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Application of Time-Synchronized Measurements in Power System Transmission Networks

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Preface

This book has been created through a research project titled "Future Grid Initiative" funded by the Department of Energy under a grant to the NSF Power Systems Engineering Research Center (PSerc). The objective was to create a book that contains some cutting-edge research results obtained by the authors, their graduate students and research staff though PSerc and other projects funded by parties outside PSerc. The focus of the book is an overview of new applications in the most critical power system applications during disturbances: state estimation, voltage stability, oscillation monitoring, transient stability, and fault location. Since all the results obtained in this book relate to the use of field data for testing and evaluation, the proposed applications have direct practical value. As such, the book may be used for teaching a graduate course or it may be used by professionals to better understand the opportunities that come with extensive use of time-synchronized measurements.

The introductory chapter of the book provides a history of time-synchronized measurements. It gives a survey of pioneering developments and points out early designs of phasor measurement units (PMUs). The discussions go on to describe other elements of a synchrophasor measurement system: phasor data concentrator and a system for dissemination of the accurate time through the communication network or directly via interfacing PMUs to the Global Positioning System (GPS) of satellite receivers. The motivation for the book is discussed at the end of the chapter.

Chapter 2 is focused on one of the most fundamental power system data acquisition and monitoring concepts, namely state estimation (SE). The history of the Energy Management Systems is outlined and the SE approaches are surveyed. Then, several new concepts in SE are analyzed: substation state estimation, PMU-based state estimation, and quasi-dynamic distributed state estimator. The discussion supports the use of synchronized measurements in daily operations of the power grid.

Chapter 3 deals with the monitoring methods to detect occurrences of instability. The power system stability phenomena covering voltage, transient and small signal stability are surveyed. Various real-time detection methods for monitoring voltage instability, oscillations, and angle instability are demonstrated using archived data from actual power system networks.

Chapter 4 is entirely devoted to the issues of assessment of the transient stability under various power system operating conditions. The use of decision trees to facilitate the transient stability assessment in real-time is emphasized. Some test results from applying such methods in an actual power system contingency are presented. This chapter also gives details of how such an assessment scheme may be implemented.

Chapter 5 is devoted to determining fault location using different time-synchronized concepts, namely the use of synchronized samples and the use of synchrophasors. The initial discussion describes how and why the two techniques may be used to locate faults. For each of the two approaches, both theoretical details and practical aspects are elaborated. The results are also verified using data from an actual power system.

The book opens quite a few research questions and hopefully creates an incentive for the readers to engage in future research that is informed and motivated by the approaches and results described in the book. It also illustrates how such techniques may be implemented and demonstrates the performance using field data. An extensive list of references about prior work is provided at the end of each chapter. The reader can explore various techniques in more detail by reading referenced papers and student dissertations reporting further results from the research teams led by the authors.

We hope this book will be a starting point for many research and implementation directions to be undertaken by the readers in the future.

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Contents

Chapter 1
Introduction

1.1 Background on Synchrophasor Technology

The use of synchronized measurements, particularly synchrophasors, has a history of over 30 years of research and development. This technology allows measurements at different physical locations to be synchronized and time-aligned, then combined to provide a precise, comprehensive view of an entire region or interconnection. Figure 1.1 depicts the locations of currently deployed devices called phasor measurement units (PMUs) that are participating in the North American Synchrophasor Initiative (NASPI) project and provide synchrophasor measurements across North America. It should be noted that there are many more installed PMUs across the USA and around the world that are not part of the NASPI project. In the last few years, the effort of deploying and demonstrating a variety of applications that can benefit from synchronized measurements has been accelerated through the NASPI and other related industry efforts. Most recently, several utilities and regional market operators have developed plans for large-scale deployment of such a technology. In the deployment of the intelligent electronic devices (IEDs) for substation synchronized measurement applications, the focus at present is on two approaches: (a) use of PMUs (dedicated high-precision recording instruments) and (b) use of PMU-enabled IEDs (digital fault recorders (DFRs), digital protective relays (DPRs), digital disturbance recorders (DDRs), and other devices that have PMU measurement capability). While the number of PMUs across the US utility networks in the NASPI network is estimated at 250, the number of PMU-enabled IEDs sold by manufacturers is more than a million and is increasing. With the recent investments through the American Recovery and Reinvestment Act (ARRA) and other funding sources, the total number of PMUs and PMU-enabled IEDs may increase by an order of magnitude as the industry starts utilizing the capabilities of this technology to improve protection, control, and operation of the system in the next 5–10 years. The effective utilization of this valuable asset will require substantial manpower for substation installation, communications, data integration, and visualization.

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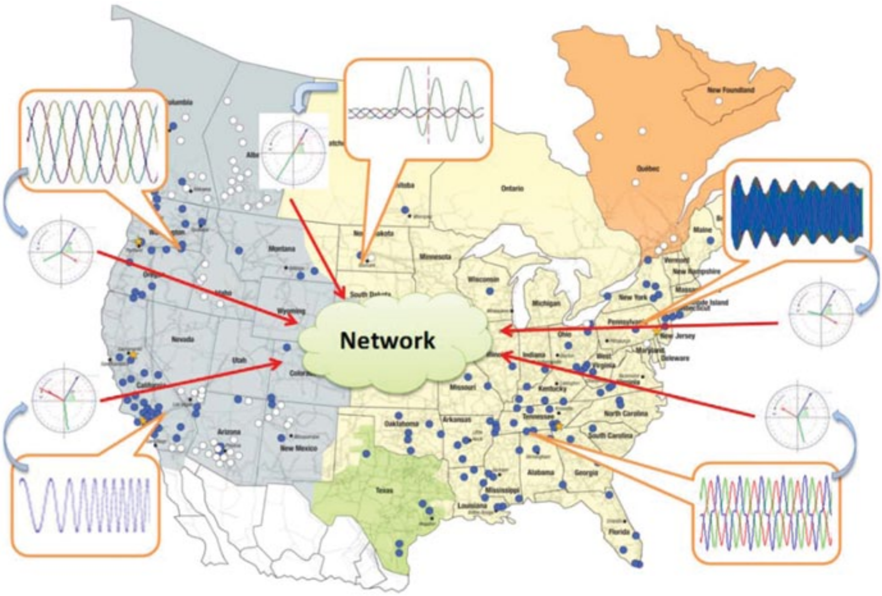

Fig. 1.1 Synchrophasor measurements aggregated across North America

1.2 Synchronized Measurement Devices

The value of synchronized measurements has been recognized in many applications. As a matter of fact, synchronization of measurements and observations was sought in ancient times. Key to this capability is the development of accurate clocks. In ancient times the "klepsidra" (water clock) was typically used for timing. Recently, it has been discovered that the ancient Greeks had also developed a clock mechanism (the antikythera mechanism) that is illustrated in Fig. 1.2. More information about the mechanism can be found in http://www.antikythera-mechanism.gr/. This mechanism consists of a number of geared wheels as in a typical mechanical watch of the twentieth century.

As technology evolved, the accuracy of clocks increased. Today, the most accurate clock is the Cesium atomic clock, with an accuracy of 1 µs in 100 years. The cost of the Cesium atomic clock is prohibitive for many applications. However, the US federal government has developed and deployed a constellation of satellites known as the global positioning system (GPS). Specifically, after years of development and experimental systems, in 1989 the launching of 24 satellites was initiated at about six per year and made available for civilian use. The final GPS satellite was launched on June 26, 1993. The GPS satellites transmit the signal of the Cesium clock throughout the globe and if the signal is received from more than three satellites, using triangulation/estimation methods, the signal of the Cesium atomic clock can be reproduced at any point on earth with an accuracy of tens of nanoseconds.

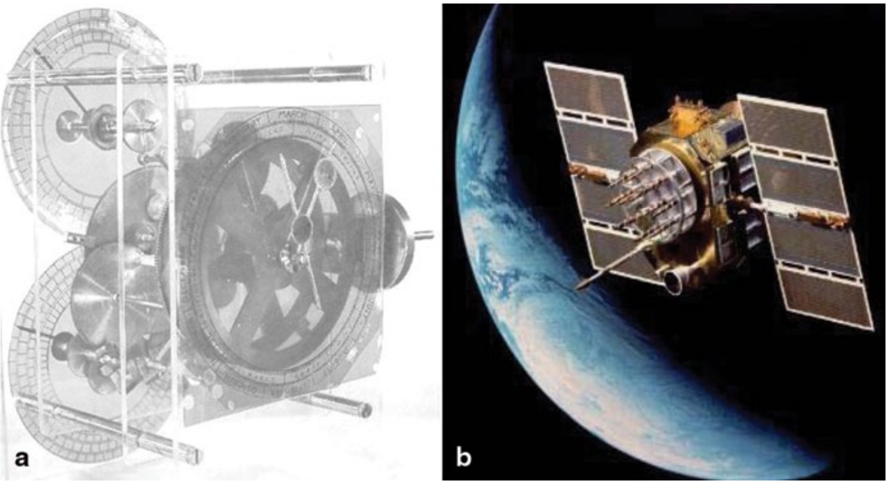

Fig. 1.2 Evolution of time pieces—from the antikythera mechanism (89 AD) (**a**) to the Global Positioning System (1989 AD) (**b**)

Note that from the power system applications point of view a timing signal with accuracy better than 1 µs is sufficient. With proper metering technology, an accuracy of 1 µs translates into measuring the phase angle with an accuracy of 0.02°, an accuracy that is adequate for present day power system applications.

With the introduction of computer relaying (G. Rockefeller, "Fault Protection with a Digital Relay", 1969) [1] and later microprocessor relays (the first commercial microprocessor relay was introduced by Ed Schweitzer in 1983), efforts were initiated to extract the phasors of an electric power system using the available time signals at that time. In 1980, Missout and Girard described a system that was developed for measuring the phase angle between Montreal and Sept-Iles [2]. In 1981, Bonanomi described a system for measuring phase angles using synchronized clocks [3]. In 1983, Meliopoulos [4] proposed to Utah Power company the development of a system of synchronized measurements using timing signals from Geostationary Operational Environmental Satellites (GOES) for monitoring the power loop flow throughout the state of Utah as well as the swings of this power flow in response to concern by this utility for the frequent loop flow problems that they were experiencing. The GOES signal has an accuracy of better than 100 µs and at that time it was the best available clock (other than a Cesium atomic clock). While this proposal was not funded, the authors proposed to New York Power Authority (NYPA) in 1989 to assess and develop the technology of synchronized measurements for the purpose of monitoring harmonic distortion on the NYPA transmission system. This work was funded, and in 1991, a prototype was developed (Meliopoulos/Cokkinides, Georgia Tech Invention Disclosure, 1991) that used signals from a GPS clock and a time-Vernier method to time tag measurements with an accuracy better than 2 µs. The device can be added to an existing non-GPS-synchronized DFR as shown in Fig. 1.3. The principle of operation is also shown in Fig. 1.3.

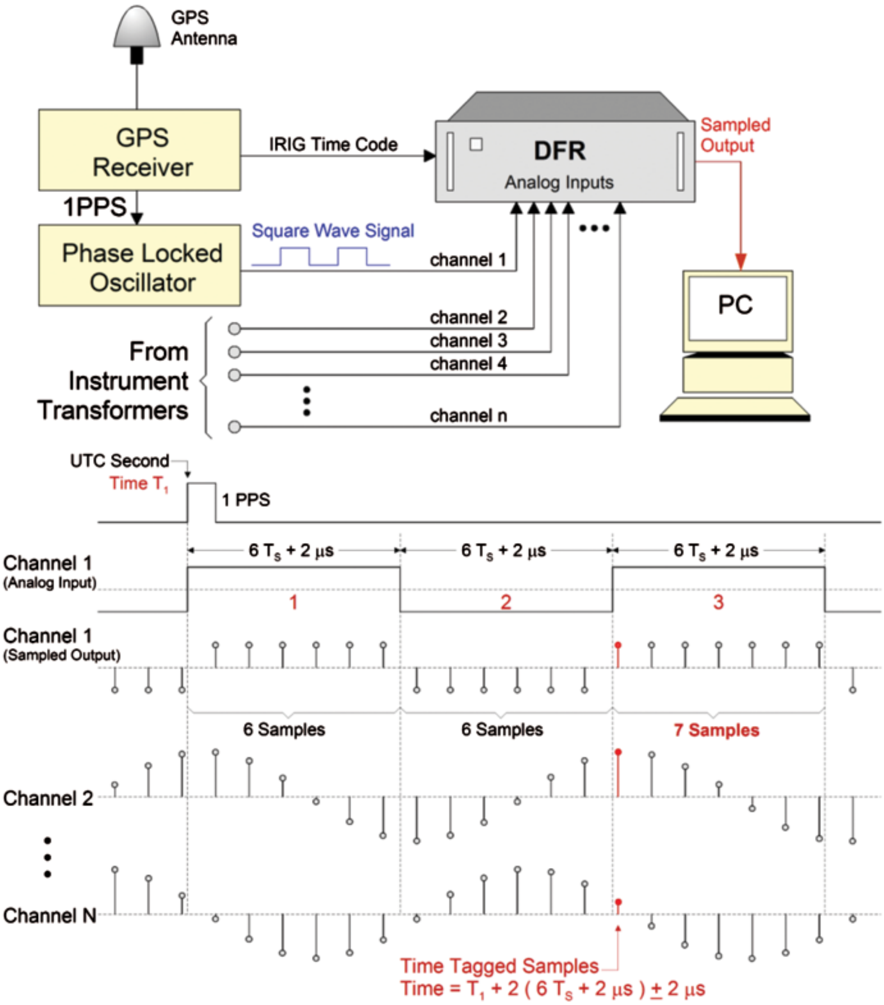

Fig. 1.3 Sample time tagging via time-Vernier scheme (1991). *GPS* global positioning system

A sequence of square pulse signals of a duration of six sampling periods plus 2 μs is generated, which is synchronized with the 1 pps signal of a GPS clock. This signal is then fed into one channel of a DFR. When the number of samples within one square pulse is 7, this indicates that the first and last sample in that pulse is taken at the time of the square pulse transition with an accuracy of 2 μs or better. Subsequently, one of these samples is time tagged as indicated in Fig. 1.3. The samples at the same time of all channels in the DFR are also assigned the same time tag, as seen in the figure. The time tag is then used to compute the Fourier transform of the sampled waveform with reference the GPS signal thus providing the phasor with reference to the GPS clock. This device can be inserted in the input channel

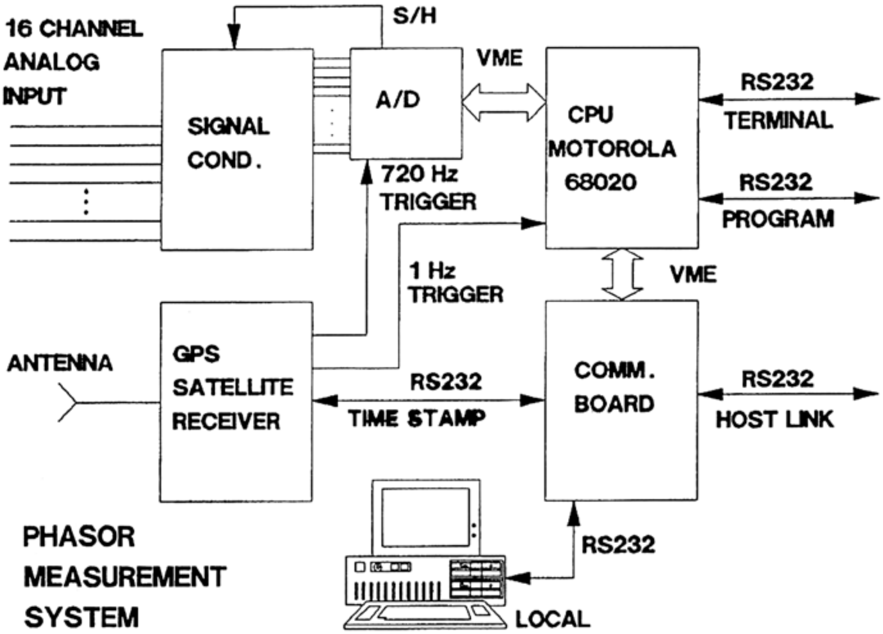

Fig. 1.4 Block diagram of Arun Phadke's PMS (from Phadke [5]). Characteristics: **a** analog anti-aliasing input filter with a cutoff frequency of 360 Hz, **b** 12 bit sample and hold A/D technology, and **c** 720 samples per second with analog multiplexing

of commercially available DFRs, and it is able to time tag the measurements with accuracy better than 2 μs.

During the period 1988–1991, Arun Phadke developed a phasor measurement system (PMS), which is illustrated in Fig. 1.4. The PMS used a GPS signal for timing, 720 samples per second, a sample and hold A/D converter, and a front-end antialiasing filter with a cutoff frequency of 360 Hz. The combination of the anti-aliasing filter and the multiplexing introduced time delays that were orders of magnitude greater than the accuracy of the GPS clock. Although this device was never tested by independent organizations, the estimated timing errors were more than 50 μs. Several PMSs were constructed and sold to utilities (for example, three to AEP, one to NYPA [5]). Despite the use of the GPS clock, the PMS was not capable of performing measurements with comparable accuracy to the GPS clock.

The first device capable of performing synchronized measurements with accuracy comparable to the GPS clock accuracy was developed by Jay Murphy of Macrodyne and was released into the market in January 1992. The device was called the Macrodyne PMU Model 1690. Murphy introduced a number of innovations to achieve the goal of performing synchronized measurements with accuracy comparable to the GPS clock shown in Fig. 1.5. The characteristics of the Macrodyne PMU are: individual channel GPS synchronization (no multiplexing), common mode rejection filter with optical isolation, and a 16 bit A/D sigma/delta modula-

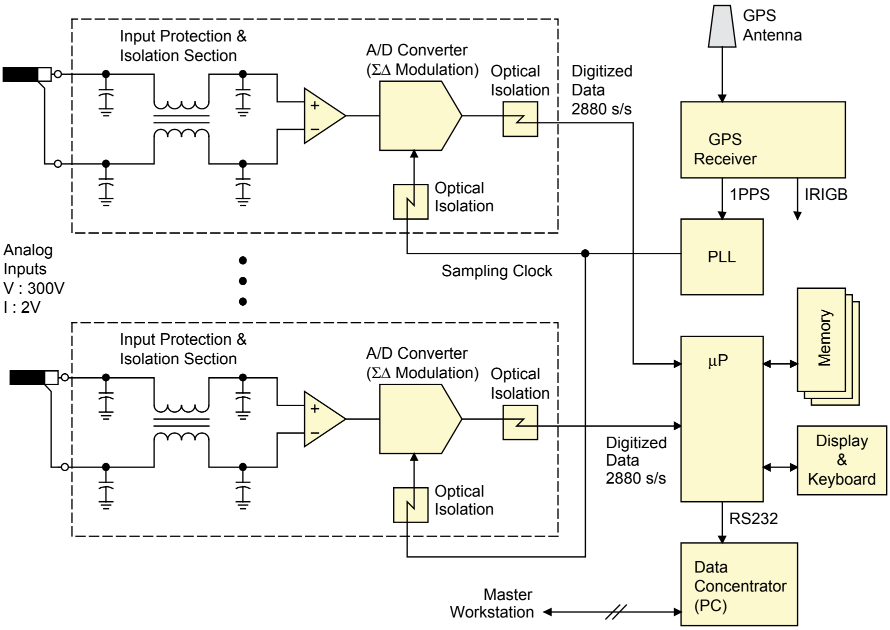

Fig. 1.5 Block diagram of Macrodyne's phasor measurement unit model 1690 (PMU). *PLL* Phase Lock Loop. (Figure created by Meliopoulos based on Model 1690 PMU design document, physical inspection of the internal construction of the unit, and validated by Jay Murphy, 1992)

tion converter operating at several megahertz and decimated to 2880 samples per second.

1.2.1 Standalone PMUs

The need to achieve synchronized measurements for state estimation (SE) has been long recognized. To achieve synchronized measurements, a very accurate clock signal with accuracy better than 1 μs is required at every key measurement location of the power system. Synchronization of the measurements can be achieved with the use of a GPS receiver and appropriate hardware. A conceptual view of such a system is illustrated in Fig. 1.6. The GPS receiver has the capability to provide a synchronization signal with precision better than 1 μs. This time reference allows the measurement of the phase angle of the fundamental frequency component with an accuracy of 0.02° on a system-wide common reference. The local system remote terminal unit (RTU) uses input signals from existing instrument transformers. The captured voltage and current waveforms are time-tagged and transmitted to the energy management system or the master station. Normally, only the first sample needs to be time tagged. Knowing the sampling rate, all other information can be easily extracted. Note that in the energy management system, one can

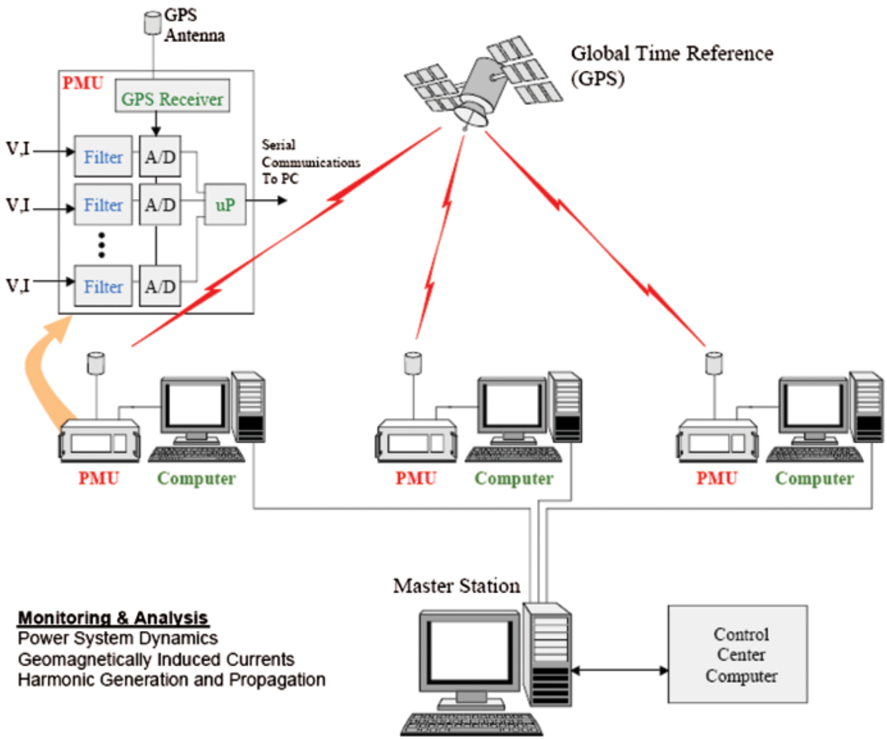

Fig. 1.6 The hardware platform used by the global positioning system (*GPS*)-synchronized measurements. *PMU* phasor measurement unit

collect all the data with the same time tag. The local systems can be programmed to obtain a set of measurements at user-selected intervals with timing accuracy of the GPS signal. A specific standard (IEEE C37.118) [6] exists that defines the standard time intervals of 10, 12, 15, 20, 30, and 60 times per second for 60 Hz systems and 10, 25, and 50 times per second for 50 Hz systems. A time reference provided by GPS can provide a very accurate time reference of better than 1 μs anywhere on earth. Specifically, the phase of voltage and current can be calculated on an almost absolute basis using a highly accurate GPS clock. This time reference allows the measurement of the phase angle of the fundamental with an accuracy of 0.02° on a system-wide common reference.

Presently, commercial PMUs have been installed throughout the eastern, western, and Texas power system interconnections in the USA. Use of synchronized measurements simplifies the SE problem. In most of the cases, PMUs are deployed with several other PMU units to back up other PMUs that might be out of order and deteriorate the computation of SE. Generally, these PMU units are integrated with a number of other functions to build a fully networked and automated power system.

PMUs and PMU-enabled IEDs are typically installed in a substation or at a power plant. Each phasor requires three separate electrical connections (one for each

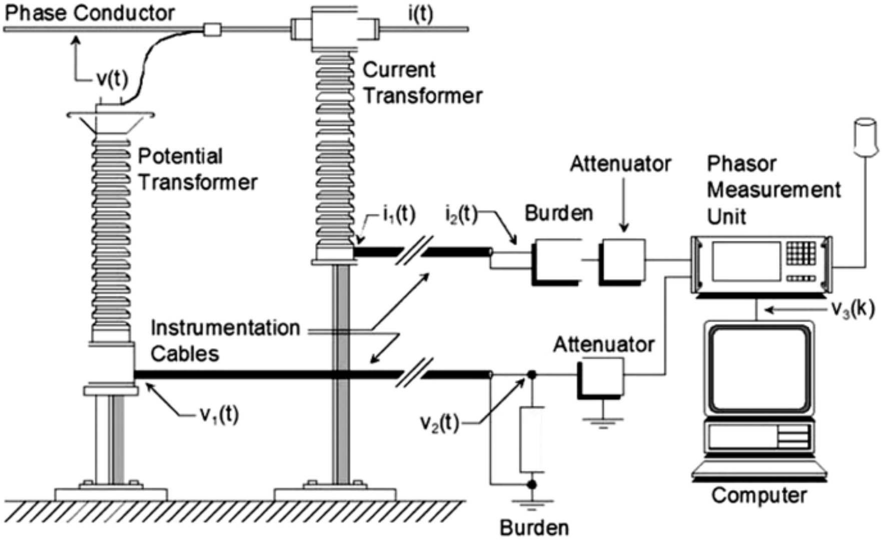

Fig. 1.7 A typical PMU installation—the instrumentation of only one phase is shown in [7]

phase) to either measure a current (from a line or power transformer bank) or a voltage (from either line or bus potential transformers, PTs). A typical PMU installation is shown in Fig. 1.7.

1.2.2 PMU-Enabled IEDs

The synchrophasor measurement functionality need not be the sole function or purpose of a device; for instance, many digital relays have PMU functionality but their primary purpose is to serve as a relay rather than as a PMU. Any device that incorporates this functionality—such as DFRs and digital relays—is considered a PMU device, i.e., a PMU-enabled IED. Other unrelated functions of the device must be shown not to affect the performance of the PMU component, and equally important, the PMU functions must not affect the other functions of the device. The main components of a PMU or PMU-enabled IED include analog input signal interface, data acquisition system, phasor estimation module, and post-processing module for output data. Each module, particularly the phasor estimation algorithm has an impact on performance accuracy. For the use of such devices in various applications, the synchrophasor and frequency values must meet the general definition as well as the minimum accuracy requirements given in standards [6, 8, 9].

Presently many IEDs have PMU functionality. PMUs output real-time streaming synchrophasor data usually in synchrophasor format (see IEEE Std C37.118 [6]) and at various rates, such as 10, 12, 15, 20, and 30 for 60 Hz systems. PMUs