

Power Electronics and Power Systems

Mladen Kezunovic
Sakis Meliopoulos
Vaithianathan Venkatasubramanian
Vijay Vittal

Application of Time-Synchronized Measurements in Power System Transmission Networks

 Springer

Power Electronics and Power Systems

Series Editors

Joe H. Chow

Troy, New York, USA

Alex M. Stankovic

Tufts University Dept. of Electrical & Computer Engineeri

Medford, Massachusetts, USA

David Hill

School of Electrical and Information Eng

The University of Sydney

Sydney, New South Wales, Australia

The Series, *Power Electronics and Power Systems*, encompasses most areas of power electronics, electric power restructuring, and power systems in general. It focuses on publishing advanced level textbooks, state-of-the-art titles, research monographs, professional books, and reference works related to the areas of electric power transmission and distribution, energy markets and regulation, electronic devices, electric machines and drives, computational techniques, and power converters and inverters. The Series publishes both authored books and edited compilations.

All titles are peer reviewed prior to publication to ensure the highest quality content. The Series features the leading international scholars and researchers as authors.

M.A. Pai, Professor Emeritus, Dept. of Electrical and Computer Engineering, University of Illinois, Urbana Champaign, IL 61801, 217-333-6790 (O), 217-344-0977 (R)

Alex M. Stankovic, Professor, Dept. of Electrical & Computer Eng., 440DA, Northeastern University, 360 Huntington Ave., Boston, MA 02115, (617) 373-3007

More information about this series at <http://www.springer.com/series/6403>

Mladen Kezunovic • Sakis Meliopoulos
Vaithianathan Venkatasubramanian • Vijay Vittal

Application of Time-Synchronized Measurements in Power System Transmission Networks

 Springer

Mladen Kezunovic
Department of ECEN
Texas A&M University
College Station, TX, USA

Vaithianathan Venkatasubramanian
School of EECS
Washington State University
Pullman, WA, USA

Sakis Meliopoulos
School of ECE
Georgia Tech
Atlanta, GA, USA

Vijay Vittal
School of Electrical
Computer and Energy Engineering Ira
A. Fulton Schools of Engineering
Arizona State University
Tempe, AZ, USA

ISSN 2196-3185

ISSN 2196-3193 (electronic)

ISBN 978-3-319-06217-4

ISBN 978-3-319-06218-1 (eBook)

DOI 10.1007/978-3-319-06218-1

Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014940150

© Springer International Publishing Switzerland 2014

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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 through 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.

Authors

Mladen Kezunovic, Texas A&M University
Sakis Meliopoulos, Georgia Institute of Technology
Vaithianathan “Mani” Venkatasubramanian, Washington State University
Vijay Vittal, Arizona State University

Acknowledgments

The authors wish to recognize many graduate students, research staff, and colleagues that contributed to the research results reported in this book. Thanks are due to the following students, research associates, and faculty at Texas A&M University for their contributions included in this book: Dr. Papiya Dutta, Ahad Esmaeilian, Dr. Zijad Galijasevic, Dr. Ashok Gopalakrishnan, Maja Knezev, Prof. Yuan Liao, Dr. Shanshan Luo, Prof. Brana Perunicic, Prof. Alex Sprintson, and Dr. Ce Zheng. The contributions of the following students and research associates at Arizona State University are sincerely appreciated: Siddharth Likhate, Ruisheng Diao, and Kai Sun. Research reported in this book from Washington State University is from the thesis works of graduate students, Guoping Liu, Qiang Zhang, Zaid Tashman, Xing Liu, Michael Sherwood, and Dongchen Hu, and their contributions are gratefully acknowledged. The contributions of the following research associates and students at the Georgia Institute of Technology are acknowledged and appreciated: Prof. George Cokkinides, Dr. Fan Zhang, Dr. George Stefopoulos, Renke Huang and Dr. Evangelos Farantatos.

This book originated from joint work by the authors in a US Department of Energy (USDOE) grant “Future Grid Initiative” under Power System Engineering Research Center (PSERC). The authors thank USDOE and PSERC for facilitating this effort.

Contents

1	Introduction	1
1.1	Background on Synchrophasor Technology	1
1.2	Synchronized Measurement Devices	2
1.2.1	Standalone PMUs	6
1.2.2	PMU-Enabled IEDs.....	8
1.2.3	Time Synchronization Options	9
1.2.4	Phasor Data Concentrators	11
1.3	Synchronized Measurement Networks	14
1.4	Motivation for the Book.....	14
	References.....	16
2	State Estimation and Visualization	17
2.1	The Energy Management System	18
2.2	Real Time Operational Requirements	19
2.3	SCADA System.....	22
2.4	System Network Configurator	25
2.5	Legacy State Estimation Algorithms.....	27
2.6	PMU-Based LSE.....	36
2.7	Substation-Based State Estimation	41
2.8	QSE	42
2.8.1	General Description.....	44
2.8.2	IEDs/PMUs and Instrumentation Channel Model.....	44
2.8.3	Definition of States.....	45
2.8.4	Quadratic Component Modeling and Quadratic Integration ...	46
2.8.5	Measurement Set and Measurement Model	48
2.8.6	State Estimation Algorithm	50
2.8.7	Performance Metrics	50
2.8.8	Visualizations.....	52
2.9	Summary and Conclusions.....	54
	References.....	56

3	Real Time Stability Monitoring	59
3.1	Stability Phenomena in Power Systems	59
3.1.1	Voltage Stability Phenomena	60
3.1.2	Small-Signal Stability Phenomena.....	61
3.1.3	Transient Stability Phenomena.....	64
3.2	Real Time Voltage Stability Monitoring	64
3.2.1	Voltage Security Index and its Motivation.....	65
3.2.2	Estimation of security index Γ_i from PMU data	68
3.2.3	Estimation Example Based on Actual PMU Data.....	69
3.2.4	Real Time Implementation from PMU Data.....	71
3.3	Real Time Oscillation Monitoring	71
3.3.1	Oscillation Monitoring System	73
3.3.2	Event Analysis Engine and Prony Algorithms	74
3.3.3	Damping Monitor Engine and Ambient Algorithms.....	85
3.3.4	Real Time OMS Implementation	89
3.4	Real Time Angle Stability Monitoring.....	91
3.4.1	Phase Angle-Based Algorithm	92
3.5	Conclusions	97
	References	97
4	Online Transient Stability Assessment	99
4.1	Online Transient Stability Assessment.....	99
4.2	Online Transient Stability Assessment Methods.....	100
4.2.1	Traditional Time Domain Simulation.....	100
4.2.2	Direct Methods.....	100
4.2.3	Artificial Learning.....	101
4.3	DTs for Transient Stability Assessment	102
4.4	Theoretical Background	103
4.4.1	Definition	103
4.4.2	CART Methodology.....	103
4.5	DT Building (Preliminary Tasks).....	105
4.5.1	Generation of Operating Scenarios	106
4.5.2	Stability Assessment.....	106
4.5.3	Selection of Attributes.....	106
4.5.4	Preparation of Database	106
4.5.5	Multiclass and Multicontingency DT Considerations.....	107
4.6	Use of PMUs for Transient Stability Assessment	107
4.7	DT-Based Online Security Assessment Scheme	108
4.7.1	Offline DT Building.....	108
4.7.2	Periodic OC Prediction and DT Updating	110
4.7.3	Online Security Assessment.....	111
4.8	Reliability of the DT	111
4.9	Preventive Control	113

4.10	Building a Better DT by Adjusting Penalties for Predictors	113
4.11	Case Study on Entergy System	115
4.12	Database Generation	116
4.12.1	Operating Conditions	116
4.12.2	Contingencies	116
4.12.3	Candidate Attributes	117
4.13	Results for Entergy System	118
4.13.1	DTs for Transient Stability (DT-U)	118
4.13.2	DTs for Damping (DT-D)	118
4.14	Evaluation of DT Reliability	125
4.15	Summary of Results for Entergy System	126
4.16	Voltage Stability Case Study on AEP System	127
4.17	OC Generation	129
4.18	Voltage Security Analysis	131
4.19	Predictor Selection and Database Generation	131
4.20	DT Training and Performance	133
4.21	DT Performance Improvement	134
4.21.1	Multiple Optimal DTs	136
4.21.2	Corrective DTs	138
4.21.3	Maximum DTs	140
	References	141
5	Transmission Line Fault Location	143
5.1	Fault Location Applications	143
5.2	Implementation Issues	144
5.3	The Use of Synchronized Samples from Two Ends	147
5.3.1	Theoretical Formulation	147
5.3.2	Implementation Details and Results	152
5.3.3	Features and Benefits	162
5.4	The Use of Sparse Synchronized Phasor Measurement for Fault Location	162
5.4.1	Theoretical Formulation	163
5.4.2	Implementation Details and Results	164
5.4.3	Features and Benefits	173
	References	173
	Index	175

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.

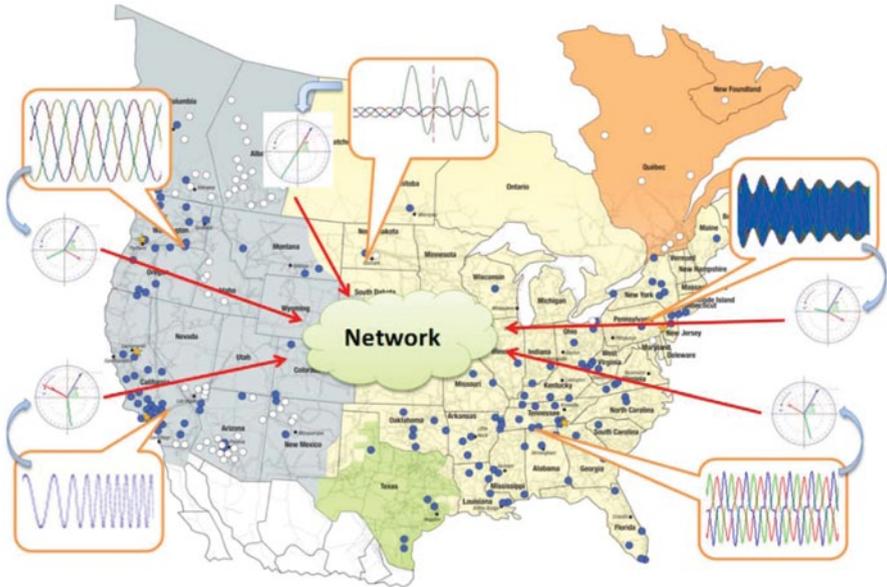


Fig. 1.1 Synchrophasor measurements aggregated across North America

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 $1 \mu\text{s}$ 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.

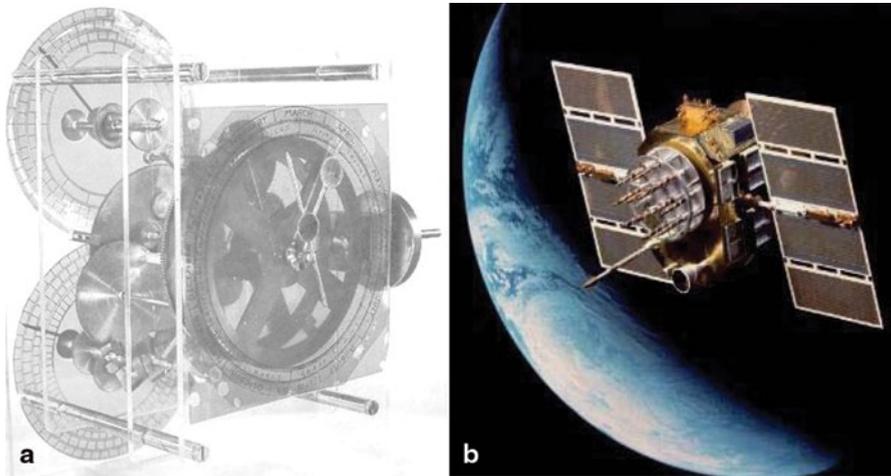


Fig. 1.2 Evolution of time pieces—from the antikythera mechanism (89 AD) (a) to the Global Positioning System (1989 AD) (b)

Note that from the power system applications point of view a timing signal with accuracy better than $1 \mu\text{s}$ is sufficient. With proper metering technology, an accuracy of $1 \mu\text{s}$ 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-Îles [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 $100 \mu\text{s}$ 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 $2 \mu\text{s}$. 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.

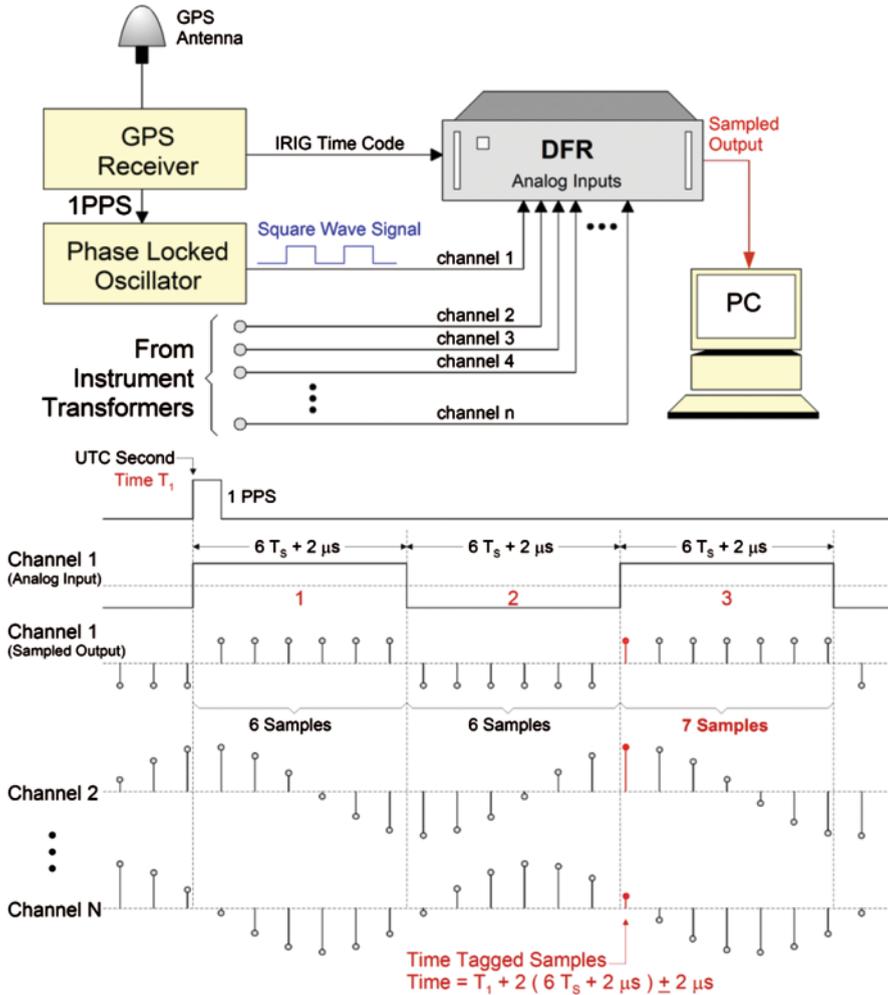


Fig. 1.3 Sample time tagging via time-Vernier scheme (1991). GPS global positioning system

A sequence of square pulse signals of a duration of six sampling periods plus $2 \mu s$ 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 $2 \mu s$ 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

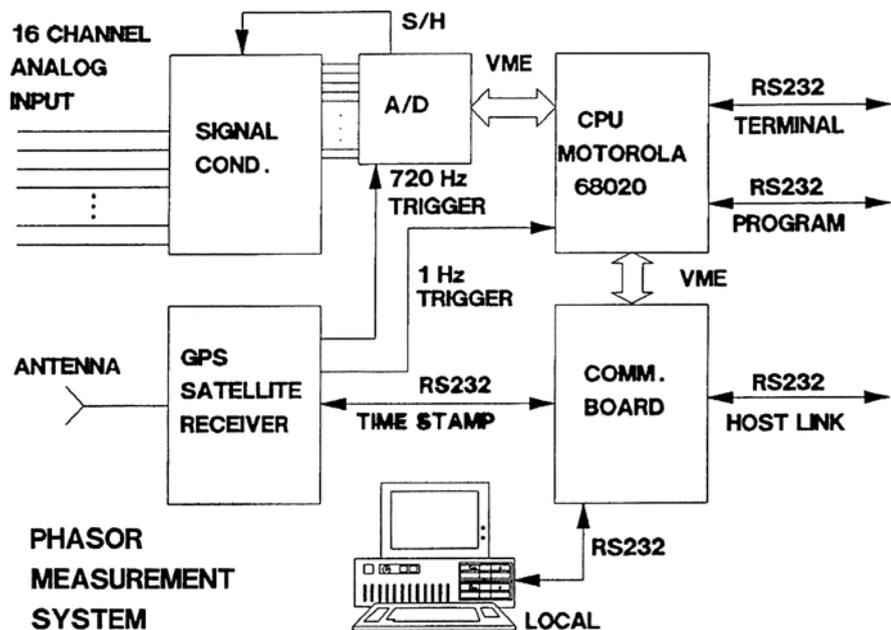


Fig. 1.4 Block diagram of Arun Phadke’s PMS (from Phadke [5]). Characteristics: a analog anti-aliasing input filter with a cutoff frequency of 360 Hz, b 12 bit sample and hold A/D technology, and c 720 samples per second with analog multiplexing

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

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 anti-aliasing 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 μ s. 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-

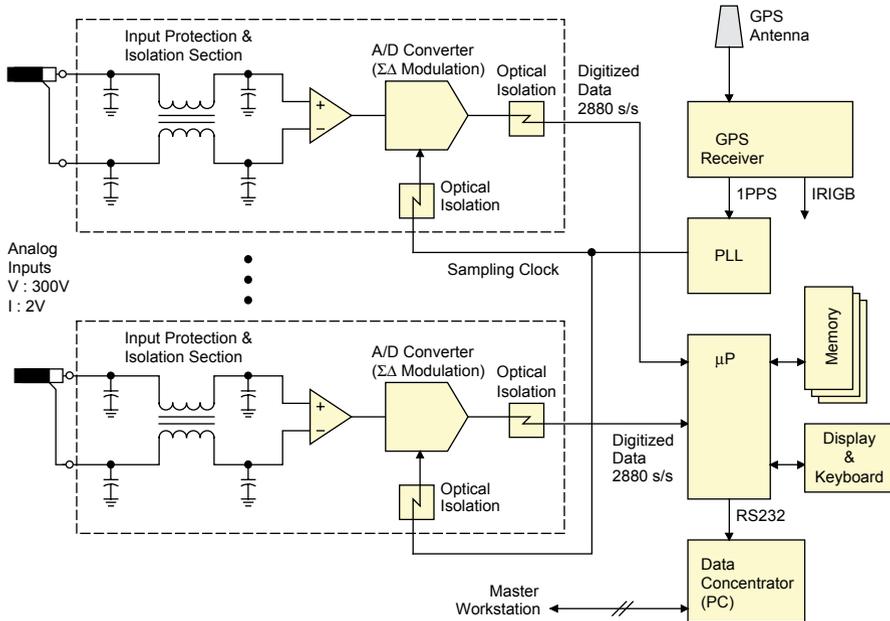


Fig. 1.5 Block diagram of Macrodyne's phasor measurement unit model 1690 (PMU). *PLL* Phase Lock Loop. (Figure created by Meliopoulos based on Model 1690 PMU design document, physical inspection of the internal construction of the unit, and validated by Jay Murphy, 1992)

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 $1 \mu\text{s}$ 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 $1 \mu\text{s}$. 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

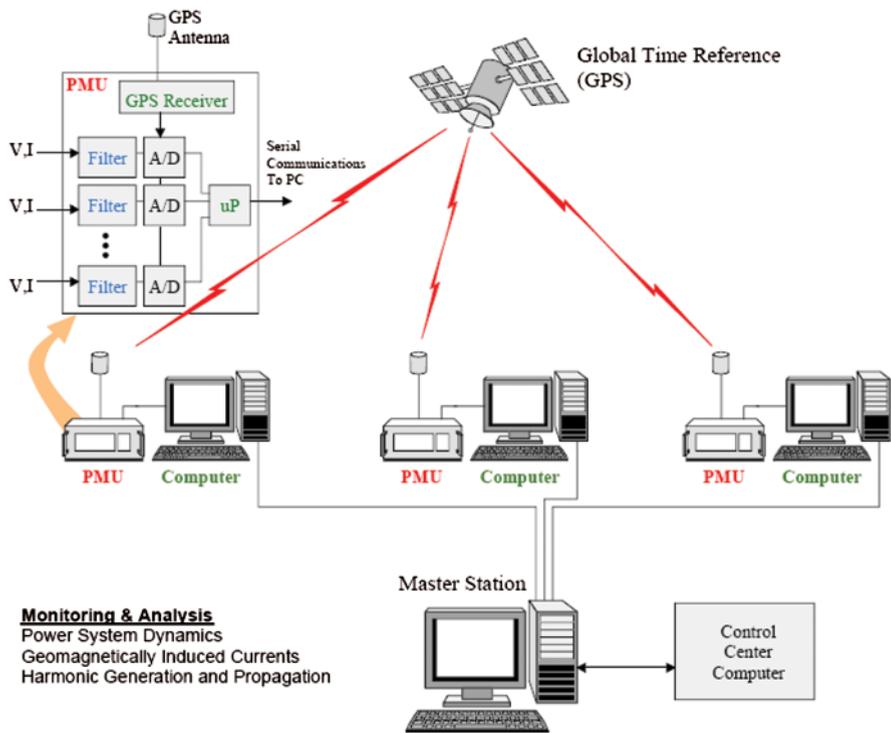


Fig. 1.6 The hardware platform used by the global positioning system (GPS)-synchronized measurements. *PMU* phasor measurement unit

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 μ s 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

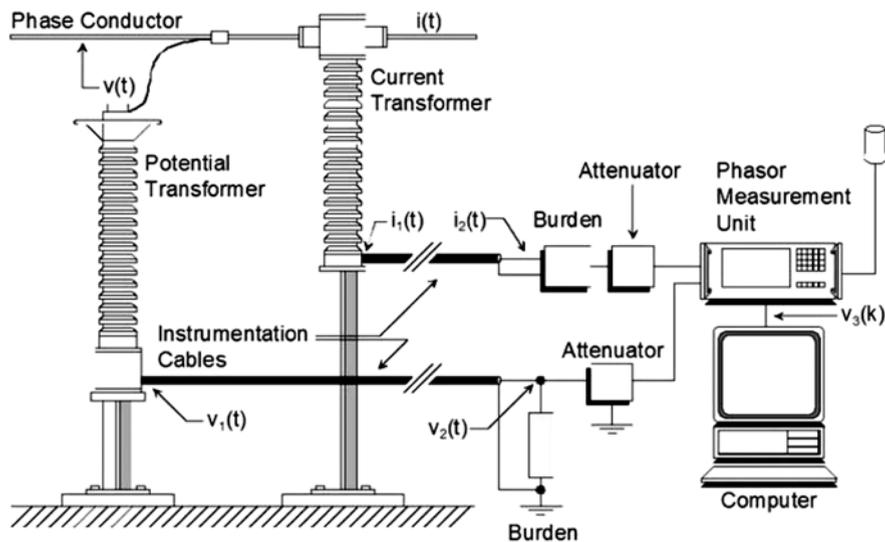


Fig. 1.7 A typical PMU installation—the instrumentation of only one phase is shown in [7]

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