a significant impact on the accuracy of the instrumentation channel.

In some jurisdictions, utility regulators have mandated the use of dedicated instrument transformers for revenue or tie line metering (including those located in HV substations) as well as the application of specific design and testing criteria for the associated secondary circuit wiring. In at least one jurisdiction, this secondary wiring is "secured" to help ensure that other devices (burdens) are not inadvertently connected – neither permanently nor temporarily. In other words, the instrument transformer secondary circuit is carefully designed and tested (measuring actual burdens) and then access is controlled to ensure the on-going accuracy of the overall revenue metering installation.

With most utilities in the long term, there is a high probability that the presence of PMUs will be overlooked when changes are made to the secondary circuits of “shared use” instrument transformers. If this happens, it will have a negative impact on the long term accuracy of individual PMU installations.

The above described issues should be taken into consideration for the purpose of assessing the quality of data from PMUs.

Instrumentation channels can be classified into five distinct categories, depending on the instrument transformer used. These are:

1. CT based instrumentation channel
2. Wound type VT based instrumentation channel
3. CCVT based instrumentation channel
4. EOVT based instrumentation channel
5. MOCT based instrumentation channel

The five categories are pictorially illustrated in Figures 2.1 through 2.5. In each one of these cases, the error is defined as follows.

Voltage Error

$$v_{measured}(t) = k_{ideal}\ v_{out}(t)$$
$$v_{error}(t) = v_{measured}(t) - v_{ps}(t)$$

Current Error

$$i_{measured}(t) = k_{ideal}\ i_{out}(t)$$
$$i_{error}(t) = i_{measured}(t) - i_{ps}(t)$$

where the subscript “out” refers to the actual output of the instrumentation channel, subscript “measured” refers to the quantity reported by the equipment and the subscript “ps” refers to the actual power level quantity. The error waveform can be analyzed to provide the rms value of the error, the phase error, etc.

The objective of this document is to characterize the error for each one of the five generic cases listed above. It is important to realize that each of the generic cases may have additional options, for example, case 1 may be implemented with different accuracy class CTs.

Appendix F presents a number of standardized (typical) instrumentation channels.

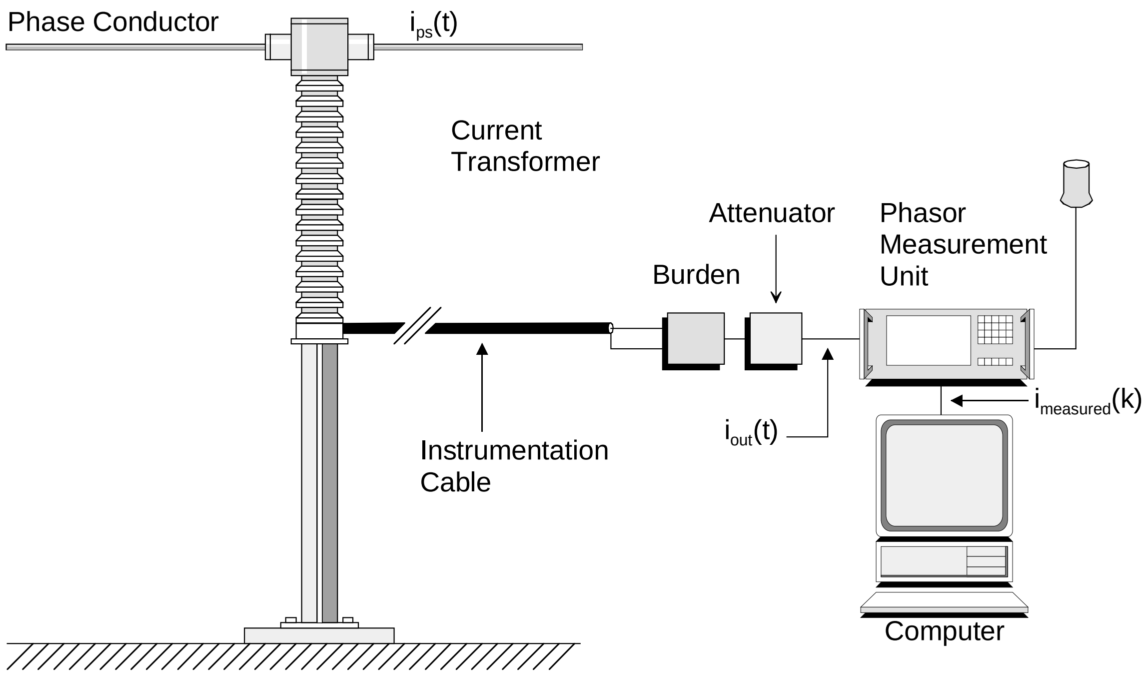

Figure 2.1 CT Based Instrumentation Channel

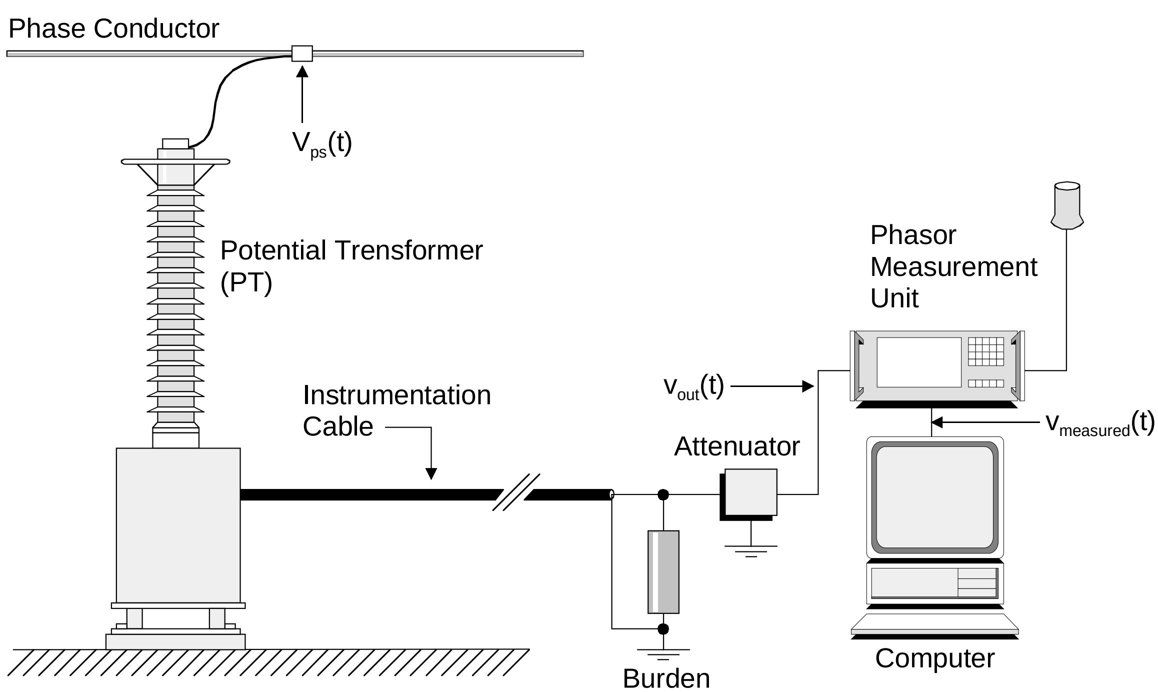

Figure 2.2 Wound type VT Based Instrumentation Channel

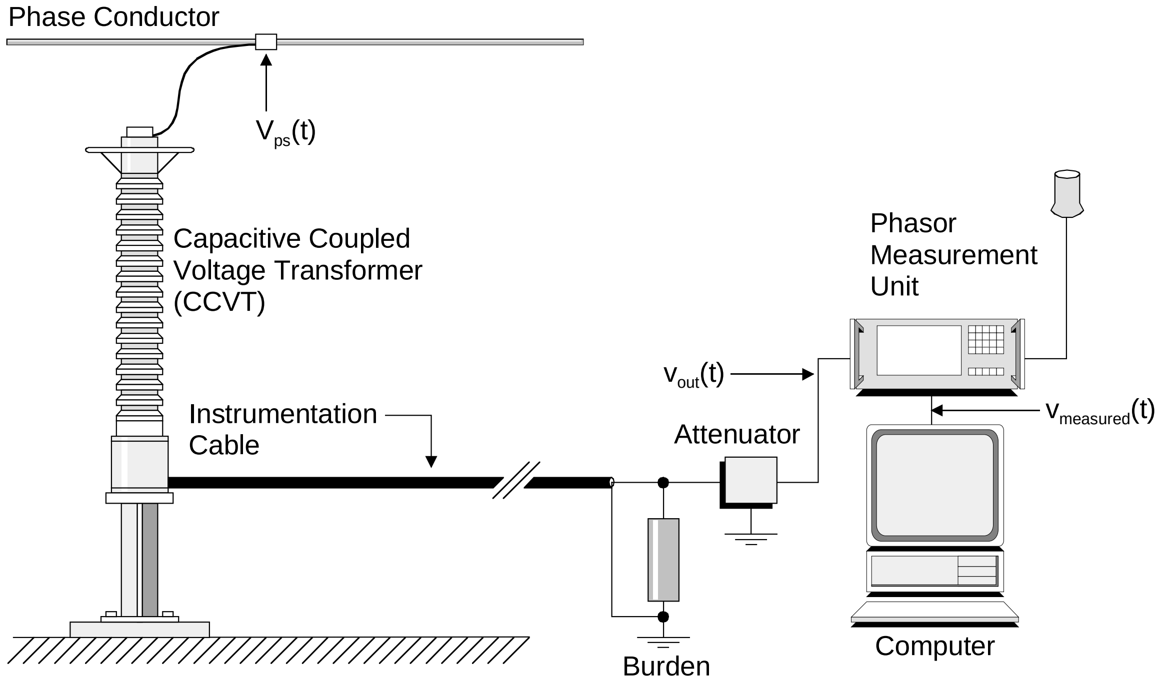

Figure 2.3 CCVT Based Instrumentation Channel

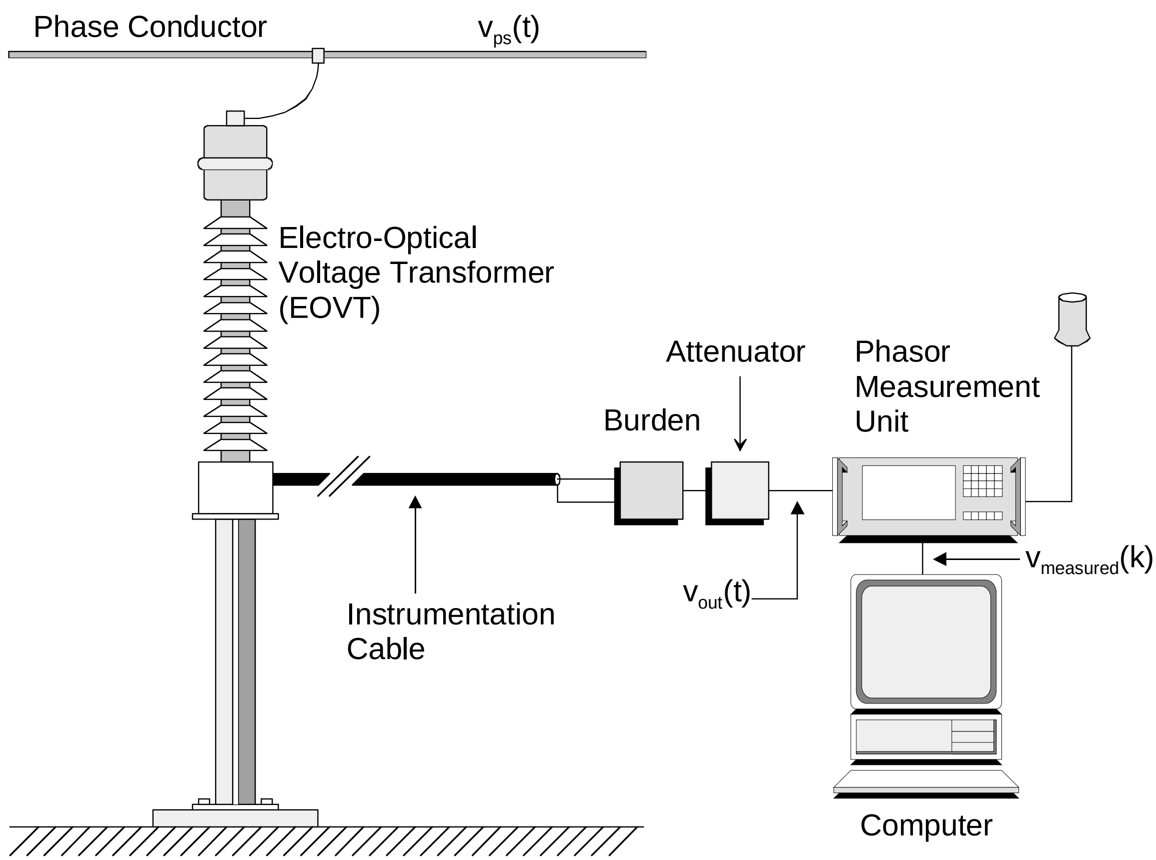

Figure 2.4 EOVT Based Instrumentation Channel

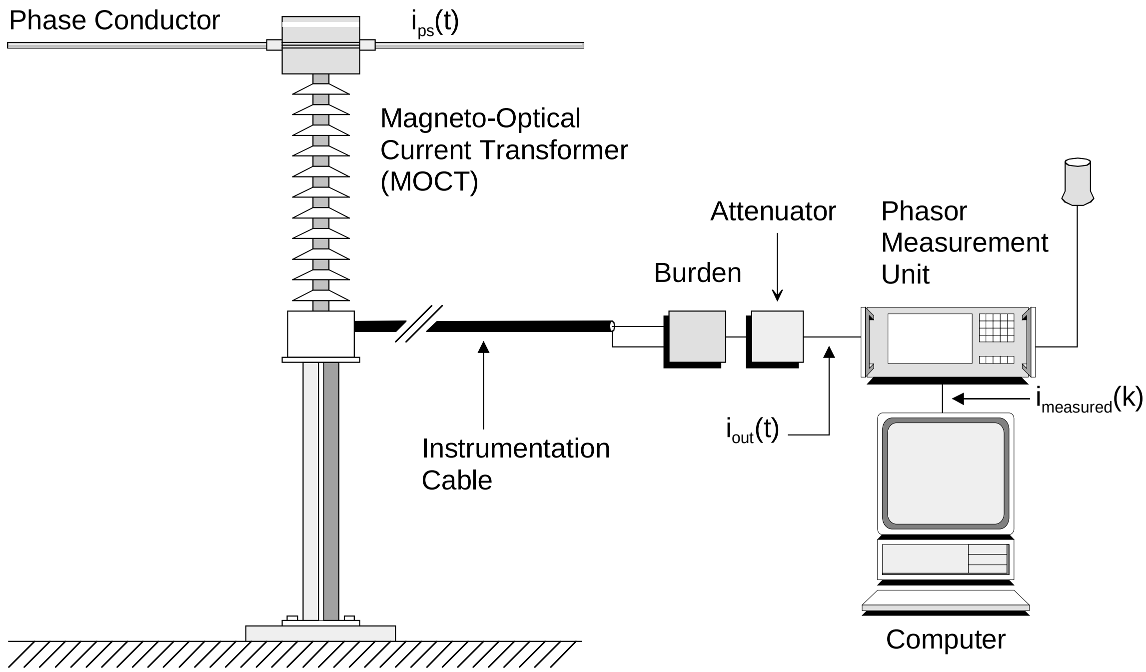

Figure 2.5 MOCT Based Instrumentation Channel

3. Characterization of GPS-Synchronized Measurement Devices

Equipment for synchronized measurements from various vendors may have different designs and therefore different ways of data acquisition and processing and different accuracy characteristics. As an example, in a recent characterization of devices from two different manufacturers we have found a difference of one degree at 60 Hz (this is equivalent to 47 microseconds error). This error can not be ignored. When all PMUs come from the same manufacturer, the systematic errors are irrelevant. However, in a multi-vendor environment (which is the case presently, and as more manufacturers start offering GPS synchronization) this issue must be addressed.

Full characterization of a GPS-synchronized device should include error analysis of both timing accuracy and magnitude accuracy over a generally accepted range of operating conditions defined in terms of (a) frequency, (b) frequency rate of change, (c) voltage magnitudes, (d) current magnitudes, (e) harmonics and (f) imbalances. A relevant document, Testing and Interoperability Guide [35] is presently under development by NASPI PRTT. That document defines the standard testing procedure and testing ranges..

It is suggested that the accuracy tests be standardized and then create a library of characterization data for the commercially available devices.

4. Characterization of Instrumentation Channels

High voltage instrumentation channels introduce errors to phasor measurements. The level of error is dependent upon the type of instrument transformers, control cable type and length and protection circuitry at the input of the A/D converters. As an example Figure 4.1 illustrates the errors for a specific instrumentation channel. Note that the VT introduces a very small error (0.01 degrees), while the 500 ft cable introduces an error of 0.4 degrees. The overall error is more than an order of magnitude higher than the error of a typical PMU.

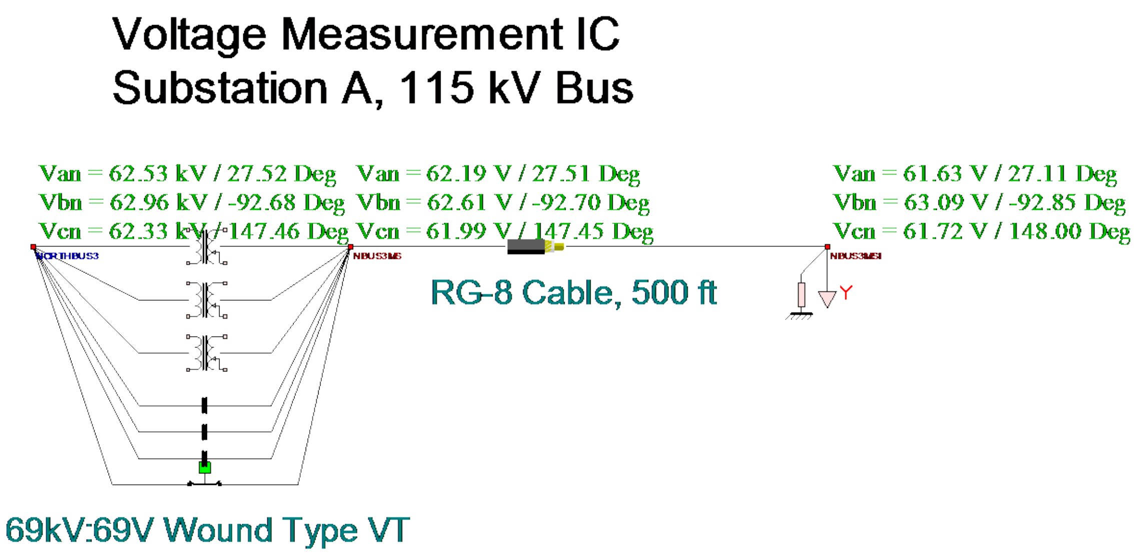

Figure 4.1. Illustration of Instrumentation Channel Errors for a Typical Case

Depending on the instrumentation channel, the characterization of these errors may be possible. Reference [34] provides some additional information. In most cases these errors can be accounted for and corrected via software. Two approaches are very promising: (a) model the instrumentation channel and provide model based correction algorithms, and (b) use state estimation methods to correct the error. A combination of the two will be ideal. Addressing this issue is very important to assure accuracy.

Appendix B provides examples of instrumentation channel characterization and the effects on the overall accuracy of the GPS synchronized measurements. We recommend further work to develop methodologies for characterizing the instrumentation channel errors and algorithms to correct for these errors. This work should be coordinated with the work on remote calibration.

It should be recognized that GPS-synchronized equipment may be also connected to existing instrumentation in substations that may be for other purposes, i.e. metering.

Many times the instrument transformers are connected in an arrangement that generates a phase shift, for example delta connection. The resulting phase shift must be accounted for.

Optical CTs and VTs present a special case. These devices are quite accurate. However, the present designs are equipped with an analog output for compliance with standards. The analog output introduces time latencies. Typical time latencies are in the order of few tens of microseconds. This is orders of magnitude greater than the time errors from typical PMUs. However, there is no need to use the analog output. The data directly from the optical CTs and VTs are digital and should be used directly without the analog output. This will eliminate the time latencies but it will require to develop new standards or adopt existing standards for data communications.

5. GPS-Synchronized Equipment Reliability

GPS-synchronized equipment have not been marketing operation for a long period of time and reliability data are scarce. In addition the few available data may not be representative of the present technology as they have been collected on first generation equipment. Table 5.1 provides reliability data over a two month period in 2002 of the PMUs on the western system. Note that the available data indicate that the technology is quite reliable and most unreliability is due to the GPS signal availability.

Synchrophasor System Performance

The Synchropahsor system performance analysis shall record statistics including data loss, signal loss, and PMU time-synchronization failures. Table 5.1 summarizes typical system performance during a randomly chosen two-month period in 2002.

Table 5.1 Synchrophasor System Performance For a Random Two-Month Period in 2002

Station	**Reliability (%)**		**Notes**
PMU	Signal[1]	Sync[2]	
GCoul	97.52	99.974	PMU fail 2 days
JDay	99.929	99.996	Normal, modem
Malin	99.997	93.74	PMU clock failure
Colstrip	99.82	100	Comm sys problems
BigEddy	99.99	99.988	Normal, fiber, digital
MValley	99.983	99.74	PMU clock problems
Keeler	99.996	99.95	Normal, modem

[1] Signal Reliability is the percent of time the system continuously received data from the PMU.

[2] Sync Reliability is the percent of time the PMU was synchronized with a global positioning system (GPS).

6. Conclusions

GPS-synchronized equipment are very accurate as compared to standard power system instrumentation. However application of this equipment to a practical power system is burdened by the errors that are introduced by the standard instrumentation channels utilized in power systems. This report provides a methodology to assess the level of inaccuracies introduced by the instrumentation channels and provides typical errors for a variety of instrumentation channel technologies.

The most accurate instrumentation channels are current instrumentation channels that use CTs. The length of the control cable is very important in determining the level of errors.

The next most accurate instrumentation channels are voltage instrumentation channels that use wound type VTs. The length of the control cable is very important in determining the level of errors.

CCVT based instrumentation channels are relatively accurate when they are well calibrated. They perform well when the frequency is near nominal. A main drawback is that the parameters of the components shift with time and subsequently introduce large errors. In addition, during transients the error is very large because their characteristics deteriorate at frequencies other than the fundamental. On the other hand, due to economic factors, CCVTs are commonly used in high voltage applications.

The optical VTs and CTs are high accuracy devices for magnitude measurement but very poor for phase angle measurement. Specifically, they exhibit a time delay in the order of few tens of microseconds that translates to phase angle error in the degree range. The data directly from the optical CTs and VTs are digital and should be used directly. This will eliminate the time latencies but it will require to develop new standards or adopt existing standards for data communications.

How will errors introduced by instrumentation channels affect applications using GPS-synchronized data will depend on specific application requirements. Characterizing those errors and addressing their effect on applications should be an integral part of deploying a GPS-synchronized system.

In any case, as improving accuracy is important for variety of applications, it is recommended to further develop algorithms to correct for these errors.

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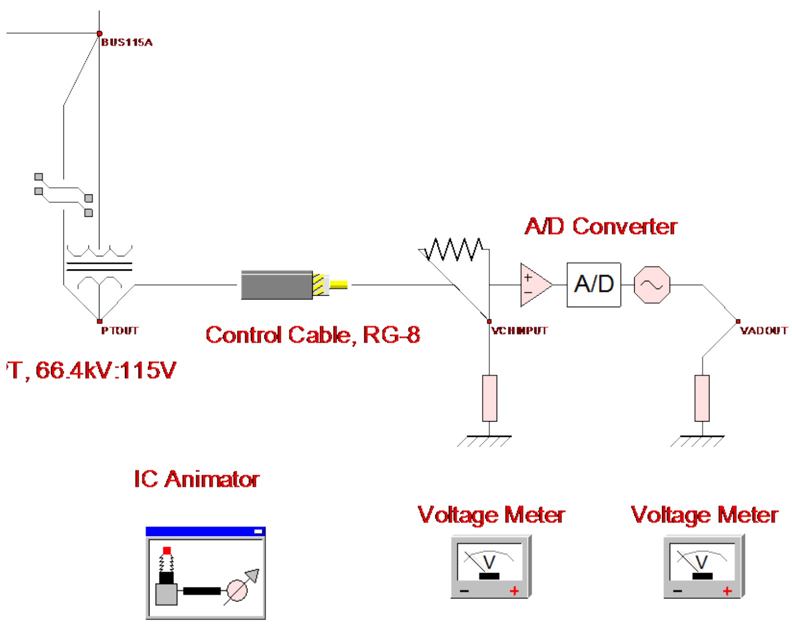
Appendix A: Instrumentation Channel Characterization

This Appendix provides characterization of errors resulting from instrumentation channel wiring, attenuators, and A/D converters.

The error resulting from these components of the instrumentation channel is complex. The approach taken here is to define a general instrumentation channel model and study the variations parametrically. As a matter of fact two generic instrumentation channels have been defined: (a) one for voltage measurement and (b) another for current measurement. The two generic instrumentation channels are shown in Figures A-1 and A-2 respectively. The important parameters are: (a) cable type and length, (b) burdens, (c) A/D conversion type, accuracy and filtering. In this section we present results of measurement accuracy in a parametric manner.

Note that the cable types used for VT and CT secondary circuit wiring would not normally be type RG-8 cable and may often be unshielded multi-conductor control type cables, i.e. non-twisted pairs. Additionally, there will normally only be one ground in the VT or CT secondary circuit (to avoid circulating currents, etc.).



RG-8 type cable

Figure A-1: Computer Model of a Voltage Instrumentation Channel

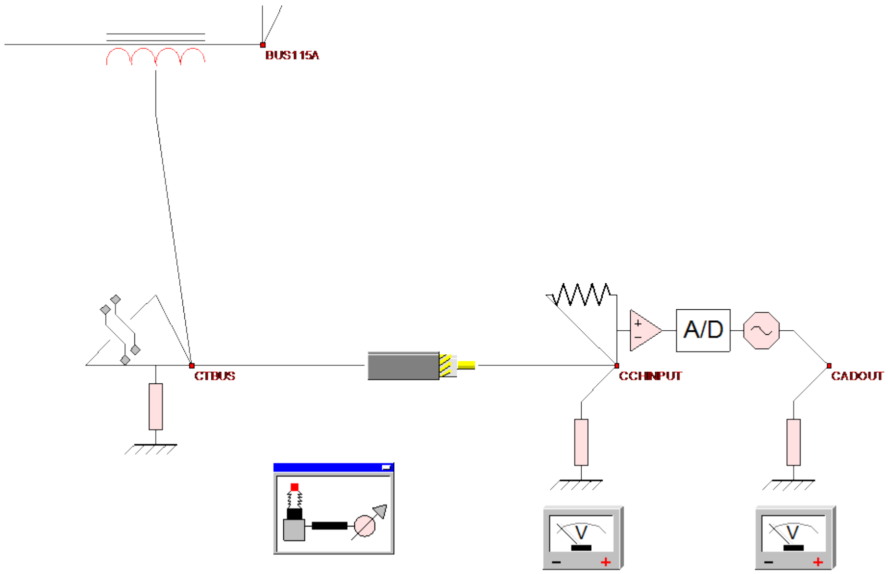


Figure A-2: Computer Model of a Current Instrumentation Channel

Appendix B: Instrument Transformer Characterization – Steady State

This Appendix provides characterization of errors resulting from instrument transformers. The instrument transformers that are considered are: current transformers, wound type voltage transformers or CCVTs.

B.1 CT Steady State Response

The conventional CT steady state response is very accurate. The steady state response can be extracted from the frequency response of the device. Figure B.1 provides a typical frequency response of a CT. Note that the response is flat in the frequency range of interest. It is important to note that errors may be present due to inaccurate determination of the transformation ratio. These errors are typically small.

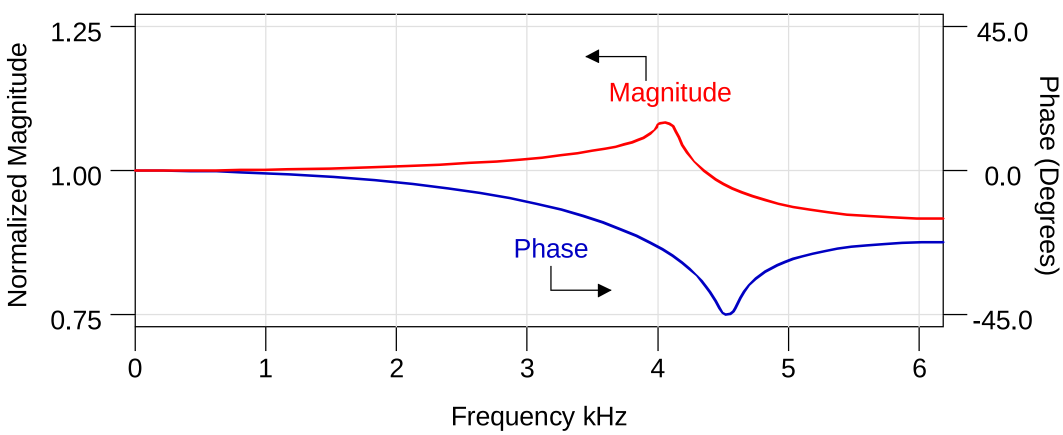


Figure B.1: Typical 600 V Metering Class CT Frequency Response

B.2 VT Steady State Response

Wound type VTs are in general less accurate than CTs. Again the steady state response can be obtained from the frequency response of the device. Figure B.2 provides a typical frequency response of a wound type VT. Note that the response is flat in a small frequency range around the nominal frequency. Our work has shown that the higher the transformation ratio of the VT the higher the errors will be.

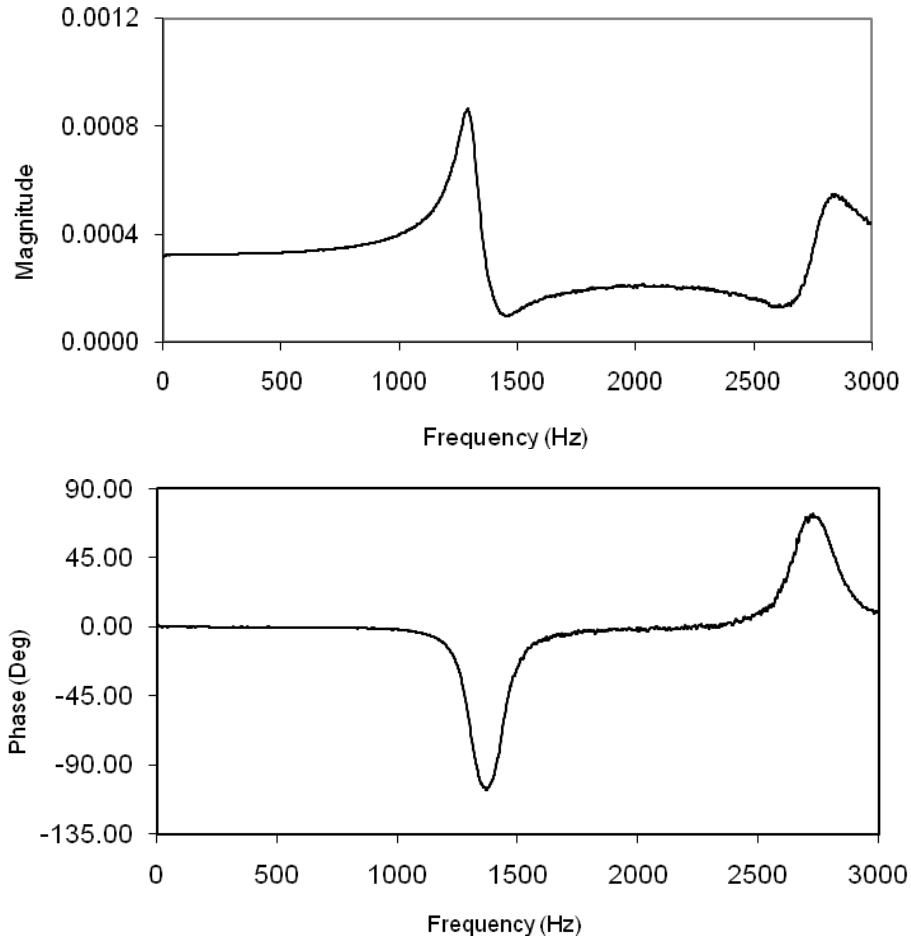


Figure B.2: 200kV/115V Potential Transformer Frequency Response

B.3 CCVT Steady State Response

By appropriate selection of the circuit components a CCVT can be designed to generate an output voltage with any desirable transformation ratio and most importantly with zero phase shift between input and output voltage waveforms. In this section we examine the possible deviations from this ideal behavior due to various causes by means of a parametric analysis, namely:

- Power Frequency Drift
- Circuit component parameter Drift
- Burden Impedance

The parametric analysis was performed using the CCVT equivalent circuit model illustrated in Figure B.3. The model parameters are given in Table B.1:

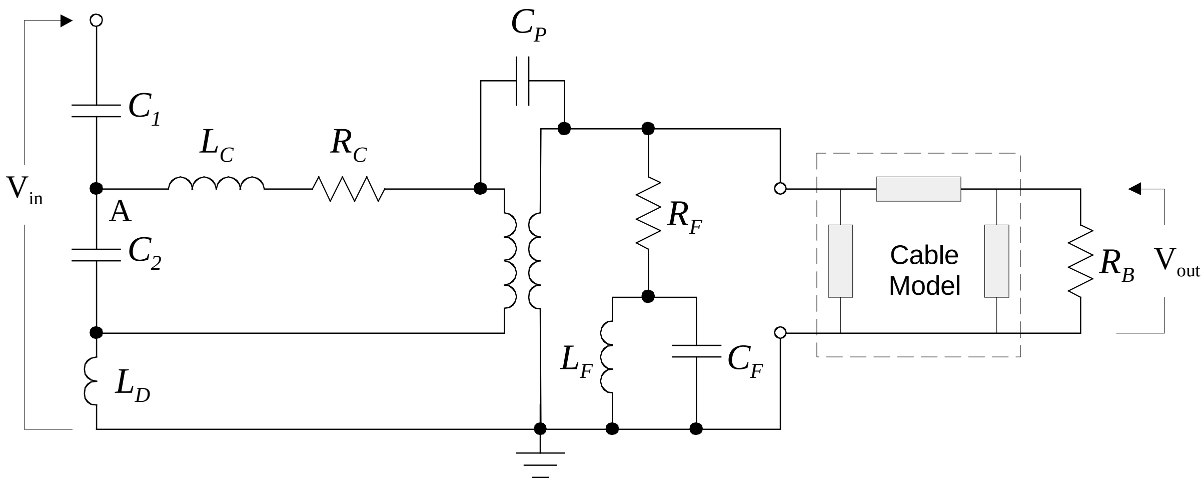


Figure B.3: CCVT Equivalent Circuit

Table B.1: CCVT Equivalent Circuit Parameters

Parameter Description	Schematic Reference	Value
CCVT Capacitance Class		Normal
Input Voltage		288 kV
Output Voltage		120 V
Upper Capacitor Size	C1	1.407 nF
Lower Capacitor Size	C2	99.9 nF
Drain Inductor	L_D	2.65 mH
Compensating Reactor Inductance	L_C	68.74 H
Compensating Reactor Resistance	R_C	3000 Ohms
Burden Resistance	R_B	200 Ohms
Ferroresonance Suppression Damping Resistor	R_F	70 Ohms
Ferroresonance Suppression Circuit Inductor	L_F	0.398 H
Ferroresonance Suppression Circuit Capacitor	C_F	17.7 uF
Cable Type		RG-8
Cable Length		100 Feet
Transformer Power Rating		300 VA
Transformer Voltage Rating		4kV/120V
Leakage Reactance		3%
Parasitic Capacitance	C_P	500 pF

Figure B.4 shows the results of a frequency scan. Note that over the frequency range of 0 to 500 Hz the response varies substantially both in magnitude and phase. Near 60 Hz (55 to 65 Hz) the response magnitude is practically constant but the phase varies at the rate of 0.25 degrees per Hz.

Table B.2 shows the results of a parametric analysis with respect to Burden resistance and instrumentation cable length. Note that the system is tuned for zero phase error for a short instrumentation cable and with a 200 Ohm Burden.

Table B.3 shows the results of a parametric analysis with respect to CCVT component parameter inaccuracies. Specifically the varied parameters were the compensating reactor inductance and the capacitive divider capacitance.

Table B.2: Phase Error (in Degrees) Versus Burden Resistance and Cable Length

	Cable Length (feet)		
Burden Resistance	**10'**	**1000'**	**2000'**
50 Ohms	0.077	-0.155	-0.365
100 Ohms	0.026	-0.096	-0.213
200 Ohms	0.000	-0.063	-0.127
400 Ohms	-0.013	-0.047	-0.080
1000 Ohms	-0.022	-0.036	-0.052

Table B.3: Phase Error (in Degrees) Versus Capacitance and Inductance

	Inductance Error (%)		
Capacitance Error (%)	**0%**	**1%**	**5%**
0%	0.000	-0.066	-0.331
-1%	-0.066	-0.132	-0.397
-5%	-0.330	-0.396	-0.661

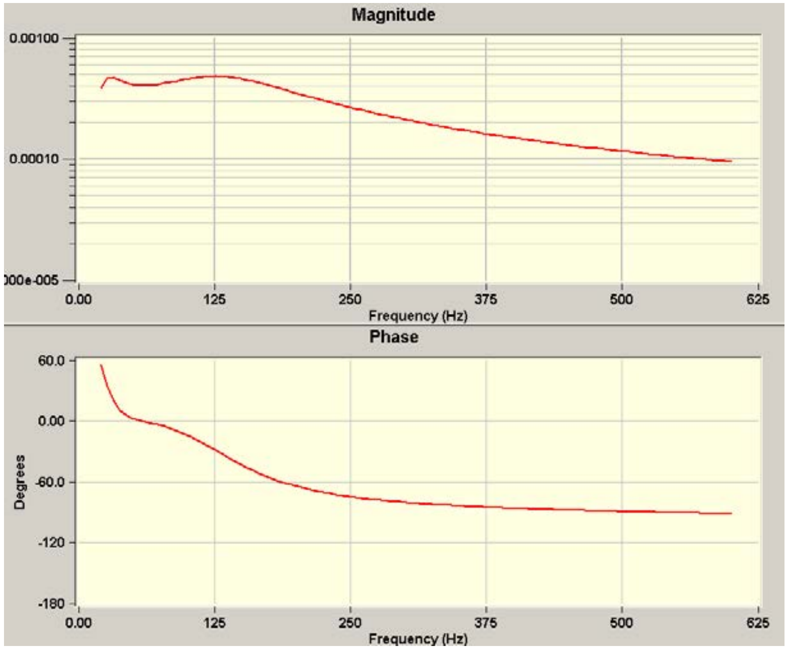


Figure B.4: CCVT Computed Frequency Response over 10-600 Hz

B.4 MOCT Steady State Response

MOCTs are relatively very accurate devices for magnitude (typical accuracy 0.1%) but relatively inaccurate in time (phase). Typical time latencies are in the order of 30 to 50 microseconds. This translates to 0.648 degrees to 1.08 degrees phase error at 60 Hz.

B.5 EOVT Steady State Response

EOVTs are relatively very accurate devices for magnitude (typical accuracy 0.1% to 1%) but relatively inaccurate in time (phase). Typical time latencies are in the order of 30 to 50 microseconds. This translates to 0.648 degrees to 1.08 degrees phase error at 60 Hz.

Appendix C: Instrument Transformer Characterization – Transients

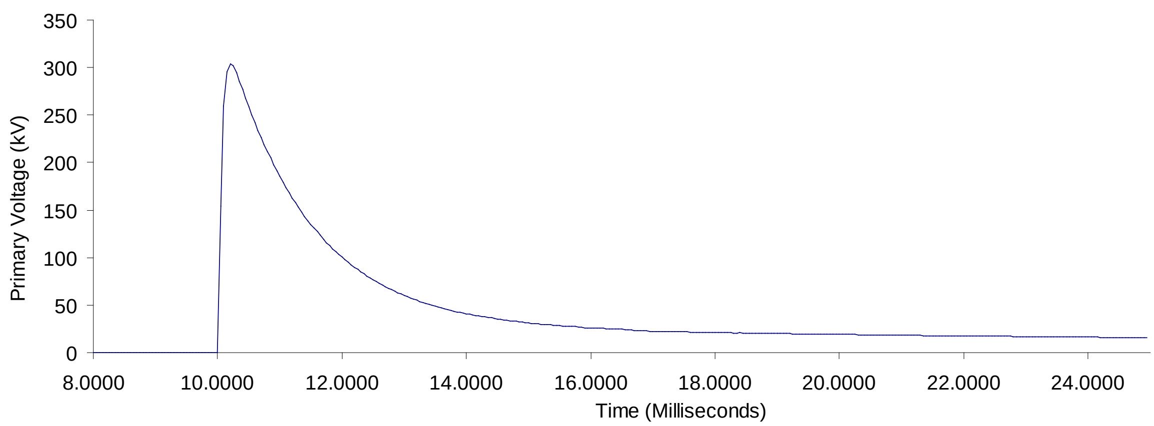
This Appendix provides characterization of errors resulting from instrument transformers during transients. The instrument transformers that are considered are: current transformers, wound type voltage transformers, CCVTs, MOCTs and EOVTs.

C.1 CT Transient Response

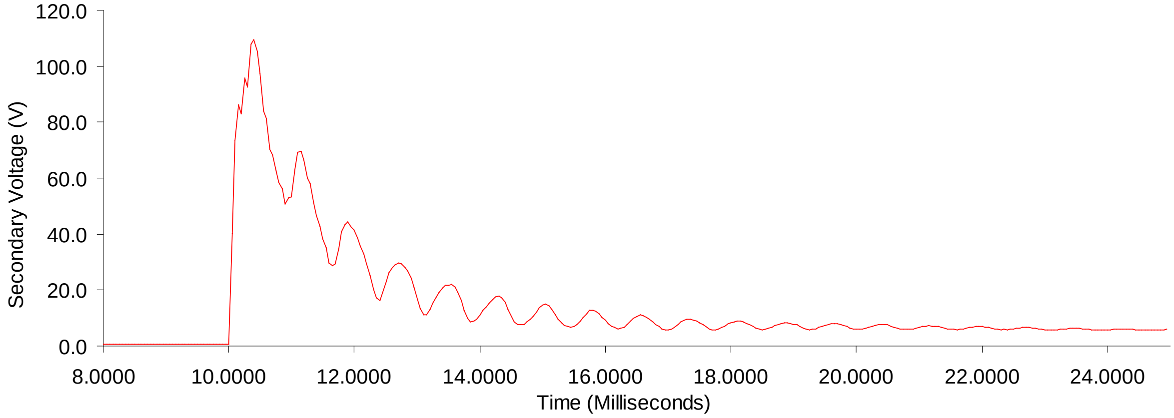
The conventional CT transient response depends on the frequency content.

C.2 Wound VT Transient Response

The transient response of potential transformers can be determined from frequency response tests, using Fourier transformation techniques, or by direct time domain test. Figure C.x illustrates the measurement data from a direct time domain test, performed on the same VT for which the frequency response was given in Figure C.x. A double exponential waveform was applied across the primary winding, while both primary and secondary voltage waveforms are recorded. Note the 1250 Hz oscillation on the secondary voltage due to resonance.



(a)



(b)

Figure C.x: Transient Response of a 200kV / 65V VT
Open Circuit Secondary
(a) Primary Voltage Waveform
(b) Secondary Voltage Waveform

C.3 CCVT Transient Response

The transient response of CCVTs is quite complex. Early CCVT's suffered from poor transient response, typically lasting up to two power frequency cycles. The main reason for this is the resonance between the divider capacitance and the compensating reactor inductance. The main factors affecting the CCVT transient response duration and magnitude of the resulting measurement errors are:

- Divider Capacitance Value
- Burden resistance
- Ferroresonance Circuit Type (Active versus Passive)
- Input Waveform Characteristics

In general, the higher capacitance CCVT's have better transient response. This is illustrated in Figure C.x, which shows typical transient response for two CCVT classes (A) High capacitance and (B) Extra High Capacitance. The input waveform is sinusoidal up to the zero crossing at 0.012 seconds, and remains at zero beyond this time. The both transient response outputs last for about 0.04 seconds, however the transient amplitude of the extra high capacitance CCVT is substantially lower [1], [2].

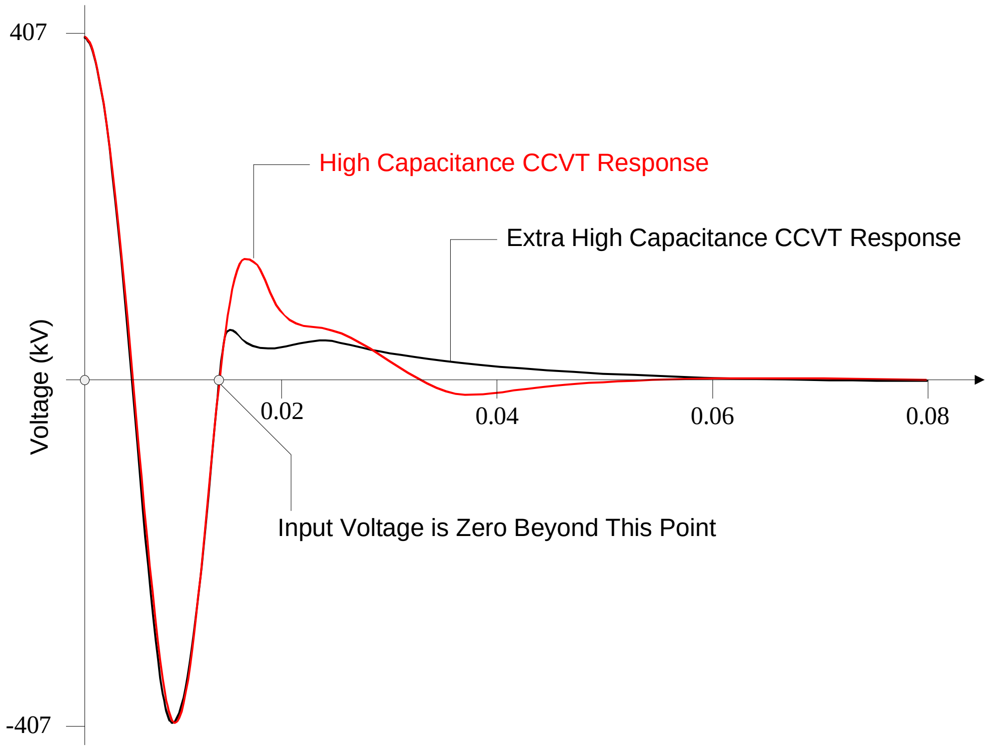


Figure C.x: CCVT Transient Response

C.4 MOCT Transient Response

At present data of transient response of MOCTs are not available. We will continue to seek test data from manufacturers.

C.5 EOVT Transient Response

At present data of transient response of EOVTs are not available. We will continue to seek test data from manufacturers.

Appendix D: System Errors

This Appendix provides characterization of errors resulting from system asymmetries and imbalances.

The imbalances affect the computation of the positive sequence phasors. In case that an application uses directly the individual phase phasors, the imbalance will be treated within the application. This section provides characterization of the error performed when there is certain imbalance and neutral voltage shift.

First it is important to recognize the following fact: the computation of the positive sequence phasors is independent of whether the inputs to the GPS-synchronized device is line-to-line voltages or phase to neutral voltages. However the results will be shifted by a specific phase angle. Specifically the following relationships hold:

$$V_{LL}^{+} = \frac{1}{3}(\tilde{V}_{ab} + a\tilde{V}_{bc} + a^2\tilde{V}_{ca}) = \frac{a^2(a-1)}{3}\left[\tilde{V}_a + a\tilde{V}_b + a^2\tilde{V}_c\right] = \sqrt{3}e^{j30^0}\tilde{V}_{LN}^{+}$$

In other words for computation of the positive sequence phasors, using the line to line voltages or the phase voltages (phase to neutral) will yield the same answer with the exception of a constant factor.

Here we provide parametric analysis of the positive sequence phasor errors as a function of (a) percent negative sequence (0, 1, 2 and 4%), (b) percent zero sequence (0, 1, 2 and 4%), and (c) percent neutral voltage shift (0, 0.1, 0.2, 0.5%). In all of these analysis we assume that the phase A phasor is 1.0 pu and at zero phase angle.

Appendix E: Instrumentation Nominal Accuracy/Standards

This Appendix provides typical data for CTs and VTs utilized in a measurement circuit for GPS-synchronized measurements. The emphasis is on standard instrumentation characteristics.

The 0.02 degree accuracy given to the PMU by the GPS signals is usually not achievable in practice due mostly to the magnitude and phase errors caused by the instrument transformers used to obtain the signal from the power system. The magnetizing current drawn by the transformer's core and the current drawn by the burden produce an impedance drop across the instrument transformers that results in a magnitude and phase error in the secondary signal compared to that of an ideal transformer. Industry standards set classes for instrument transformers based on the allowed limits in the phase and magnitude errors of the secondary signal.

Testing of the instrument transformers prior to installation can be performed to determine a more accurate phase and magnitude error of each individual transformer that will allow the use of correction factors to reduce the error in the measurements. Unfortunately for installed transformers testing is not possible and the only error information available is obtained from the transformer class limits as set by the existing IEEE and IEC standards. The magnitude and phase errors required by the different standards are presented in tables at the end of this document. Tests have been proposed that will allow field determination of the transformer and instrumentation error using state estimation techniques [16].

The following tables show the maximum limits on the transformers for the different standards with the magnitude of errors expressed in per unit and the phase errors expressed in degrees and microseconds for 60Hz signals. Phase errors should be doubled when referenced phasor are being used. Actual devices under normal operating conditions (no faults) exhibit much lower errors. Optical PTs and CTs (EOVT and MOCTs) present a special case as these devices are internally quite accurate but the final output exhibits time latencies in the order of 40 to 70 microseconds which translates to a substantial phase error.

Table 1 Maximum magnitude and phase error for ANSI class type CTs

ANSI CT Type	Load Current	Max. Magnitude Error pu	Max. Phase Error (degrees)	Max. Phase Error (μseconds)
Relaying	10 to 2000%	0.10	Not tested	Not tested
Metering 1.2	10%	0.024	2.08	96
	100%	0.012	1.04	48
Metering 0.6	10%	0.012	1.04	48
	100%	0.006	0.52	24
Metering 0.3	10%	0.006	0.52	24
	100%	0.003	0.26	12

Table 2 Maximum magnitude and phase error for ANSI class VTs

ANSI VT TYPE	Max. Magnitude ± Error P.U.	Max. Phase Error (± degrees)	Max. Phase Error (± μseconds)
Relaying	0.1	Not tested	Not tested
Metering 1.2	0.012	2.08	96
Metering 0.6	0.006	1.04	48
Metering 0.3	0.003	0.52	24

Table 4 Maximum magnitude and phase errors of IEC class CTs

IEC CT Type	Load	Max. Magnitude Error ± P.U.	Max. Phase Error ± degrees	Max. Phase error ± μseconds
Relay Type 10P	100%	0.1	Not tested	Not tested
	max. limit	0.5	Not tested	Not tested
Relay Type 5P	100%	0.3000	2.000	92.6
	max. limit	1.0000	2.000	92.6
Metering Type 1.0 Accuracy	5%	0.0300	6.000	277.8
	20%	0.0150	3.000	138.9
	100%	0.0100	2.000	92.6
	120%	0.0100	2.000	92.6
Metering Type 0.5 Accuracy	5%	0.0150	3.000	138.9
	20%	0.0075	2.000	92.6
	100%	0.0050	1.000	46.3
	120%	0.0050	1.000	46.3
Metering Type 0.2 accuracy	5%	0.0075	1.000	46.3
	20%	0.0035	0.500	23.1
	100%	0.0020	0.167	7.7
	120%	0.0020	0.167	7.7
Metering Type 0.1 Accuracy	5%	0.0040	0.500	23.1
	20%	0.0020	0.333	15.4
	100%	0.0010	0.167	7.7
	120%	0.0010	0.167	7.7

Appendix F: Description of Typical Instrumentation Channels

This Appendix provides a set of typical instrumentation channels. In selecting the instrumentation channels the following have been considered.

Voltage Transformer technologies include:

- Wound type Potential Transformers (PT)
- Capacitively Coupled Voltage Transformers (CCVT)
- Capacitive Voltage Dividers (CVD)
- Resistive Voltage Dividers (RVD)

Generally voltage dividers provide accurate wide bandwidth measurements with flat frequency response; however, these technologies are limited to laboratory grade instrumentation. In high voltage power system applications (outdoor relaying and metering units), PT's and CCVT's are commonly used.

Current transformers are typically core type transformers with current output. The ratings depend on the maximum permissible voltage that can be developed on the secondary before saturation occurs. For PMU type applications, saturation is not a concern as the current through the CT is typically much lower than the capability of the CT.

A number of instrumentation channels have been defined. The parameters of these instrumentation channels have been selected to represent near actual systems. They have been constructed by considering combinations of the following important instrumentation channel parameters: CT types, VT types, CCVT types, communication cable (type, shielded/unshielded, length). Other instrumentation channels based on optical CTs and VTs have not considered.

The typical instrumentation channels listed here have been constructed from data provided by Entergy and TVA. Additional input form other utilities is solicited. Using this typical instrumentation channels, the errors introduced are evaluated and tabulated.

F.1 Description of the Typical Instrumentation Channels

The instrumentation channels are defined in terms of the following:

1. Instrument transformer (ratio, impedance, parasitic capacitance)
2. Cable type, size and length

3. Attenuators, if present
4. Burden
5. Intelligent Electronic Device (in this case PMU)

Table F.1 Lists of Test Instrumentation Channel Models

I-Channel # & Type	I-XFMR	Cable	Attenuators	Burden	IED
1 – V (PT)	69kV:69V, 2.5%, 25nF	RG-8, 200 feet	1.0	10,000	16 bit, 2V, Sigma/delta
2 – V (PT)	199kV:115V, 2.5%, 50nF	RG-8, 200 feet	0.1, 300 ohm	10,000	16 bit, 2V, Sigma/delta
3 – C (CT)	600A:5A, 1%, negligible	RG-8, 200 feet	1.0	0.14	12 bit, 10V, multpx
4 – C (CT)	3000A:5A, 1%, negligible	RG-8, 200 feet	1.0	0.14	16 bit, 2V, Sigma/delta
5 – V (CCVT)	288kV:120V, 1.5%, 100nF	RG-8, 200 feet	0.1, 300 ohm	10,000	12 bit, 10V, multpx

The error characterization for each one of these channels is as follows.

VT Instrumentation Channels: The *voltage magnitude error* is defined as the percentage difference between the primary voltage of the PT and voltage seen by the relay scaled by a nominal factor $k_{nominal}$. That is:

$$\%Error_{V,magnitude} = \left| \frac{V_{primary} - k_{nominal} \cdot V_{relay}}{V_{primary}} \right| \times 100\%$$

where: $k_{nominal} = \dfrac{V_{primary,nominal}}{V_{relay,nominal}}$

In addition, the *phase error* is defined as the phase angle difference between the reading at the primary side of the PT and voltage reading seen by the relay.

CT Instrumentation Channels: The *current magnitude error* is defined as the percentage difference between the primary current of the CT and voltage seen by the relay scaled by a nominal factor $k_{nominal}$. That is:

$$\%Error_{I,magnitude} = \left| \frac{I_{primary} - k \cdot I_{relay}}{I_{primary}} \right| \times 100\%$$

In addition, the *phase error* is defined as the phase angle difference between the current reading at the primary side of the PT and current reading seen by the relay.

F.2 Potential Transformer Instrumentation Channel Error

Each potential transformer instrumentation channel defined above (cases 1 and 2) has been analyzed and the error introduced from each component of the channel has been tabulated. Therefore, these results provide a quantitative analysis of the impact of the potential transformer instrumentation channel on the quality and accuracy of the data from PMUs.

The PT instrumentation channel model is shown in Figure F-1. The model includes the effect of parasitic capacitances and instrumentation cable. The relay burden is also model by a large resistance (typically in the order of few thousand ohms).

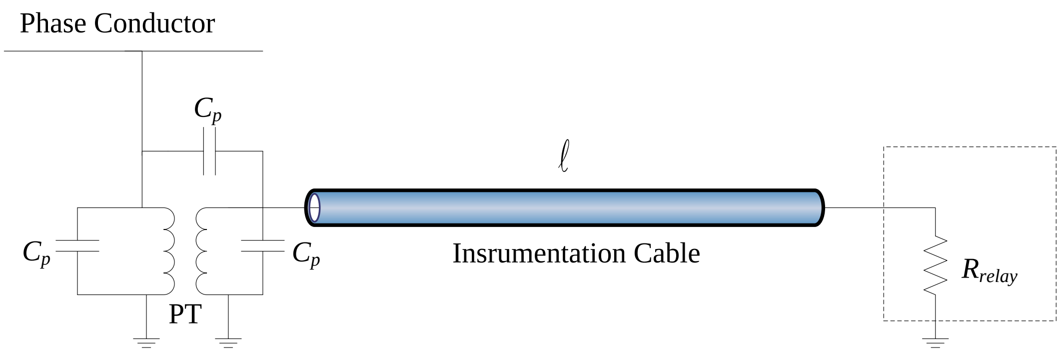


Figure F-1: PT instrumentation channel model parameters

The system that is used to perform this parametric analysis is shown in Figure 3. The simulation is performed for different values of the model parameters. The error is quantified in terms of magnitude and phase error.

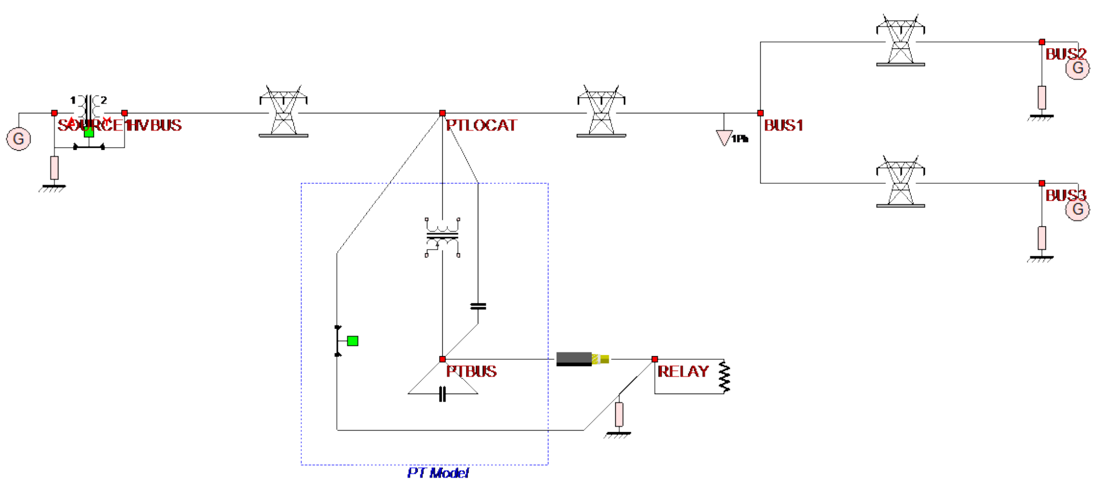


Figure F-2: System model used for PT instrumentation channel error characterization

F.2.1 Case 1: 69kV/69V PT

The base case model parameters are shown in Table F-2. The error results are shown in Tables F-3, F-4, F-5 and F-6.

Table F-2: Base-case parameters for 69kV/69V PT instrumentation channel model simulation

Parameter Description	Value
Nominal Ratio	69kV/69
PT VA rating	30 kVA
PT Resistance	0.01 pu
PT leakage reactance X_ℓ	0.06 pu
PT Nominal Core Loss	0.005 pu
PT Nominal Magnetization Current	0.005 pu
PT parasitic capacitance C_p	25 nF
Instrumentation cable type	#10 Copper Pair
Instrumentation cable length ℓ	200 ft
Relay burden resistance R_B	10 kΩ

Table F-3: 69kV/69V PT instrumentation channel voltage magnitude error in % for different burden resistances

	Instrumentation Cable length ℓ (ft)			
Burden Resistance R_B (Ω)	100 ft	200 ft	500 ft	800 ft
5k	0.007	0.009	0.012	**0.015**
10k	0.008	0.010	0.012	**0.015**
20k	**0.008**	**0.010**	**0.012**	**0.015**

Table F-4: 69kV/69V PT instrumentation channel voltage phase error in degrees for different burden resistances

	Instrumentation Cable length ℓ (ft)			
Burden Resistance R_B (Ω)	100 ft	200 ft	500 ft	800 ft
5k	0.07	0.10	0.15	**0.23**
10k	0.05	0.08	0.12	**0.18**
20k	**0.05**	**0.08**	**0.12**	**0.18**

Table F-5: 69kV/69V PT instrumentation channel voltage magnitude error in % for different parasitic capacitances

	Instrumentation Cable length ℓ (ft)			
Parasitic Capacitance C_p (nF)	**100 ft**	**200 ft**	**500 ft**	**800 ft**
10	0.004	0.006	0.016	**0.025**
25	0.010	0.015	0.030	**0.045**
50	**0.020**	**0.037**	**0.090**	**0.158**

Table F-6: 69kV/69V PT instrumentation channel voltage phase error in degrees for different parasitic capacitances

	Instrumentation Cable length ℓ (ft)			
Parasitic Capacitance C_p (nF)	**100 ft**	**200 ft**	**500 ft**	**800 ft**
10	0.06	0.12	0.26	**0.49**
25	0.14	0.27	0.67	**1.07**
50	**0.28**	**0.59**	**1.30**	**2.21**

F.2.2 Case 2: 199kV/69V PT

The base case model parameters are shown in Table F-7. The error results are shown in Tables F-8, F-9, F-10 and F-11.

Table F-3: Base-case parameters for 69kV/69V PT instrumentation channel model simulation

Parameter Description	Value
Nominal Ratio	**199kV/69**
PT VA rating	**30 kVA**
PT Resistance	**0.01 pu**
PT leakage reactance X_ℓ	**0.025 pu**
PT Nominal Core Loss	**0.005 pu**
PT Nominal Magnetization Current	**0.005 pu**
PT parasitic capacitance C_p	**50 nF**
Instrumentation cable type	**#10 Copper Pair**
Instrumentation cable length ℓ	**200 ft**
Relay burden resistance R_B	**10 kΩ**

Table F-8: 199kV/69V PT instrumentation channel voltage magnitude error in % for different burden resistances

	Instrumentation Cable length ℓ (ft)			
Burden Resistance R_B (Ω)	**100 ft**	**200 ft**	**400 ft**	**800 ft**
5k	0.009	0.016	0.22	0.52
10k	0.009	0.015	0.19	0.48
20k	0.009	0.014	0.18	0.41

Table F-9: 199kV/69V PT instrumentation channel voltage phase error in degrees for different burden resistances

	Instrumentation Cable length ℓ (ft)			
Burden Resistance R_B (Ω)	**100 ft**	**200 ft**	**400 ft**	**800 ft**
5k	0.121	0.212	0.425	0.638
10k	0.115	0.198	0.411	0.614
20k	0.115	0.196	0.399	0.589

Table F-10: 199kV/69V PT instrumentation channel voltage magnitude error in % for different parasitic capacitances

Parasitic Capacitance C_p (nF)	Instrumentation Cable length ℓ (ft) 100 ft	200 ft	400 ft	800 ft
25	0.008	0.012	0.17	0.41
50	0.009	0.015	0.19	0.48
75	0.015	0.026	0.22	0.61

Table F-11: 199kV/69V PT instrumentation channel voltage phase error in degrees for different parasitic capacitances

Parasitic Capacitance C_p (nF)	Instrumentation Cable length ℓ (ft) 100 ft	200 ft	400 ft	800 ft
25	0.090	0.185	0.382	0.538
50	0.115	0.198	0.411	0.614
75	0.196	0.235	0.479	0.779

F.3 Current Transformer Instrumentation Channel Error

Each current transformer instrumentation channel defined above (cases 3 and 4) has been analyzed and the error introduced from each component of the channel has been tabulated. Therefore, these results provide a quantitative analysis of the impact of the current transformer instrumentation channel on the quality and accuracy of the data from PMUs.

The CT instrumentation channel model is shown in Figure F-3. The model includes the parasitic capacitances and instrumentation cable. The relay burden is also modeled (usually 0.1 or 0.14 ohms).

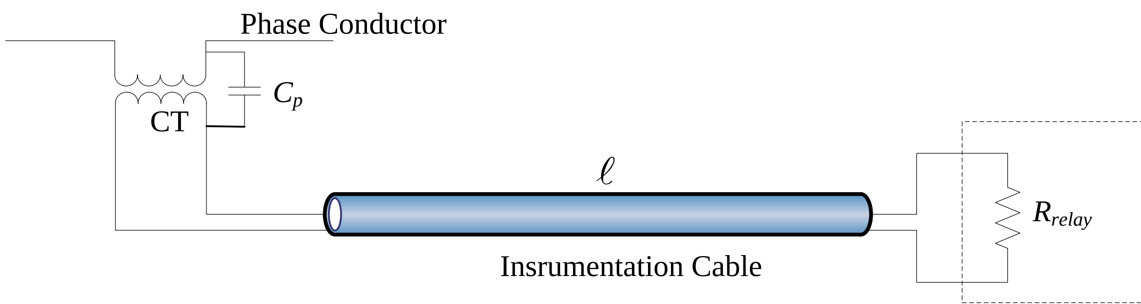


Figure F-3: CT instrumentation channel model parameters

The system that is used to perform this parametric analysis is shown in Figure F-4. The simulation is performed for different values of the model parameters. The error is quantified in terms of magnitude and phase error.

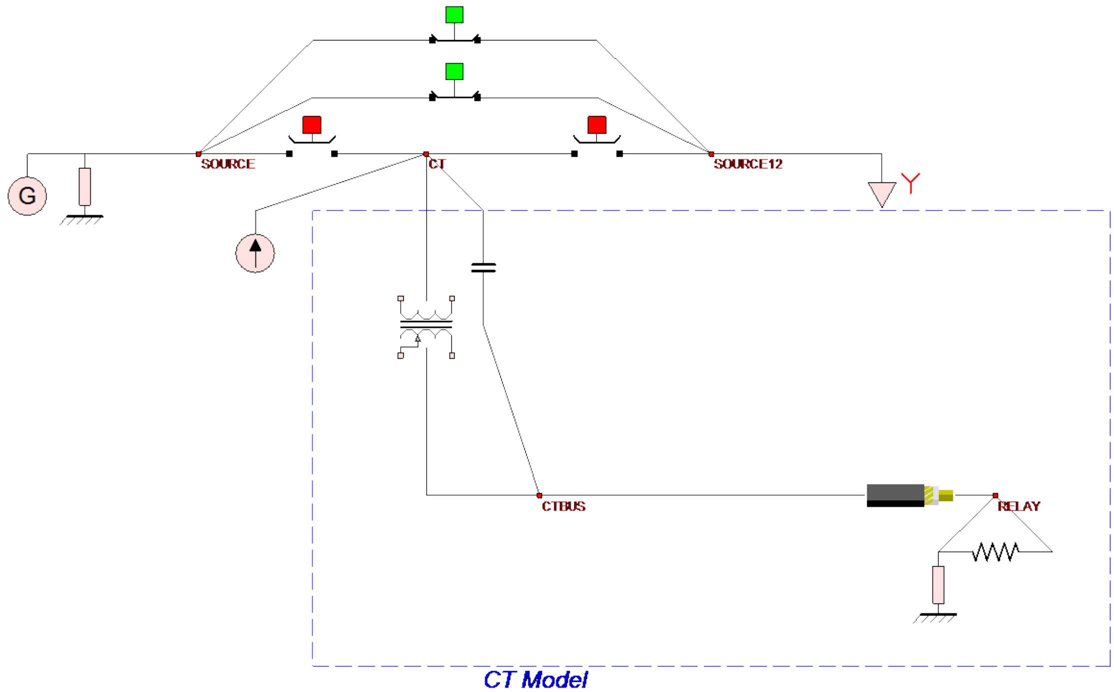


Figure F-4: System model used for CT instrumentation channel error characterization

F.3.1 Case 3: 600/5A CT

The base case model parameters are shown in Table F-12. The error results are shown in Tables F-13, F-14, F-15 and F-16.

Table F-12: Base-case parameters for 600/5A CT instrumentation channel model simulation

Parameter Description	Value
Nominal Ratio	**600/5A**
CT VA rating	**300 VA**
CT Resistance	**0.001 pu**
CT leakage reactance X_ℓ	**0.003 pu**
CT Nominal Core Loss	**0.004 pu**
CT Nominal Magnetization Current	**0.005 pu**
CT parasitic capacitance C_p	**5 nF**
Instrumentation cable type	**#10 Pair**
Instrumentation cable length ℓ	**200 ft**
Relay burden resistance R_B	**0.05Ω**

Table F-13: 600/5A CT instrumentation channel voltage magnitude error in % for different burden resistances

	Instrumentation Cable length ℓ (ft)			
Burden Resistance R_B (Ω)	**100 ft**	**200 ft**	**400 ft**	**800 ft**
0.1	0.066%	0.066%	0.066%	**0.066%**
0.14	**0.066%**	**0.066%**	**0.066%**	**0.066%**

Table F-14: 600/5A CT instrumentation channel voltage phase error in degrees for different burden resistances

	Instrumentation Cable length ℓ (ft)			
Burden Resistance R_B (Ω)	**100 ft**	**200 ft**	**400 ft**	**800 ft**
0.1	0.03°	0.04°	0.09°	**0.23°**
0.14	**0.03°**	**0.04°**	**0.09°**	**0.23°**

Table F-15: 600/5A CT instrumentation channel voltage magnitude error in % for different parasitic capacitances

	Instrumentation Cable length ℓ (ft)			
Parasitic Capacitance C_p (nF)	100 ft	200 ft	400 ft	800 ft
1	0.06656%	0.06656%	0.06656%	**0.06656%**
5	0.06656%	0.06656%	0.06656%	**0.06656%**
10	**0.06656%**	**0.06656%**	**0.06656%**	**0.06656%**

Table F-16: 600/5A CT instrumentation channel voltage phase error in degrees for different parasitic capacitances

	Instrumentation Cable length ℓ (ft)			
Parasitic Capacitance C_p (nF)	100 ft	200 ft	400 ft	800 ft
1	0.02^o	0.03^o	0.08^o	**0.20^o**
5	0.03^o	0.04^o	0.09^o	**0.23^o**
10	**0.05^o**	**0.08^o**	**0.14^o**	**0.32^o**

F.3.2 Case 4: 3000/5A CT

The base case model parameters are shown in Table F-17. The error results are shown in Tables F-18, F-19, F-20 and F-21.

Table F-17: Base-case parameters for 3000/5A CT instrumentation channel model simulation

Parameter Description	Value
Nominal Ratio	**3000/5A**
CT VA rating	**500 VA**
CT Resistance	**0.001 pu**
CT leakage reactance X_ℓ	**0.003 pu**
CT Nominal Core Loss	**0.004 pu**
CT Nominal Magnetization Current	**0.005 pu**
CT parasitic capacitance C_p	**5 nF**
Instrumentation cable type	**#10 Pair**
Instrumentation cable length ℓ	**200 ft**
Relay burden resistance R_B	**0.1Ω**

Table F-18: 3000/5A CT instrumentation channel voltage magnitude error in % for different burden resistances

	Instrumentation Cable length ℓ (ft)			
Burden Resistance R_B (Ω)	**100 ft**	**200 ft**	**400 ft**	**800 ft**
0. 1	0.066%	0.066%	0.066%	**0.066%**
0.14	**0.066%**	**0.066%**	**0.066%**	**0.066%**

Table F-19: 3000/5A CT instrumentation channel voltage phase error in degrees for different burden resistances

	Instrumentation Cable length ℓ (ft)			
Burden Resistance R_B (Ω)	**100 ft**	**200 ft**	**400 ft**	**800 ft**
0.1	0.03^o	0.04^o	0.09^o	**0.23^o**
0.14	**0.03^o**	**0.04^o**	**0.09^o**	**0.23^o**

Table F-20: 3000/5A CT instrumentation channel voltage magnitude error in % for different parasitic capacitances

	Instrumentation Cable length ℓ (ft)

Parasitic Capacitance C_p (nF)	100 ft	200 ft	400 ft	800 ft
1	0.066%	0.066%	0.066%	**0.066%**
5	0.066%	0.066%	0.066%	**0.066%**
10	**0.066%**	**0.066%**	**0.066%**	**0.066%**

Table F-21: 3000/5A CT instrumentation channel voltage phase error in degrees for different parasitic capacitances

	Instrumentation Cable length ℓ (ft)			
Parasitic Capacitance C_p (nF)	**100 ft**	**200 ft**	**400 ft**	**800 ft**
1	0.02º	0.03º	0.08º	**0.20º**
5	0.03º	0.04º	0.09º	**0.23º**
10	**0.05º**	**0.08º**	**0.14º**	**0.32º**

F.4 CCCVT Instrumentation Channel Error

Each CCVT instrumentation channel defined above (case 5) has been analyzed and the error introduced from each component of the channel has been tabulated. Therefore, these results provide a quantitative analysis of the impact of the CCVT instrumentation channel on the quality and accuracy of the data from PMUs.

The basic CCVT configuration is illustrated in Figure F-5. The capacitive divider is formed by capacitors C_1 and C_2. In typical high voltage CCVTs (115-500kV), the capacitor values are selected so that the voltage at the tap point A is in the order of 4 to 10 kV. The transformer scales this voltage to standard instrumentation voltage level, i.e. 69V or 120V. The output of the transformer is connected to a burden via instrumentation cable (usually a coaxial cable). The burden represents the relay input impedance, which is typically resistive. Since the interaction of the capacitive divider and the resistive burden introduces considerable phase shift, a series inductor L is added to compensate the divider output capacitance. The CCVT equivalent model is shown in Figure F-6. Table F-22 summarizes the parameters of the CCVT model.

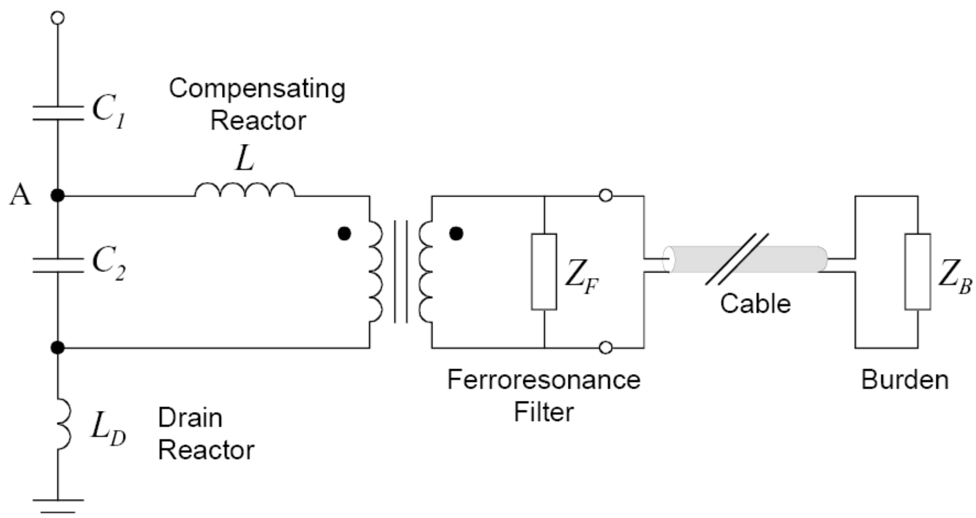


Figure F-5: CCVT Physical Circuit

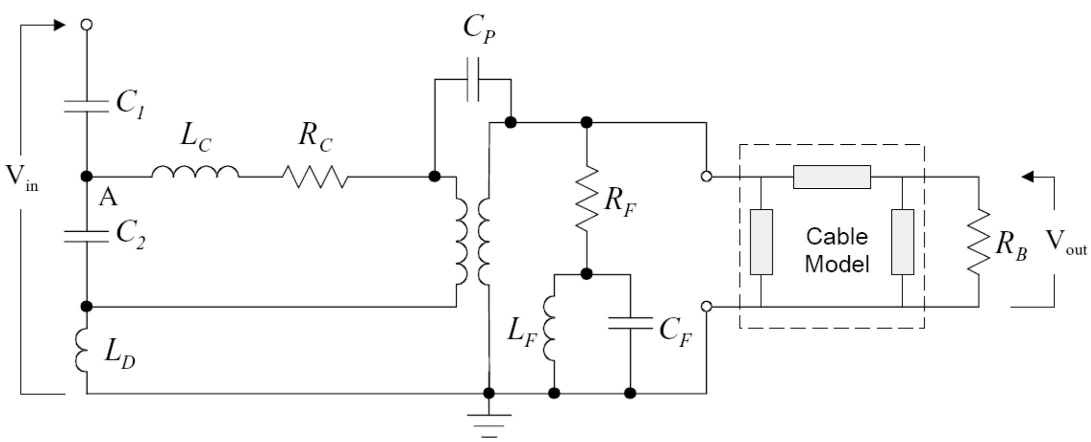


Figure F-6: CCVT equivalent model

Table F-22: CCVT parameters summary

Parameter Description	Schematic Reference
Upper Capacitor Size	C_1
Lower Capacitor Size	C_2
Drain Inductor	L_D
Compensating Reactor Inductance	L_C
Compensating Reactor Resistance	R_C
Burden Resistance	R_B
Ferroresonance Suppression Damping Resistor	R_F
Ferroresonance Suppression Circuit Inductor	L_F
Ferroresonance Suppression Circuit Capacitor	C_F
Parasitic Capacitance	C_P

The inductor L is selected by setting the sum of the equivalent capacitive reactance and the inductive reactance to zero at the power frequency. Note that the Thevenin equivalent capacitive reactance at point A is the sum of the upper and lower leg capacitances, C_1+C_2, thus:

$$j\omega L + \frac{1}{j\omega(C_1 + C_2)} = 0$$

or equivalently:

$$L = \frac{1}{\omega^2(C_1 + C_2)}$$

The Reactor L_D, known as the drain reactor, is for the purpose of power line carrier filtering and may be optionally shorted by a manual switch. For the purpose of low frequency analysis (0-1kHz) this reactor has negligible effect and is ignored.

In standard CCVT designs, typical values of capacitor dividers are selected so that the sum of the capacitances C_1+C_2 is in the order of 100 nF. The corresponding compensating reactor inductance for 60 Hz power frequency is in the order of 70 Henries. A reactor of such large inductance must have a magnetic core, and will also have a substantial resistance. As a result, the compensating reactor is also subject to saturation. Furthermore, its resistance makes the CCVT transformation ratio dependent on the burden resistance. Recently, CCVTs with larger capacitance values and smaller compensating reactors have become available. These devices exhibit improved transient response, as well as less sensitivity to burden resistance.

Some manufacturers classify CCVTs as (a) Normal Capacitance, (b) High Capacitance, (c) Extra High Capacitance, although the threshold values separating these classes are vague. CCVTs of total capacitance value (C_1+C_2) as high as 400 nF are presently commercially available.

The interaction of the transformer saturation characteristics with the divider capacitance makes this circuit subject to ferroresonance. Specifically, during transients, a resonance may occur at the frequency determined by the transformer magnetizing reactance and the circuit equivalent capacitance. This results in overvoltages developing across the transformer which drive the core into saturation. This nonlinear high amplitude oscillation causes severe measurement errors and can damage the circuit components. For this reason, CCVTs include a ferroresonance suppression circuit, usually located across the transformer secondary winding (Z_F in Figure F-5). Several ferroresonance suppression circuit topologies are presently in use. These circuits are considered proprietary by some manufacturers, and thus the circuit details are not readily available. However, two generic circuit models capture the basic behavior of these filters: The "active" suppression circuit illustrated in Figure F-7, and the "passive" suppression circuit illustrated in Figure F-8.

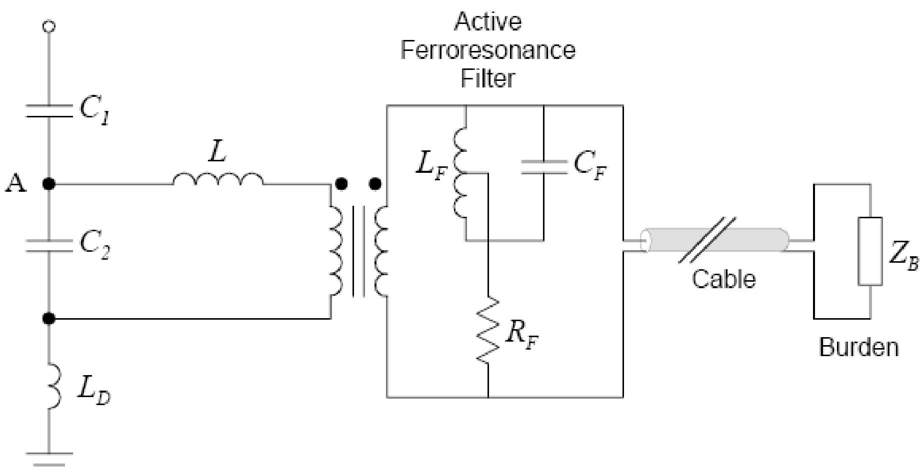


Figure F-7: Equivalent Circuit of a CCVT with Active Ferroresonance Suppression Circuit

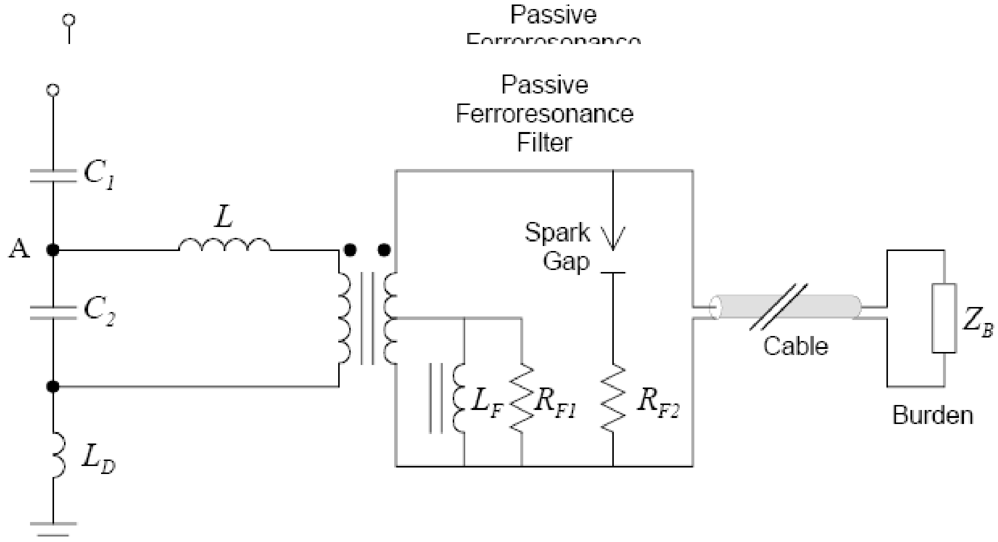


Figure F-8: Equivalent Circuit of a CCVT with Passive Ferroresonance Suppression Circuit

The active suppression circuit inductor L_F and capacitor C_F are tuned to the power frequency. Thus during normal steady state operation, the impedance of the $L_F//C_F$ branch is very large and the suppression circuit draws negligible current. During transients, the impedance of $L_F//C_F$ branch is lower and thus the resonating energy is dissipated through the filer resistor R_F.

The passive suppression circuit (see Figure F-8) consists of a saturable core reactor L_F and a damping resistor R_{F1} connected at the center tap of the transformer secondary, plus a spark gap in series with a second damping resistor R_{F2}.

During steady state 60 Hz operation, both of these filter circuits have negligible effect on the CCVT response. However during transients they generally prolong the CCVT transient response. It has been shown that CCVTs with passive ferroresonance suppression circuits have better transient response characteristics (error decays to negligible levels faster). They are also more expensive than active circuits.

The CCVT simulation model is shown in the Figure F-9. The model explicitly represents the upper and lower capacitors, the drain inductor, the compensating reactor inductance and resistance, ferroresonace suppression damping, the parasitic capacitance and the burden resistance. In addition, the control cable is modeled with an RG-8 copper cable model.

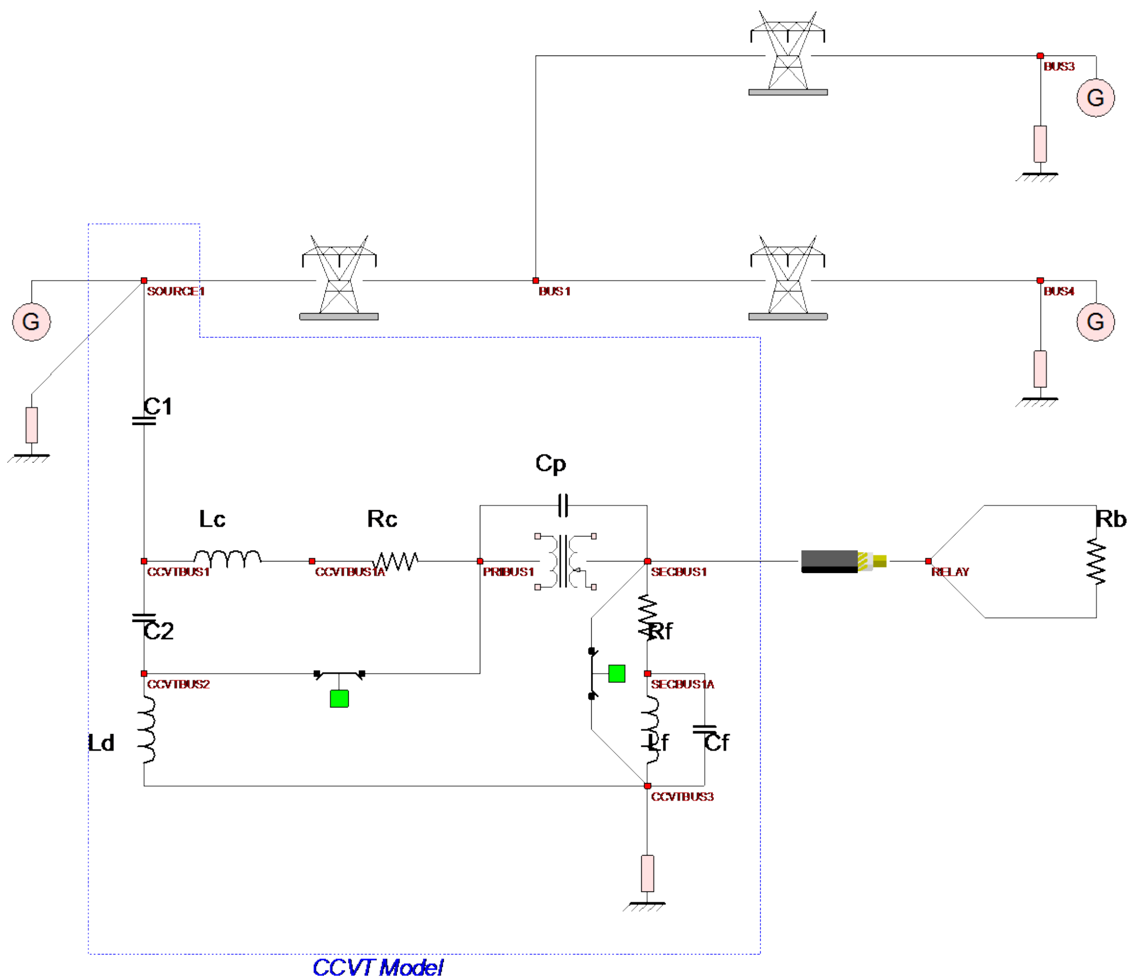


Figure F-9: CCVT simulation model

F.4.1 Case 5: 288kV:120V CCVT

The base case parameter values for this CCVT are given in Table F-23. The simulation is repeated for different instrumentation cable lengths. In addition, different values of burden resistance, and different inductance and capacitance values are used to generate the rest of the phase error results.

Tables F-24 and F-25 summarize the voltage phase error results.

Table F-23: Base-case CCVT instrumentation channel simulation parameters

Parameter Description	Schematic Reference	Value
CCVT Capacitance Class		Normal
Input Voltage		288 kV
Output Voltage		120 V
Upper Capacitor Size	C_1	1.407 nF
Lower Capacitor Size	C_2	99.9 nF
Drain Inductor	L_D	2.65 mH
Compensating Reactor Inductance	L_C	68.74 H
Compensating Reactor Resistance	R_C	3000 Ohms
Burden Resistance	R_B	200 Ohms
Ferroresonance Suppression Damping Resistor	R_F	70 Ohms
Ferroresonance Suppression Circuit Inductor	L_F	0.398 H
Ferroresonance Suppression Circuit Capacitor	C_F	17.7 uF
Cable Type		RG-8
Cable Length		100 Feet
Transformer Power Rating		300 VA
Transformer Voltage Rating		4kV/120V
Leakage Reactance		3%
Parasitic Capacitance	C_P	500 pF

Table F-24: Phase Error (in Degrees) Versus Burden Resistance and Cable Length

	Cable Length (feet)		
Burden Resistance	**10'**	**1000'**	**2000'**
50 Ohms	0.077	-0.155	-0.365
100 Ohms	0.026	-0.096	-0.213
200 Ohms	0.028	-0.063	-0.127
400 Ohms	-0.013	-0.047	-0.800
1000 Ohms	-0.022	-0.036	-0.520

Table F-25: Phase Error (in Degrees) Versus Capacitance and Inductance

	Inductance Error (%)		
Capacitance Error (%)	**0%**	**1%**	**5%**
0%	0.020	-0.066	-0.331
-1%	-0.066	-0.132	-0.397
-5%	-0.330	-0.396	-0.661

Appendix G: Control Cables of Typical Instrumentation Channels

This Appendix provides a set of typical instrumentation channels. In selecting the instrumentation channels the following have been considered.

LOW VOLTAGE POWER AND CONTROL CABLES IN SUBSTATIONS

600 and 1000 Volts SHIELDED
CROSS-LINKED POLYETHYLENE (XLPE) INSULATED
CHLORINATED POLYETHYLENE (CPE)
MULTIPLE CONDUCTOR CONTROL CABLES

1. The cables described in this document are 600 and 100 Volt, multiple conductor shielded control cables.
2. The control cables supplied are suitable for installation in high-voltage (60-500 kV) substation environments. The cables are suitable for installation indoors or outdoors (wet or dry); in raceway of surface trench, duct, conduit, or cable tray.
3. The cables may not be suitable for installation in corrosive environments. Cables described in this report, however, are suitable for installation in either grounded (100%) or ungrounded (133%) electrical systems.
4. Some systems may be using 1000 Volt shielded multiple conductor XLPE-CPE cables – Samples of the 1000 Volt Shielded conductor specification are covered in Table IA for PMU accuracy considerations.

Notes: Over the course of history, the users may have:

- ✓ Interchangeably applied either the 1000 V or the 600 Volts XLPE based on market factors at the time of application.
- ✓ Also, in some installations (power companies) cable splicing may be OK, and some users do not permit splicing and require one continuous cable.
- ✓ Other factors such as availability of supply may require alternate cable of equal ratings to be used. Therefore, a non-homogeneous low voltage cable environment may provide a more conservative approach for voltage circuits.

Minimum 3000 feet (or 80% length of cable needed) continuous cables and increments of 500 feet there after are common practice.

5. General

- ✓ Cables applicable requirements include
- ✓ ICEA publications S-95-658 (NEMA WC 70) and S-73-532 (NEMA WC 57)
- ✓ Cable operating temperature range:
- ✓ Maximum conductor temperature of 90^o C for normal operation, 130^o C for emergency overload conditions, and 250^o C for short-circuit conditions
- ✓ Suitable for operation in either wet or dry environments, indoors and outdoors

6. Conductors
   - ✓ Conductor Metal: Bare annealed copper
     - o Requirements described in ASTM B 3.
   - ✓ Some companies may use tinned copper conductor in place of bare conductor.
     - o Requirements described in ASTM B 33.
   - ✓ Conductor Stranding:
     - o Class B concentric-lay-stranded in accordance with ASTM B-8 for copper conductors.

7. Insulation
   - ✓ Flame retardant, heat and moisture resistant, thermosetting cross-linked polyethylene (XLPE) or ethylene propylene rubber (EPR) compound.
   - ✓ Minimum average insulation thickness are shown in Table I - The minimum thickness at any point not less than 90% of the specified minimum average thickness.

Table I and Table IA are typical specifications for 600V and 1000 Volts low voltage cables respectively.

TABLE I					
600 VOLT, SHIELDED, XLPE or EPR INSULATED, CPE or CSPE JACKETED MULTIPLE CONDUCTOR CONTROL CABLES					
Size AWG	Number of Conductors	Insulation Thickness mils	Shield Thickness mils	Jacket Thickness mils	Nominal OD inches
#12	7	30	5	60	0.5970
#12	4	30	5	45	0.4773
#10	7	30	5	60	0.6690
#10	4	30	5	60	0.5651
#8	7	45	5	80	0.8890
#8	4	45	5	60	0.7097
#6	4	45	5	60	0.8013
#4	4	45	5	80	0.9570

TABLE IA					
1000 VOLT, SHIELDED, XLPE INSULATED, CPE JACKETED, MULTIPLE CONDUCTOR CONTROL CABLES					
Size AWG	Number of Conductors	Insulation Thickness mils	Shield Thickness mils	Jacket Thickness mils	Nominal OD inches
#12	7	45	5	60	0.7500
#12	4	45	5	60	0.5500
#10	7	45	5	80	0.8500
#10	4	45	5	60	0.6500
#8	7	55	5	80	1.1000
#8	4	55	5	80	0.9000
#6	4	55	5	80	1.0000
#4	4	55	5	80	1.2500

TABLE II - INSULATION PROPERTIES

Property	Requirement (max/Min)
Original Physicals	
Tensile Strength, psi	1800 (min) for XLPE, 700 (min) for EPR
Elongation, %	250 (min)
Air-Oven Aging, after 7 days @ 121 degrees C	
Tensile Strength, % retained	75 (min)
Elongation, % retained	75 (min)
Hot Creep @ 150 degrees C	
Elongation, %	100 (max)
Set, %	5 (max)
Accelerated Water Absorption	
Dielectric Constant (SIC) 24 Hours	4.0 (max) *
Increase in capacitance, %	
1 to 14 days	3.0 (max) for XLPE, 3.5 (max) for EPR
7 to 14 days	1.5 (max)
Stability Factor, after 14 days	1.0 (max)
Alternate to Stability Factor	0.5 (max)

* - Requirement is more stringent than ICEA S-95-658 & ICEA S-73-532