12-2010

Concept for Next Generation Phasor Measurement: A Low-Cost, Self-Contained, and Wireless Design

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To the Graduate Council:

I am submitting herewith a thesis written by Brian Ray Miller entitled "Concept for Next Generation Phasor Measurement: A Low-Cost, Self-Contained, and Wireless Design." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

Fangxing Li, Major Professor

We have read this thesis and recommend its acceptance:

Leon M. Tolbert, Yilu Liu

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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A Thesis Presented for
the Master of Science
Degree
The University of Tennessee, Knoxville

Brian Ray Miller
December 2010

Acknowledgements

Thank you to my beloved wife, my kids, my parents, the faculty at the University of Tennessee, my fellow graduate students, and the United States Air Force.

Abstract

Phasor measurement is a growth technology in the power grid industry. With new funding, grid reliability concerns, and power capacity margin motivating a smart grid transformation, phasor measurement and smart metering are taking center stage as the implementation methods for grid intelligence. This thesis proposes a novel concept for designing a next generation phasor measurement unit.

The present generation phasor measurement unit relies upon venerable existing current and voltage transducer technology that is expensive, bulky, and not well suited to the modern age of digital and computerized control signals. Also, the rising proliferation of installed phasor measurement units will soon result in data overload and huge obligations for network bandwidth and processing centers. This brute-force approach is ill-advised. Forward thinking is required to foresee the future grid, its fundamental operation, and its sensor controller needs. A reasonably safe assumption is a future grid containing sensors numbering in the thousands or millions. This number of sensors cannot transmit raw data over the network without requiring enormous network capacity and data center processing power.

This thesis proposes a novel concept—combining existing technologies such as improved current transducers and wireless precision time protocols to design a next generation phasor measurement unit. The unit is entirely self-contained. It requires no external connections due to inclusion of high performance transducers, processor, wireless radio, and even energy harvesting components. With easy, safe, and low cost installation, proliferation of thousands or millions of sensors becomes feasible. Also,

with a scalable sensor network containing thousands or millions of parallel distributed processors, data reduction and processing within the network relieves the need for high bandwidth data transmission or supercomputing data centers.

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Chapter 1

Introduction and Overview

1.1. Introduction

The electric power grid delivers the energy to support the nation's economy. "Though today's grid is a 20th century engineering marvel, the smart grid of tomorrow promises to revolutionize how we manage our homes, offices, and factories while maximizing the use of next-generation clean energy resources" [1]. Today, the world's power grids make up the largest networks on the planet. In most cases, the basic power grid technology is roughly 100 years old with some additional modern components. The opportunity to fundamentally reinvent how energy is produced, distributed, and consumed by revolutionizing the grid is extraordinarily large [1]. Toward the goal of transforming the present grid into a modern marvel for the next century, a contemporary research movement is wide area grid monitoring and control.

Research is needed to provide a better understanding how future power grids can provide accommodation and leverage the use of distributed generation and energy storage technology as it develops. New renewable energy regulations and interested customers are creating a market demand for renewable energy, resulting in ever increasing installed penetration of intermittent renewable power generation systems. New policies involving climate change will encourage utilities and provide rewards for the use of renewable

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[1] General Electric, 2010.

generation [2]. Change is eminent and a fairly accurate prediction of the future grid would allow progress toward preparing for these future requirements.

At the University of Tennessee, a proposed Center for Ultra-wide Area Resilient Electric Energy Transmission (CURENT) seeks to enhance the capabilities of the existing power grid without major overhaul. Data is collected from existing utility sensor sources such as Phasor Measurement Units (PMUs) or from data recorders positioned throughout the United States by the university and its partners. This data is then used to monitor, visualize, and eventually control the power grid as the proper algorithms are developed, modeled, and tested via simulation. This thesis does not seek to reinvent the existing research or progress by others. Instead, this thesis looks beyond the existing power system to predict how the future grid will look and what sensors, especially the PMUs, it will most likely require.

This thesis proposes a novel combination of existing and developing technologies for combination into a next-generation sensor device for phasor measurement. This concept is likely to succeed in the future when the present generation of PMUs becomes increasingly unsuitable for application within a state-of-the-art intelligent power network. This proposal is also novel in terms of placing distributed computational abilities within the PMU itself—truly making the grid inherently "smart" and scalable without relying on any number of central processing facilities to derive intelligence for a "dumb" network of sensors.

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[2] EPRI, Portfolio, 2008, p.6-8.

1.2. Overview of Research Framework

Instead of a problem/solution research framework, this thesis will follow a similar construct—the evaluation research framework. After Chapter 2 establishes background information about phasor measurement topics, Chapter 3 presents the research method and criteria used for evaluation of the proposed PMU design versus existing models. These criteria will be used in Chapter 4 to analyze two important elements: current measurement and time synchronization. To ensure adequate academic rigor in research, this thesis mainly covers only these two aspects of the concept phasor measurement unit. Two other aspects are also briefly discussed: power harvesting and distributed data reduction/processing. These additional aspects are great topics for additional future research either by the CURENT center, industry, or graduate students. At the end of Chapter 4, a table summarizes the evaluation of the proposed next generation PMU versus traditional PMU technology. Finally, Chapter 5 presents conclusions and recommendations for future work.

Phasor measurement devices contain a broad range of materials and technologies from many disciplines including material science, electronics, magnetics, computer hardware, software programming, power systems, etc. Therefore, comprehensive coverage of all aspects of a next generation PMU is impossible within the scope of a single thesis work. The objective of this thesis is only to provide a conceptual vision of challenges the future grid will impose upon its PMUs. Then, a selection of possible solutions will be presented. This thesis may inspire future research into various aspects of this next generation PMU, provide motivation for industrial partnership with academia, and provide justification for research grants to perform related studies.

This chapter introduced the subject matter and explained the thesis research framework. The next chapter provides background information and literature review.

Chapter 2

Background and Literature Review

Proper understanding of next generation PMU concepts first requires detailed background information and review of current literature on the subject. Numerous excerpts from contemporary literature are included throughout this thesis, so this chapter will focus only on background material. The literature excerpts are referenced by concise footnotes. Full bibliographical information is provided in the list of references.

The United States power grid is used as an example in this thesis, but any other major power grid facing a "smart grid" renaissance is an equally compelling example. The grid is the system which forms the context and scope for all discussions of grid monitoring. Next, the term "synchrophasor" is defined as it relates to measuring the state of the power grid. The synchrophasor measuring device, the PMU, is discussed in its present state of technological development. The future power grid, its sensing devices, and its controls for management may be significantly different than what exists today.

2.1. Synchrophasor Measurement

The voltage angles throughout the power grid buses usually cannot be measured directly because of the geographical separation distance between the buses or nodes. However, time stamped measurements can be used to indirectly compute the angle. The active and reactive power flow through each line is calculated by using the voltage magnitudes and phase angles at these buses, along with the line impedance between two adjacent buses. The voltage magnitudes and phase angles of all the system buses are the state variables of the power system. All state variables must be uniquely determined for effective management of the power grid. Until recently, great difficulty was experienced when measuring the phase angles of the system in real time due to the challenge of synchronizing measurements over great distances [3]. One of the Electric Power Research Institute's (EPRI) objectives "is to upgrade the transmission grid to a machine that uses state-of-the-art systems engineering, information technology, sensors, communications, microprocessors, and visualization technologies to optimize performance and efficiency" [4]. This would automate the control of the power grid by detecting and predicting system behavior in order to make appropriate control decisions.

2.2. Phasor Measurement Units

The synchrophasor measurement device is called a phasor measurement unit. "Phasor Measurement Units (PMUs) are among the most interesting development in the field of real-time monitoring of power systems. PMU units provide real-time measurement of positive sequence voltages and currents at power system substations. Typically the measurement windows are 1 cycle of the fundamental frequency, and the measurements are time-stamped to a common GPS time synchronization signal. Data from substations are collected at a suitable site, and by aligning the time stamps of the measurements a coherent picture of the state of the power system is created" [5]. The results of a research study by Depablos et al revealed that data from tested PMU units is reliably accurate only at nominal frequency operating conditions. At frequencies off

[3] Chakrabarti et al, 2009, p.2452.
[4] EPRI, 2009, p.1.
[5] Depablos et al, 2004, p.1.

nominal system operation, every PMU tested produced a different phase and magnitude for a known voltage signal [6]. This error is produced by the instrument transformer and is addressed in later chapters of this thesis. The important fact to understand about PMUs is the insight they provide to system operators and researchers. Figure 2.1 is a visualization of the power system angles. To the trained eye, such visualization provides extremely important high-level information such as net power flow across wide areas and the wide area effects of acute power system events.

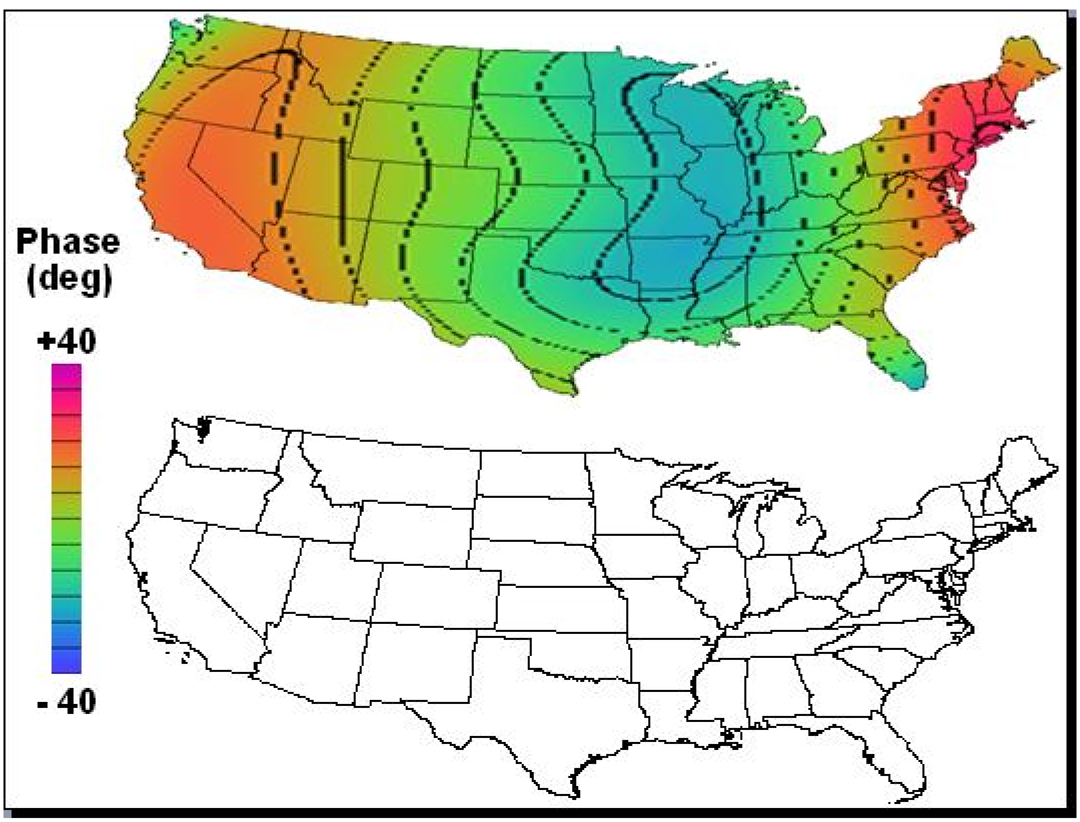

Figure 2.1. Wide area voltage angle visualization [7]

[6] Depablos et al, 2004, p.1.
[7] Premerlani et al, p.62.

According to the North American Synchrophasor Initiative (NASPI), PMUs are scheduled for installation at the following locations by 2014 [8].

• Major transmission interconnections and interfaces

• All 500kV and above substations and most 200kV and above substations

• Key generating plants (all > 500 MW) in generator switchyards, even on some individual generators

• Major load centers

• Large wind generators, solar and storage locations

• Other locations to assure visibility in areas with sparse PMU coverage

Also, additional functionality will be included within the PMUs of the future, with eventual unification of functions across all intelligent systems [9].

• PMU and DFR capabilities merging for monitoring and visualization

• Remote addressability for firmware upgrades

• Plug-and-play interoperability (interoperability testing will be required to assure this)

• Automated grid control capabilities linked to relays

• Local data storage to hold 2 weeks or more of data

• Linkage to communications architecture to support a variety of applications

• Higher speed data collection and delivery into real-time analytical system supporting tiers of applications (monitoring and alarms, SCADA and state estimation backup and enhancement, automated operations and protection, automated disturbance reports)

• More efficient at processing and publishing compressed data

[8] NASPI, 2009, p.2.
[9] NASPI, 2009, p.2.

• Self-diagnosis and return coordinates response

• Dynamic performance and measurement subject to technical standards

• Full Critical Infrastructure Protection (CIP) compliance

The primary motivation for this thesis is to ensure the future grid lives up to the challenge. With the PMU being such a vital component, this thesis's author anticipates a potential problem with conventional PMU technology's capability to meet the future needs. This problem is detailed in later chapters. One potential solution is wireless sensor nodes which are currently being developed for monitoring applications in other industries. "Recent advances in VLSI, MEMS, as well as in wireless communications technologies have made it possible to build sensor networks, enabling a paradigm shift in the science of monitoring. … These networks consist of a large number of densely deployed nodes that gather local data and communicate with each other and do not have a fixed architecture. Their nodes integrate sensing, computational and communications capabilities, and as a result of the resources scale with network size" [10]. Figure 2.2 shows a block diagram of a generic wireless sensor node which could be configured as a PMU for power grid application. "Ad-hoc deployable, wireless sensor networks can observe the environment in a fundamentally different way than previous classes of systems—close to the phenomena in question, over a wide area, and densely in both time and space. They may succeed in applications where traditional solutions have failed. This vision has captured the interest and imagination of many scientists. … Sensor networks hold the promise of revealing previously unobservable phenomena in the

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[10] Kompis and Aliwell, 2008, p.15.

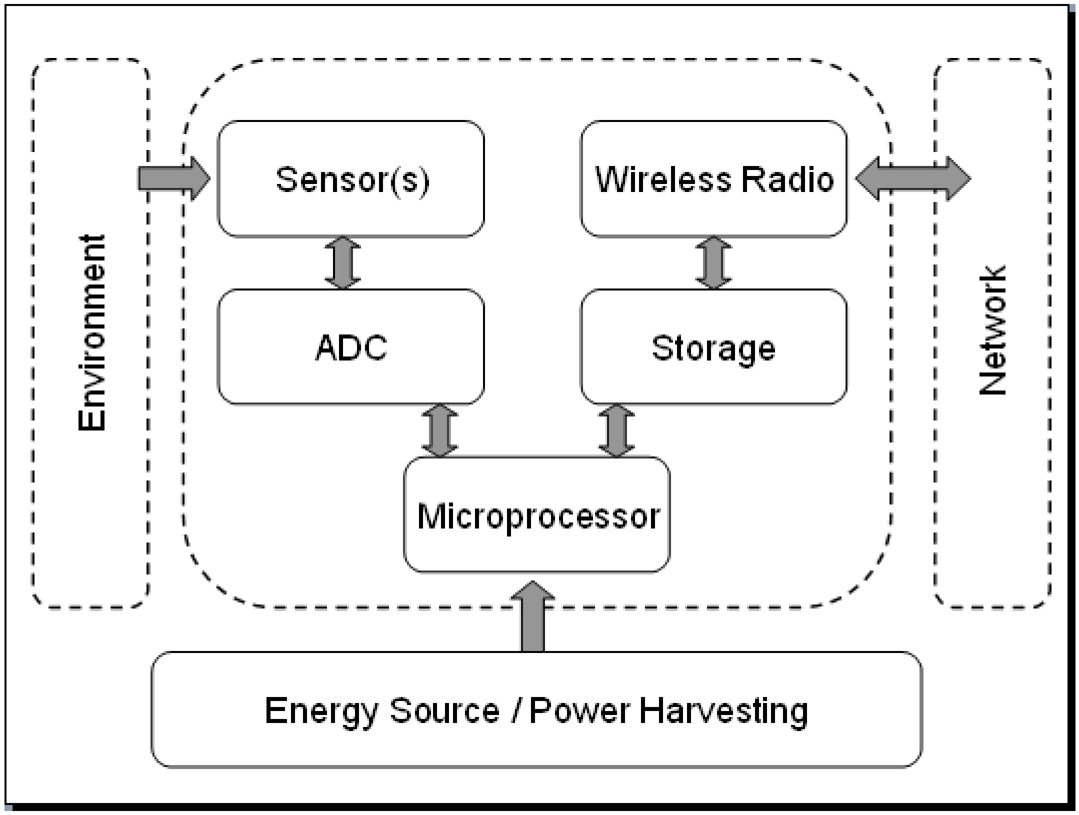

Figure 2.2. Typical architecture of a wireless sensor node [11]

environment. Eventually, such systems will also be capable of actuation—affecting the environment rather than solely observing it" [12].

Chapter 2 established adequate background information as a foundation for a research effort into PMU technology. Chapter 2 also provided several excerpts from current literature to illuminate the present state of PMU deployment, technology, and development. Next, Chapter 3 will establish a clear research method and evaluation

[11] Kompis and Aliwell, 2008, p.16.
[12] Elson, 2003, p.2.

criteria by which formal investigation can continue in a structured process. This thesis then investigates the selected criteria in detail in Chapter 4.

Chapter 3

Methodology and Evaluation Criteria

The research methodology of this thesis is per the standard evaluation framework. First, clear and justifiable criteria are established in this chapter. Then, in Chapter 4, the concept next generation PMU will be evaluated against the current PMU technology. This is accomplished via a strategy of collecting relevant information from highly credible primary sources such as academic papers. Two primary criteria are chosen for the task: adequacy of current sensing transducer and adequacy of wireless network time synchronization. Two additional PMU aspects (distributed processing and power harvesting) are not used as the primary focus of this thesis and are not listed as criteria in this chapter. However, these secondary aspects will also be explored in the next chapter. The research method attempts to establish clear quantifiable levels of measurement being used for evaluation if available. However, for some criteria no quantification is available and only a qualitative evaluation is possible.

3.1. Adequacy of Current Sensing Transducer

To determine the precision of state variables data obtained by using the PMUs, the corresponding measurement uncertainties within the unit must be evaluated. The main sources of PMU measurement uncertainties are: 1) the instrument transformers; 2) the analog interfaces between the instrument transformer output and the digital equipment input; and 3) the non-deterministic timing of the analog-to-digital converters

(ADCs) and the associated microcontroller or processor [13]. The adequacy of the current sensing transformer is determined by how accurately it completes all three steps in producing digital data that corresponds to the physical truth with the least error.

Conventional current sensors consist of an iron core and secondary windings to divide current as shown in Figure 3.1. Other technologies exist and each has strengths and weaknesses. These aspects will be evaluated and analyzed in the next chapter to determine the current sensor technology that holds the most potential suitability for future PMU application. For now, the basic issues are detailed so they can be used as evaluation criteria. Traditional iron core type current transformers (CTs) are the technology of choice for use in power systems to measure the conductor current and drive an analog relay coil to produce an action. The technology for the protection and

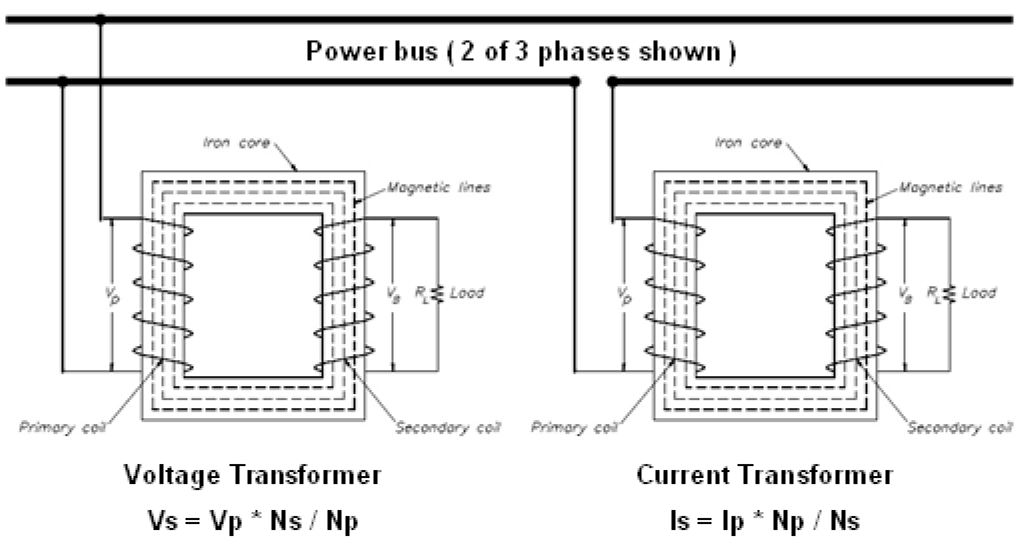

Figure 3.1. Illustration of existing instrument transducer technology

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[13] Zhu et al, 2006.

measuring system current has since become digital and the analog instrument transformers are no longer suited to microprocessor technology. This natural evolution of technologies drives an equal evolution in instrument transformer technology to include the other technical aspects described in the next paragraph [14].

First, as power systems upgrade for additional capacity (greater insulation for higher voltage levels and larger conductors for higher current), the matching current transformer becomes bulkier and costlier [14]. This also places additional mechanical strain on the components during fault due to the larger short circuit current capacity. Second, utility companies question the reliability of conventional current transformers. Tennessee Valley Authority and BC Hydro have experienced violent destructive failures of CTs which caused fires and impact damage to adjacent apparatus in the switch yard, electric damage to relays, and power service disruptions" [14]. Third, the iron core of the conventional CT imposes performance limits. Accurate measurements of fault current cannot be obtained due to magnetic saturation of the iron core. Also, because of the limited dynamic range of the CT, two separate CTs for metering and relaying are typically required at each measurement point [14]. Fourth, conventional CTs have a low bandwidth centered at the system fundamental frequency, making them undesirable for measuring transients or harmonics. Finally, the conventional CT is typically designed to output five amps at the rated primary current. However, this output can increase by an order of magnitude during fault and induce magnetic interference in PMU circuitry [14]. This can be mitigated by adding an additional isolator or another step-down CT, but these additional components add cost and further signal degradation.

[14] Carazo, 2000, p.195-196.

All the above mentioned limitations of the conventional CTs provide the strong motivation to find alternative ways to conduct current measurements [15]. There is one additional factor to consider in our evaluation of current sensors. According to Dr. Aleksandar D. Dimotrovski, a staff researcher at the Power and Energy Systems Group, Energy and Transportation Science Division, Oak Ridge National Laboratory, a recent challenge is creating a successful sensor to detect the existence of high impedance line faults, pinpoint their exact location, and keep record of fault occurrences which may appear only intermittently [16]. This application requires a current sensor that features this capability, therefore this thesis includes it in the evaluation criteria of a next generation PMU's current sensor. With the above requirements in mind, the current sensors of traditional and next generation PMUs will be compared in Chapter 4.

3.2. Adequacy of Wireless Network Time Synchronization

The second evaluation criterion for the future PMU is its time synchronization. The advantages of a wide area sensor network allow advanced measurement and control applications, but become more complex with larger numbers of nodes. "Most of these applications can be enhanced through the use of local clocks (for example, in sensors, actuators, or other devices) at each node to achieve an accurate distribution-wide sense of time. Each of these individual clocks, however, tend to drift apart due to instabilities inherent in source oscillators and environmental conditions such as temperature, air circulation, mechanical stresses, vibration, aging, etc" [17]. Various methods exist for

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[15] Carazo, 2000, p.195-196.
[16] Dimotrovski, Aleksandar D., 2010.
[17] Balasubramanian et al, 2003.

keeping accurate time over a wide area. The usual approach for PMUs is to include a GPS unit to synchronize timing with the satellite's atomic clock. To reduce the cost and power requirements of a GPS in each sensor, the sensors that have GPS can keep the non-GPS sensors in synch by using a time synchronization protocol as shown in Figure 3.2.

Timing is of upmost importance to phasor measurement. Even non-absolute time computations such as the determination of power system frequency depend on accurate internal timing. The three main algorithms for frequency measurement are period determination by the measurement of time interval between zero-crossings, Discrete

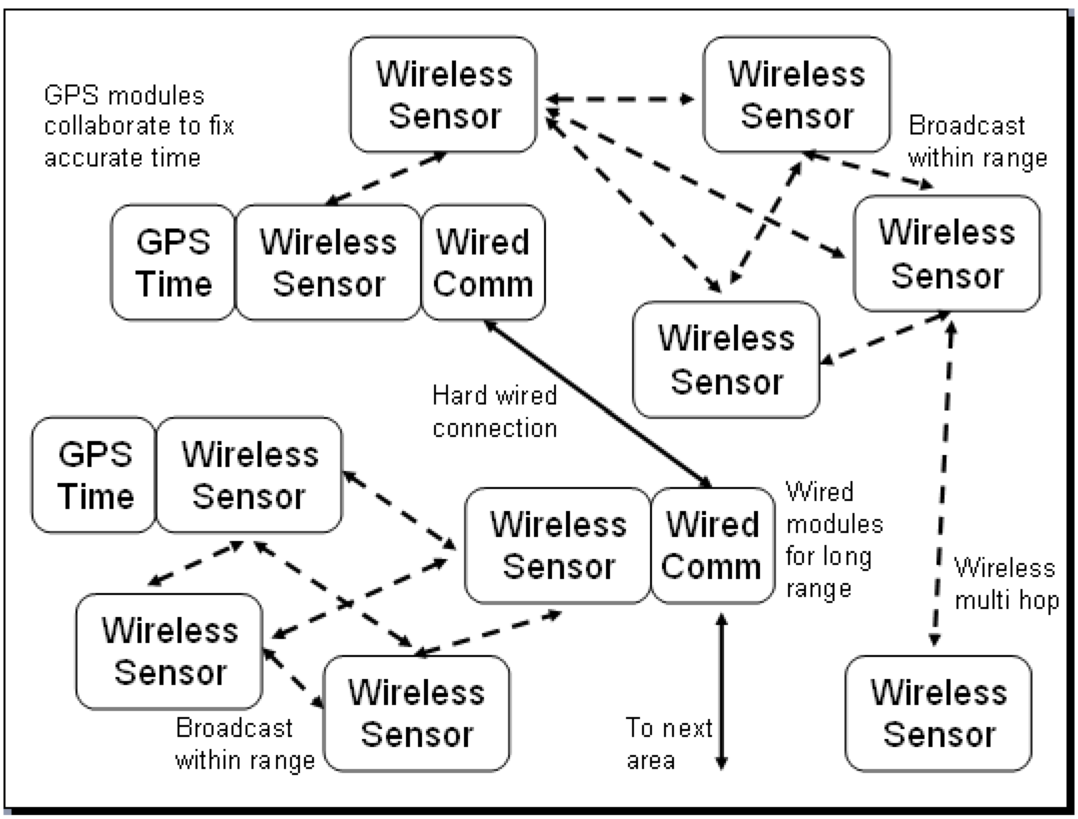

Figure 3.2. High level system timing view [18]

[18] Meier, 2010, p.13.

Fourier Transform (DFT) based techniques using the frequency domain, and orthogonal phasor decomposition to determine the period of rotation. The performance of the respective methods for frequencies other than the fundamental depends on the kind of disturbance. For example, zero-crossing methods remain accurate even with harmonic distortion, since they harmonics do not affect the fundamental period. Frequency transform methods must be implemented as block algorithms and therefore require from two to eight cycles to compute frequency. This reduces and flattens the transient response. All methods are highly sensitive to transient distortion [19]. Therefore, the variable nature of the power system frequency can wreak havoc on phasor measurement even if time synchronization is adequate. In the next chapter, the suitability of timing technology will be evaluated based on these aspects.

Chapter 3 defined the framework of this thesis as an evaluation format. The two criteria chosen for evaluation are current sensing and time synchronization. The requirements of each criterion were briefly explained. In the next chapter, each criterion is examined in greater detail in order to compare existing PMU technology versus the concept next generation PMU. Also, two additional PMU aspects will be examined: distributed computing and power harvesting.

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[19] Manana et al, p.2.

Chapter 4

Evaluation of Concept PMU versus Conventional PMU

By using the evaluation criteria established in Chapter 3, existing PMU technology will be compared to the concept next generation PMU. Results of this evaluation reveal two very important trends. First, existing PMU concepts seem likely to rapidly develop scalability problems and a lack of desired advanced features as the future grid takes shape. Second, although the concept next generation PMU proposed by this thesis is better for coping with future grid requirements, many shortcomings still exist and will require further study. The proposed CURENT center at University of Tennessee could use such shortcomings as topics for dozens of future papers and graduate thesis work. As each criterion is detailed, new opportunities for future study become apparent.

4.1. Overview of Concept Next-Generation PMU

This thesis proposes a simple yet powerful concept. This concept replaces a traditional PMU which is hardwired to existing substation current/voltage transformer (CT/VT) equipment, hardwired to the network, equipped with only basic analysis features, and time disciplined with GPS. Instead, the next generation PMU requires no connections at all—it can be simply clamped on or around a line conductor. It senses current and voltage by measuring the magnetic and electric field strength. It also derives electrical power for itself by harvesting a small amount of power from the magnetic field of the current carrying power line. Along with wireless radio communications, these features make the device completely self-contained and extremely safe due to total electrical isolation.

The small size, low cost, and easy installation of the concept PMU will enable viable deployment in the thousands. The next generation PMU also includes powerful features such as high-rate sampling to capture harmonic frequencies and high-precision sampling to capture tiny superimposed signals, such as those created by high-impedance line faults. Due to the high bandwidth nature of this data stream, along with sensor deployment in the thousands, raw data transmission will become impractical in the near future. Research in wireless sensor grids includes concepts such as data reduction (data is collaborated and concentrated as it hops from node to node) and distributed processing (data is processed in small increments by thousands of parallel processors). These concepts should be proactively implemented in the next generation PMU.

Communications between PMUs will be a hybrid of wireless and wired links. It is useful to connect wirelessly to the sensors mounted on high-voltage lines, but other nodes are better served by hardwired connection. For example, a hardwired node (or two for redundancy) at each substation premises can connect via hardwired internet for long haul communications, share this long haul communication the substation's many wireless sensors, and include more power-hungry modular components such as a GPS. Data and command signals must be able to flow both directions throughout the hybrid wired/wireless network.

A final yet vital aspect of the next generation PMU is its lack of fixed network architecture. The sensor net must self-reconfigure on its own because system architecture containing thousands to millions of sensors is impractical for human management. This means each sensor must be able to identify itself and its neighbors. For example, PMU #xxxxxxxx must be able to query its neighbors and determine that it is connected at the substation end of phase "B" of a tie line from generator #xxxxxxxx to substation bus #xxxxxxxx. Sensors must be able to fail, others must dynamically adapt by reconfiguring network architecture, and a maintenance notice must be sent to human operators. Time synchronization must also be architecture free. Some sensor nodes throughout the system will have internal GPS and thus have input toward collaborative time synchronization.

Figure 4.1 shows the author's prototype next-generation PMU. At the size of a large coin, it is designed to demonstrate proof-of-concept. It clamps around a conductor, measures the current in the conductor and measures the voltage field between the conductor versus an adjacent conductor or ground reference. Figure 4.2 is the test setup.

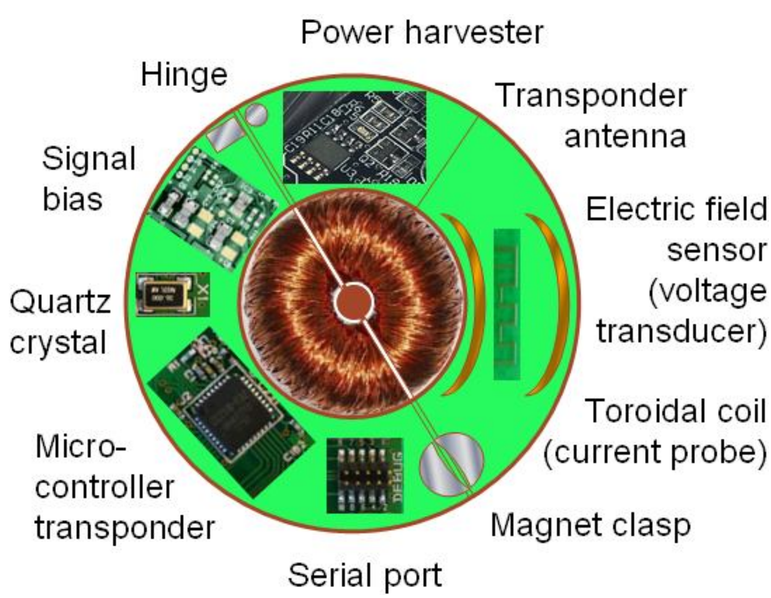


Figure 4.1. Author's concept PMU (complete system is 1.3" diameter disk)

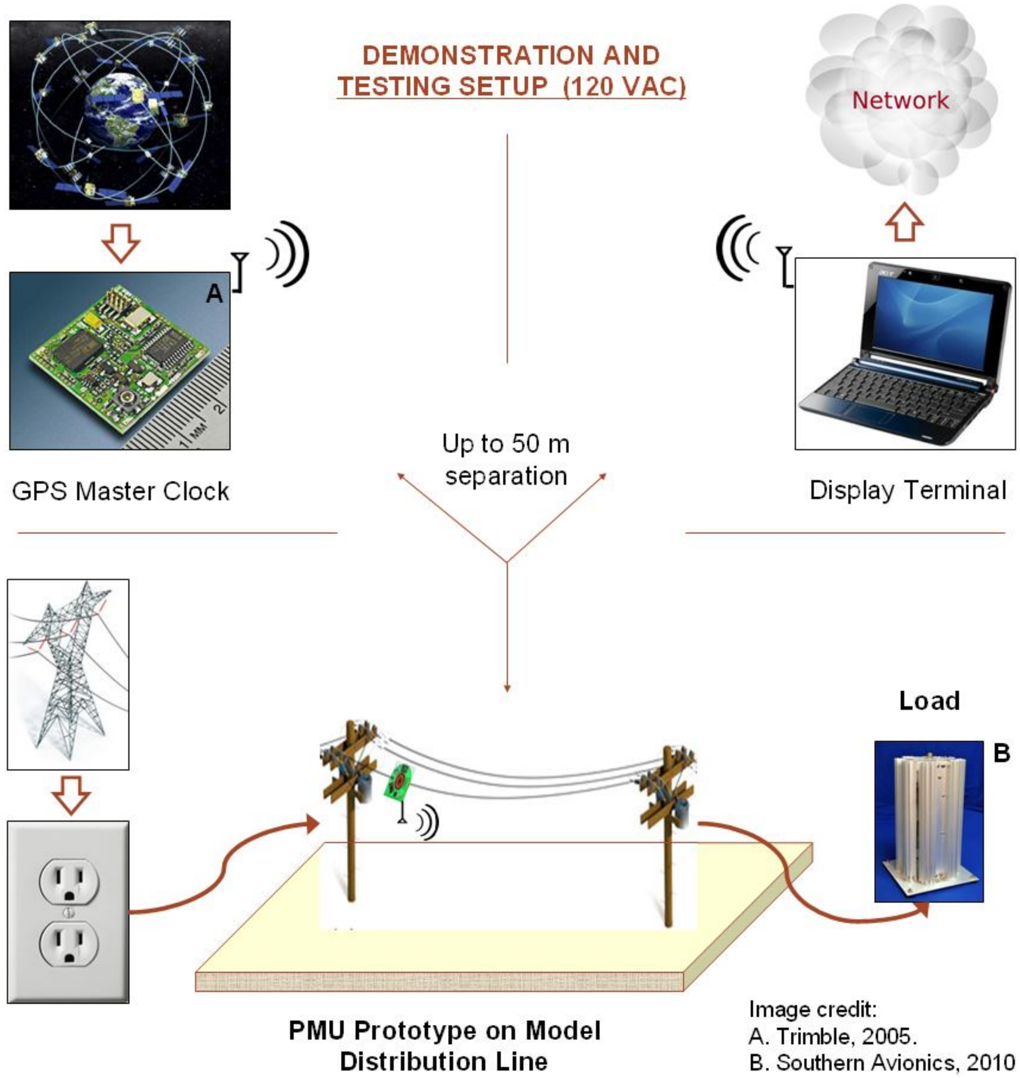


Figure 4.2. Author's test setup for concept next generation PMU

For testing and demonstration, the test stand of Figure 4.2 is employed. A photo of the actual rig during a presentation to the National Science Foundation is shown in Figure 4.3. A scale model power distribution line is connected between the wall outlet and dummy load (to create current in the line). The prototype wireless PMU can then be placed on the line. Elsewhere within wireless range (up to 50 meters with clear line-of-

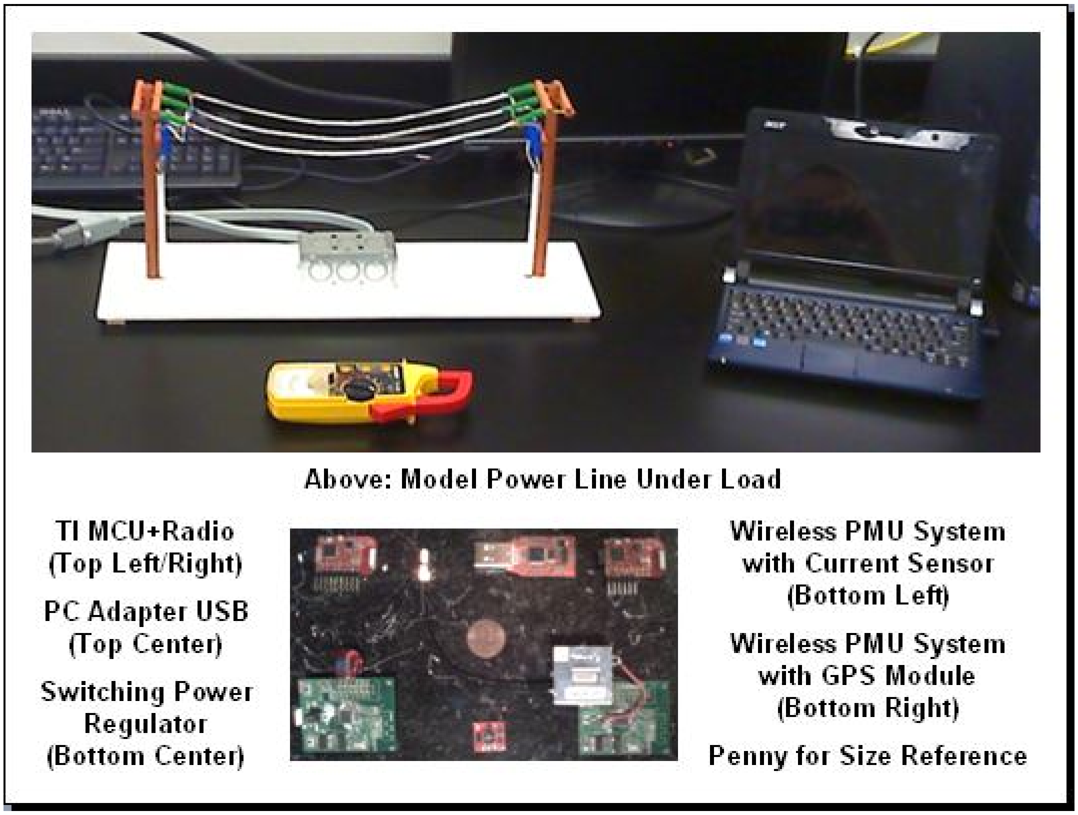


Figure 4.3. Author's hardware prototype and model power line

sight), another wireless node provides time synchronization by way of GPS discipline. Also within 50 meters (or less if walls or other obstructions attenuate the wireless signal), a notebook computer with wireless dongle is used to monitor data transmissions, display results, send commands, or interface the internet, but not to take any computational role

4.1.1. Specifications of Proposed PMU

Innovation, if intended to replace an existing technology, typically requires an order of magnitude (ten fold) improvement in order to succeed. To achieve this level of performance compared to existing PMUs, the next generation concept PMU relies on a combination of performance upgrades including the elimination of separate transformers, reduction of required GPS modules, and implementation of intelligent processing algorithms within each PMU for distributed data reduction. More detail on these features will be discussed in later chapters of this thesis. A final and extremely valuable benefit of the proposed PMU is the simplicity of installation. By merely clamping onto a line, installation costs are slashed by an additional order of magnitude.

An important aspect of the new PMU is that performance is not improved by applying faster processors or higher precision analog-to-digital converters (ADCs) because these are not the limiting factors in existing PMUs. Instead, the PMU is improved by developing solutions to measurement, timing, and algorithms. The author's proof-of-concept hardware relies on 16-bit processing such as the Texas Instruments MCU430 and industry standard 8086 core. However, a next generation PMU for production would benefit from a 32-bit processor. This would facilitate distributed data processing and leverage the low cost of today's chips without adding significant power demands (an acceptable trade-off must be found). Also, a 32-bit core allows for future firmware upgrades without imposing a 16-bit limitation.

Table 4.1 lists the desired specifications for the proposed next generation PMU. The most important features are high bandwidth for measuring harmonic current, low power consumption to enable self contained power harvesting, and internal data reduction capabilities to minimize the communications burden. Most other specifications are common to existing PMU technology according to IEEE Standard C37.118.

Table 4.1. Concept PMU specifications

Desired Specifications for Next Generation PMU			
Voltage measurement range	> 500 kV	Current measurement range	> 1,000 A
Voltage measurement precision	< 0.005 %	Current measurement precision	< 0.005 %
Voltage measurement frequency	> 7,680 Hz	Current measurement frequency	> 7,680 Hz
Voltage peak withstand	N/A (floating)	Current peak withstand	> 10 kA
Analog to digital converter	> 16 bit	Processor frequency	> 100 MHz
Frequency algorithm precision	< 0.0005 Hz	Processor data width	32 bit
		Processor power consumption	< 50 mA
Data storage	60 days	Processor features:	Hardware encryption
Data storage	4 GB		External memory
			Digital signal coprocessor
Environment temperature	< 150 ºF		Radio interface
Environment humidity	N/A (sealed)	Processor clock synchronization	< 500 ns

4.1.2. Cost Estimation and Comparison

The author's proof-of-concept hardware cost less than $100 for parts to produce timing and measurement accuracy comparable to a single channel of an existing PMU. However, the performance specifications did not meet the desired goals in Table 4.1. It is estimated that parts to build a successful prototype would cost $200 not including the cost of development, construction, and testing which could require over $10,000. Taken to production over the course of one to three years, the retail cost of each unit is estimated at $1,000 to $2,000. For comparison, a traditional PMU costs $14,000 on average. This alone is nearly an order of magnitude cost reduction. However, installation costs for an existing PMU typically exceed $20,000. The concept next generation PMU is trivial to install (requires a bucket truck and high voltage line workers) by simply clamping onto a power conductor. The installation of the proposed PMU is also expected to save an order of magnitude in labor costs.

4.2. Adequacy of Current Sensing Transducer

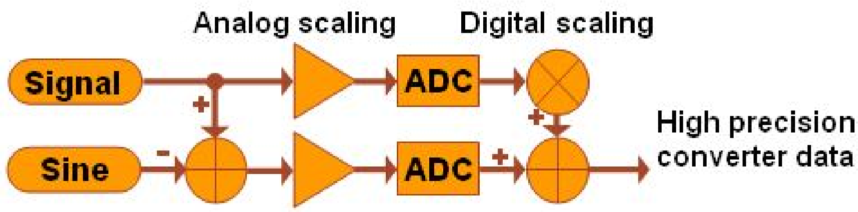
According to Dr. Isabelle B. Snyder, a staff researcher at the Power and Energy Systems Group, Energy and Transportation Science Division, Oak Ridge National Laboratory, existing PMUs communicate with different protocols [20]. Her work involves networking PMU systems so the data can accumulate in a common database for monitoring and research. Although the PMU itself is costly to procure and install, it requires a network connection which dominates the cost and difficultly of placing PMUs into the system. Also, these PMUs do not interface to the power line directly—they rely on current transformers (CTs) and potential transformers (PTs) for readable signals. This leads to other shortfalls with existing PMU technology. If no CT or PT is already installed, the installation cost and substation footprint can be cost prohibitive and unfeasible. Even if CTs and PTs exist, the type of device and differences between manufacturers can produce unacceptable variances in signal. The concept next generation PMU does not rely on the installation of separate CTs, PTs, or hardwired

[20] Snyder, Isabelle B., 2010.

communications. Therefore it avoids the cost, footprint, and possible variations in signal produced by various transducers.

Another aspect to consider is high impedance fault detection capability. If phasor measurement units are placed at each end of a line, the current passing through each sensor should be equal after correcting for line power loss. Even though this loss may vary due to environmental conditions such as changes in temperature affecting line resistance or changes in weather affecting the leakage current across insulators, a high impedance fault should be observable by intelligently monitoring line loss and applying appropriate algorithms. However, existing PMU technology lacks the required precision to detect tiny variations in current superimposed in a high current carrying power line. High precision current measurement allows for the detection and determination of location for high impedance faults. The next generation concept PMU includes a precision sine wave tracking converter along with a full-range converter (see Figure 4.4) to provide dynamic range impossible with traditional current sensing technology. It combines a typical DC-referenced ADC with a range five times the system voltage (for detecting surges/spikes), but also includes a sine wave (phase locked to grid frequency) biased ADC that focuses on detecting harmonics and other small signals with very high resolution. The same approach is used for current sensing.

Manufacturer variations in CT and PT performance are especially crippling for advanced PMU features such as power quality monitoring. Current transformers are non-linear devices and even if correction factors are implemented in software, higher harmonics drown in error because typical CTs are only designed to operate decently



	Range	Resolution	@120V	@13,800V
Low ADC	±2.5%	0.005%	10mV	1V
High ADC	±500%	1%		

Figure 4.4. Author's proposed tracking ADC for high precision sampling

around the vicinity of 60 Hertz. Newer current transducer technology, such as the closed loop Hall Effect sensor shown in Figure 4.5, is a potential solution. The drawback of closed loop Hall Effect sensing is the power requirement for the feedback coil. Another potential solution is a Rogowski air coil. Rogowski current coils are ideal for detecting pulsed and transient current in power systems because they have high bandwidth and low insertion impedance [21]. This is the transducer technology chosen for the next generation PMU. It lacks the ability to produce significant current and is thus unsuitable to drive the relays of the past. However, the high input impedance of digital microcontrollers is well suited to the Rogowski coil. Unfortunately, a drawback of this type of coil is its unsuitability for simultaneous power harvesting.

4.3. Adequacy of Wireless Network Time Synchronization

The next generation PMU must remain in tight time synchronization without using GPS within each sensor. GPS would dominate the power requirement of the PMU

[21] Hewson and Ray, 2003, p.1.

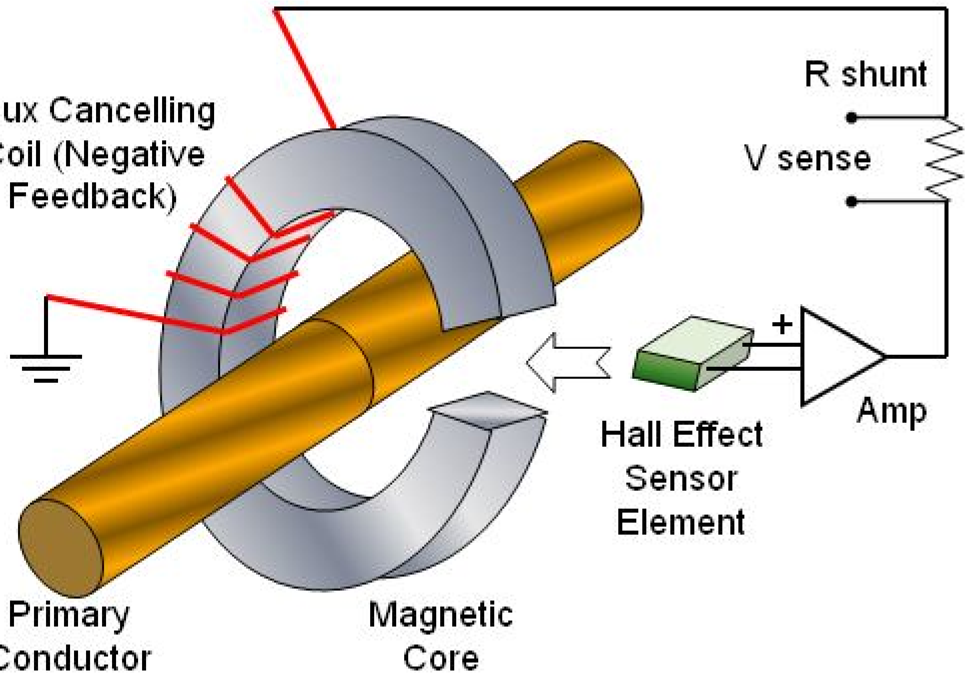


Figure 4.5. Basic topology of closed loop Hall Effect current sensor [22]

and require an antenna with sky view (may not be possible in all sensor locations). The next generation PMU relies on Precision Time Protocol (PTP) as defined by IEEE Standard 1588 to propagate time synchronization to the nodes without GPS. A prime application of the features of IEEE 1588 is electric power system that requires synchronization of measurements taken across a large-scale distributed power grid management system to enable smooth power dispatch and maintain power supply quality across a network of systems consisting of devices from many different manufacturers exposed to extreme heat and cold. "Reliability, durability and longevity are particularly important for power management, and timing accuracy is critical to maintain protection of the power grid. It is expensive to have a GPS device in every substation, especially

[22] Milano, 2002, p.3.

when IEEE 1588 could do the same job for a fraction of the cost" [23]. IEEE 1588 allows the connection of numerous devices with low-cost Ethernet cable, inexpensive hubs, and routing switches to synchronize their clocks within roughly 500 s using packet data alone. Devices with hardware-assisted PTP equipment, such as packet receipt timers, can increase accuracy of their clocks to the nanosecond range. Every PTP system must have one or more master clock, perhaps disciplined via atomic clock or GPS. Through a double exchange of time checking and reporting messages, each slave clock can determine the amount of delay and offset of its own clock and then synchronize itself to the master clock time. Without any deterministic (known latency) or hard wired connection, it is possible to get synchronization within 50 ns [24]. A diagram of the message-bouncing scheme is shown in Figure 4.6.

The synchronization interval must be delayed enough to minimize the network load and power consumption of the system, but short enough to keep the oscillator within an acceptable level of drift [25]. The synchronization interval is reduced until reaching a certain optimal period, which depends on the drift of the oscillator. A higher quality or temperature compensated crystal would require less frequent synchronization. Further increase of the message exchange frequency does not produce significant additional improvements. Based on the testing performed by Loschmidt et al, the optimal sampling time was chosen to be at an interval of 0.5 seconds. It has also been shown for an interval of 2 seconds or greater, the quality of the time stamp data is more important than

[23] Intel, 2009, p.17.
[24] Schreier, Paul G., 2009, p.1.
[25] Loschmidt et al, 2008, p.16.

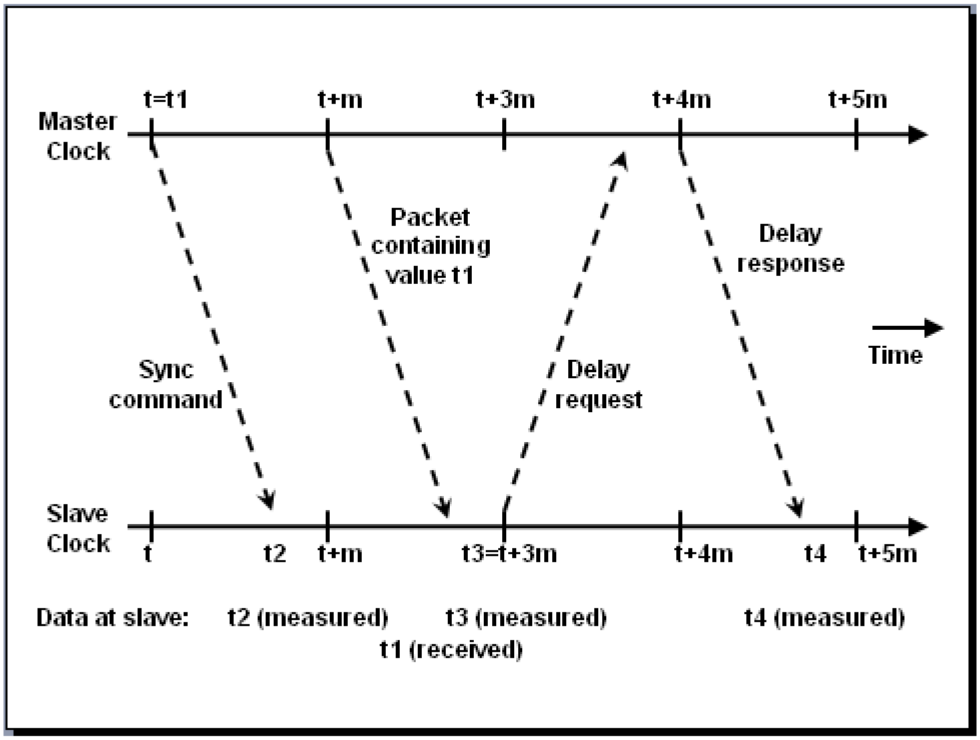


Figure 4.6. Synchronization of IEEE 1588 slave to master clock time [26]

the message latency [27]. The process is shown in Figure 4.7. The local oscillator (preferably a temperature compensated crystal oscillator) is compensated in software to match the timing provided by PTP messages. It is not recommended to correct time stamps only—the entire sensor must be in time synch in order to maintain proper sleep/wake cycles as a low power device and still receive prescheduled network transmissions.

By taking advantage of IEEE 1588, engineers find it much simpler and less expensive to improve timing rather than replacing all their dedicated equipment. “And if

[26] Schreier, Paul G., 2009, p.1.
[27] Loschmidt et al, 2008, p.16.

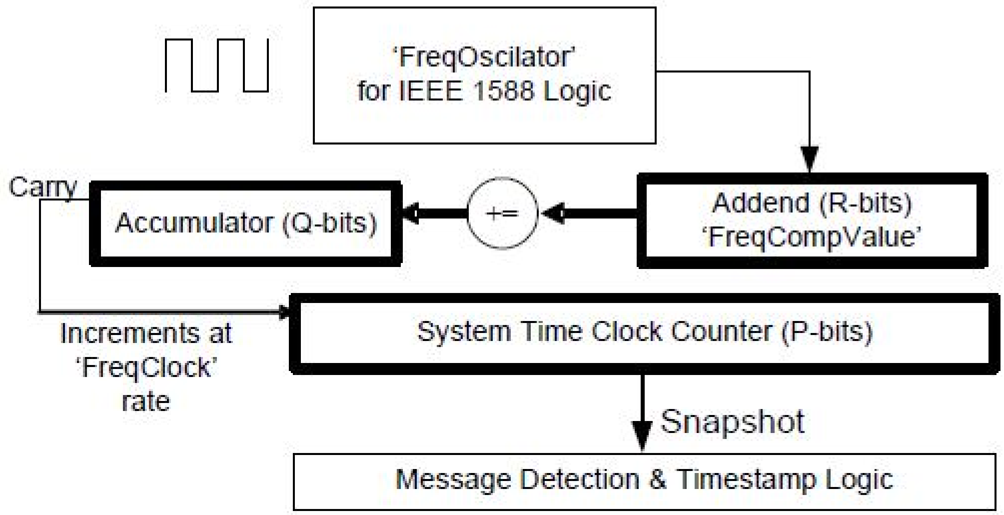
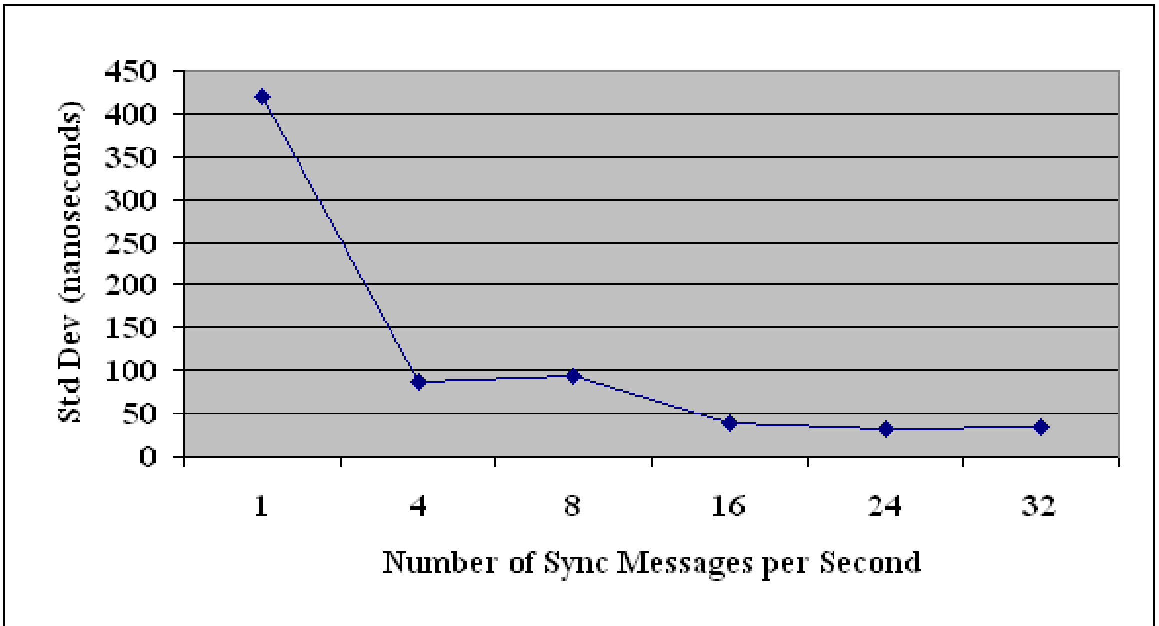


Figure 4.7. Frequency compensated clock logic [28]

you are going to invest in infrastructure, why not add nanosecond accuracy [29]?" As mentioned earlier, accuracy is affected by the number of PTP synchronization messages per second as shown in Figure 4.8. However, increased messages will require additional power and network bandwidth. A balance must be achieved and should be dynamic for best results (next generation PMUs near the GPS may need less frequent timing messages than sensors farther away, with more radio interference, etc).

As mentioned in the last chapter, the variations in power system frequency can cause inaccurate results even if sensor timing is precisely synchronized. This must be overcome in software. A potential solution is the Sezi algorithm as shown in Figure 4.9. Regardless of the approach or algorithm utilized, it must be tolerant of off-nominal system frequency. Many other approaches exist, but any method chosen for the next

[28] Intel, 2009, p.12.
[29] Schreier, Paul G., 2009, p.5.



F sync (hz)	1	4	8	16	24	32
Mean (ns)	5.82	-12.96	-15.49	-14.82	-15.23	-13.5
Std dev (ns)	421	86	94	38	31	35

Figure 4.8. Time synchronization for various sync message rates [30]

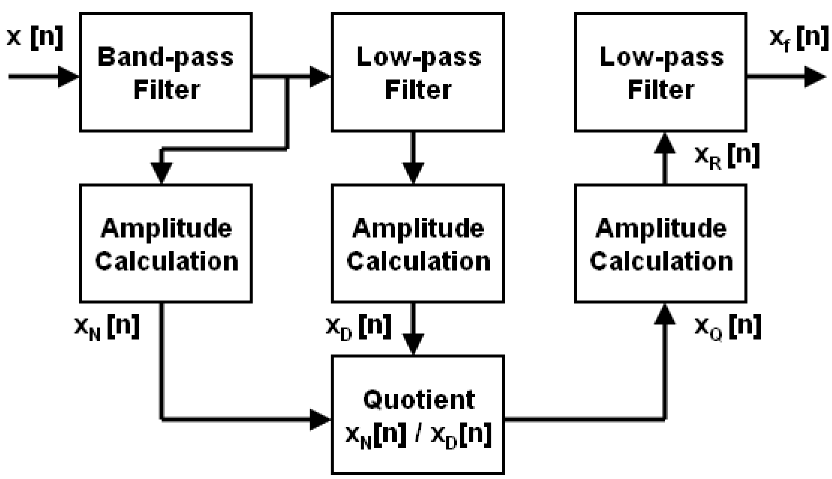


Figure 4.9. Sezi method frequency measurement algorithm [31]

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[30] Cho et al, p.6.

generation PMU must be capable of leveraging the precision time protocol synchronization to boost the accuracy of frequency measurement and also maintain accuracy during off-nominal frequency events. Often, the data obtained during grid disturbances is very informative for forensic study. Therefore, accuracy even during grid events is required to prevent false forensic conclusions based on inaccurate data.

4.4. Other Aspects of Next Generation PMU

Two other aspects of the next generation PMU are worthy of mention in this thesis. They are just as vital to the future success of this concept PMU as the current sensor and time synchronization aspects chosen for the focus of this thesis. First, decentralized distributed data processing allows the network to scale into the thousands or millions as envisioned for the future grid. Second, power harvesting is a key requirement for the operation of this concept PMU due to the fact it has no connections to any source of power or ground.

4.4.1. Distributed Processing and Data Reduction

Centralized processing is not feasible in large scale sensor networks. Such a design requires a practical way to transmit every raw sensor value generated throughout the network to a single data center for processing. Even in a traditional distributed network, this would be unwise. Scaling becomes clumsy or impossible, and a single point of failure can affect the entire system, making the system much less robust. In sensor networks, centralization is particularly fatal due to a requirement for energy

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[31] Sezi, T., 1999.

efficiency beyond that required in other distributed systems [32]. For traditional PMUs, the raw data is transmitted to data concentrators and then forwarded to a central control center. Even with this approach, scalability is limited and the inherent massive parallel processing power of the sensor network is not utilized. "The use of local processing, hierarchical collaboration, and domain knowledge to convert data into increasingly distilled and high-level representations or data reduction is key to the energy efficiency of the system" [33]. An ideal system would reduce the data as much as possible as early as possible, rather than transmitting raw sensor values further into the network. Many of the different data reduction schemes depend on time synchronization in order to recognize simultaneous events. One example is duplicate suppression, a form of collaboration that prevents redundant notification of an event by more than one sensor in the network of nearby sensors that observed the same event. In some cases, data reduction within the network takes the form of multi-sensor collaboration to determine a joint measurement. For example, transmitting the phasor vector result is far more efficient than sending a complete time series of raw voltage measurements from all of the sensors. This improvement becomes increasingly significant as the sensor locations become further in distance from the ultimate destination (the data processing center or operator) [34].

4.4.2. Power Harvesting

The final additional aspect of the next generation PMU is power harvesting. High bandwidth sensor elements, such as magnetic and electric field transducers, must be

[32] Elson, 2003, p.32.
[33] Elson, 2003, p.38.
[34] Elson, 2003, p.38.

designed and perfected for next generation PMUs. A potential area of research is the creation of a current sensor that can simultaneously scavenge power from the magnetic field of the line it is monitoring. The harvested power is utilized to operate the entire PMU for its entire lifetime without batteries. Research can be conducted to determine if switch-mode current sensors are a potential solution for overcoming the undesirable non-linear nature of analog current transformers. "Monitoring line conditions, disturbances, and faults is essential to ensure proper operation of a power system. Autonomous wireless sensors are key future elements which will keep such monitoring simple, easy, and cost effective. Such sensors will probe the necessary currents, voltages, and impedance properties of a power line in a non-intrusive manner and then relay such data to a decision station wirelessly" [35]. A very promising solution for the energy needs of the internal circuits within wireless sensors is to scavenge energy from the sensor's environment. However, numerous power harvesting schemes presented in literature are either unsuitable for use on power lines or cannot provide adequate power to enable the processing and radio power requirements of wireless sensors. A thesis presented by Bhuiyan et al describes a novel "energy coupler" by which wireless sensors can harvest magnetic field energy from the current carrying conductors of power lines. "The energy coupler is constructed by winding hundreds of turns of very thin conducting wires around a core made by shaping a few layers of flexible high permeability magnetic materials (mu-metals) to enclose a power line conductor ensuring maximum magnetic flux

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[35] Bhuiyan et al, 2010, p.1249-1250.

coupling. A comparable (but not identical) structure to this energy coupler is a Rogowski coil" [36].

Like large power generation and transmission systems, the impedance and voltage/current profile must be matched so the energy harvested can be utilized without excessive losses. "Any inefficiency in the conversion electronics associated with an energy-harvesting device can dissipate that hard-won energy almost entirely" [37]. Figure 4.10 shows the power consumption of a low-power wireless sensor such as the concept PMU. Low-power operation involves keeping the radio powered down as much

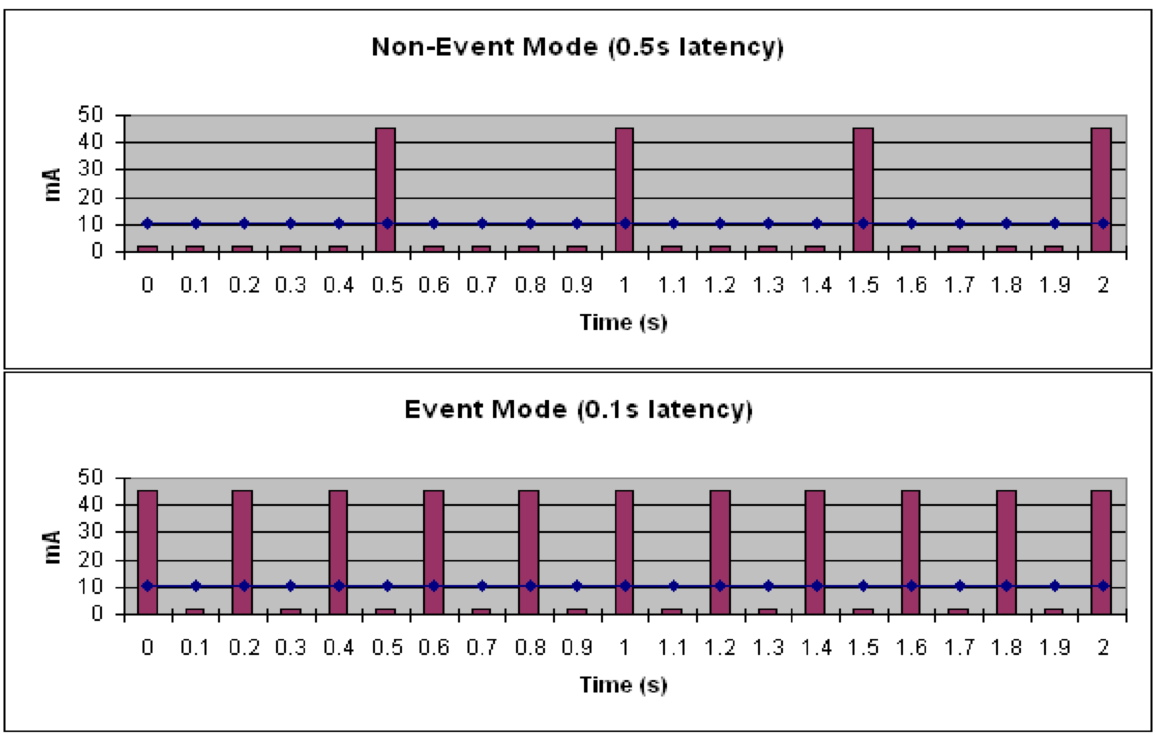

Figure 4.10. Power harvesting (lines) versus power consumption (bars)

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[36] Bhuiyan et al, 2010, p.1249-1250.
[37] Kompis and Aliwell, 2008, p.22.

as possible in order to minimize the size of the required generation via power harvesting. To calculate power requirements, several parameters are required. For power consumption, the "active radio" and "radio off" current draw and duty cycle are required. It is assumed that the processor will remain always active, drawing a near constant current, to process data and queue the results for later transmission. The minimum required power harvest generation is roughly equal to the average current draw of the processor and radio (assume these two components dominate the power draw of the entire device).

In general, the following equations can be utilized to estimate power harvesting requirements. Start by working backward from power consumption, given by simple multiplication of the direct current voltage and average current of the entire PMU.

$$\mathbf{P_{ave}^{consumed} = V_{dc} * I_{ave}^{consumed}}$$

As mentioned earlier, the PMU power is dominated by the processor and radio. It is assumed that the processor will run constantly and the radio will run intermittently with a low duty cycle "D". Therefore, the average current is approximated by a simple sum.

$$\mathbf{I_{ave}^{consumed} \approx I^{processor} + I^{radio} * D}$$

The duty cycle is given by the ratio of active time "τ" over the repeating period "T".

$$\mathbf{D = \tau / T}$$

Now that average power consumption is calculated, the minimum output of the power harvesting circuit can be computed. The device is designed to operate at minimum power generation which occurs when the minimum ambient energy is available for harvesting. In the PMU concept case, this occurs when the minimum expected value of current is flowing on the power line. Also, the efficiency "η" of power transfer (mostly resistive loss in the coupling transformer winding and voltage drop in the voltage regulator) from the generator to the PMU supply rail must be compensated.

$$\mathbf{P_{min}^{generated} = P_{ave}^{consumed} / \eta}$$

Since the energy is harvested from an alternating magnetic field, the power generated is alternating current. The average power generation is given by integrating one period

$$\mathbf{P_{ave}^{generated} = T^{-1} \int^{T} p^{generated}(t)\, \partial t}$$

Where the product of sinusoidal voltage and current is usually constant for a given line current (depending on number of coil winding, voltage gain is inversely proportional to current reduction) assuming the device is designed to avoid saturation.

$$\mathbf{p^{generated}(t) = p^{coil}(t) * p^{coil}(t)}$$

Finally, the energy stored in the PMU storage (super capacitor for example) is given by

$$\mathbf{E(t)^{stored} \approx (P_{ave}^{generated} - P_{ave}^{consumed})* t \qquad 0 \le E(t)^{stored} \le E_{max}^{capacity} \qquad t \ge 0}$$

which is a valid approximation if the storage capacity is orders of magnitude larger than the capacity depleted during each period.

For the author's prototype, the radio is active for 0.1s every second and draws 50mA at 3.3 volts. The processor is always active and draws 0.2mA at 3.3 volts. This gives an average draw of 5.2mA—well within the realm of power harvesting's capacity. The harvesting device is then designed to produce this capacity at the lowest expected value of primary line current (higher current will provide excess power for the PMU most of the time). Depending on the variability of line current, energy storage (a super capacitor for example) will be required to provide a minimum of 30 minutes of unpowered operation. For the author's PMU hardware, this corresponds to 2.6mAh.

This chapter provided a detailed examination of two primary criteria for the next generation PMU: current sensing and time synchronization. Traditional current sensing technologies are bulky, expensive, dangerous, and inaccurate. A new concept for current sensing is needed and Rogowski air coils are a proposed solution. For time synchronization, traditional PMUs rely on a built-in GPS. However, the next generation PMU must not rely on internal GPS because of power consumption, cost, and sky view concerns. Precision time protocol (PTP) over wireless link is a proposed solution. This chapter also examined two additional aspects of a next generation: distributed computing and power harvesting. A summary of findings is displayed in Table 4.2.

Table 4.2. Evaluation of traditional PMU versus concept PMU

	Traditional PMU	Concept PMU
Current Sensing	External CT required: requires footprint, cost, and non-trivial installation; can be unsafe and inaccurate; useful only for 60hz signal	Accurate internal CT: saves space, cost, and makes installation trivial; allows total isolation for safety; features high bandwidth
Time Synchronization	Internal GPS required: draws power, adds cost, and needs clear sky view; no collaboration to improve timing precision	Network PTP required: timing collaboration; fewer GPS units to save cost; each PMU saves power and does not require sky view
Distributed Computing	Raw data transmitted over network to a small number of data concentrators, then to central processing center: requires high capacity network and data center	PMUs closest to data source perform data reduction and share in data processing: requires least amount of network capacity; no data processing center needed
Power Harvesting	Not a low power device: needs a plug or maintained battery for operation; not suitable for remote areas	Low power device: capable of harvesting power for self-sufficient operation; ideal for remote areas

Chapter 5

Conclusions and Recommendations

This thesis evaluated concepts for a next generation PMU. The research delved into two different evaluation criteria (current sensing and time synchronization) and touched on two additional aspects (distributed computing and power harvesting) for the future success of the concept. As research progressed, many assumptions were required to predict what a future intelligent grid would require for monitoring and control. Therefore, additional research in predicting future grid requirements would be extremely valuable.

5.1. Conclusions

The future grid is likely to require thousands or millions of PMUs to optimize grid monitoring and management. A novel PMU concept was proposed to eliminate the need for traditional current and voltage transformers. It would rely on wireless short range communications, provide advanced distributed processing capabilities, and harvest its own power. By eliminating traditional transducers, the next generation PMU is able to avoid non-linearity errors, installation costs, and safety concerns. By also relying on wireless communications and power harvesting, the next generation PMU needs no external connections, becomes fully self-contained, and is trivially easy to install. This makes deployment in the thousands or millions possible, but leads to additional requirements for time synchronization and data processing. The time synchronization issue is overcome using IEEE 1588 Precision Time Protocol (PTP) over wireless radio link from the few nodes possessing GPS satellite time discipline. Distributed parallel data processing within the sensor network was proposed as a solution to the data reduction and processing issue. By placing the processing within each sensor unit instead of a central processing center, the intelligence truly exists within the "smart" grid itself. By all the above factors, the next generation PMU will outperform the traditional PMU and also fulfill increased demands of the future grid.

5.2. Recommendations

This thesis highlights gaps in phasor measurement technology and makes it easier to focus future research in the most appropriate directions. This thesis evaluated a conceptual design for a new generation of PMUs by looking at several focused criteria. As each criterion was researched, a better understanding of the future grid was revealed, yet much remains uncertain. These revelations may illuminate a vision to help gain an understanding of what the future grid may be. Even if these predictions are inaccurate, the task is beneficial for motivating new innovations. However, the shortcomings identified by this thesis also show a lack of information and a need to better understand the aspects and details of the future grid. Therefore, it is highly recommended that further research be conducted to predict what a future intelligent grid would consist of. Then, given this vision of the future grid, what would it take to monitor and control it? The answers to the questions could very well change the future grid outlook, change the criteria for the next generation PMU, and allow the necessary innovations to commence. The grid of the future will be a true marvel of engineering.

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Vita

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