

An Architecture for Wireless Sensors in Distributed Management of Electrical Distribution Systems

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Abstract

This thesis presents a distributed architecture for the use of wireless sensors in the management of electrical distribution systems. Although the general concept of using wireless sensors for measuring quantities of power lines has previously been introduced, the proposed solutions have not been well integrated within the power system equipment and the automation system. This has severely compromised the applicability of the sensors in the field. However, wireless sensors have several features that make them an attractive instrumentation solution in the harsh environment of electrical distribution networks. Wireless sensors do not need signal or power cables and they are therefore easy to install and use in system refurbishment. They thus provide an interesting and cost effective alternative that is worth studying.

In this thesis, the concept developed for enhancing the applicability and integration of wireless sensors within the power distribution system is based on an architecture that uses the properties of the system itself to preserve functionality and to minimise the power consumption and thus the size and weight of the wireless sensors. In this architecture the following essential components and aspects are identified.

First, a time synchronisation method for wireless sensors is developed. The main goal with this method is to provide energy optimised means to determine the phase angle in wireless sensor cells where several sensors measure phase current and one sensor measures voltage. Secondly, a fault detection and location method with wireless sensors is proposed. This method enables implementation of fault management using wireless sensors that operate autonomously and asynchronously and measure only phase current. With this approach the hardware and software implementation of a sensor can be simplified compared to previous solutions. The combination of these developed methods enables the construction of lighter, smaller and more flexible wireless sensors. Consequently, the ability to integrate the sensors within components and equipment as well as their robustness and functionality are enhanced.

Third, an architecture for the distributed management of electrical distribution networks is developed. The primary intention with this architecture is to provide a distributed computing platform that integrates the wireless sensors within the automation system and manages the related functionality in a controlled and simple way. The developed architecture also creates a generic concept for distributed and local control in the management of electrical distribution systems. This concept will be valuable in the future when the vast amount of data produced by sensors must be locally processed to avoid saturating the communication and computational resources of the control centre.

Keywords: Wireless sensors, time synchronisation, agent technology, distribution automation communication, distributed fault management, distributed state estimation.

Preface

This research work has been carried out in the Power Systems and High Voltage Engineering Laboratory of Helsinki University of Technology during the years 2000-2004. The Graduate School of Electrical Engineering, the Academy of Finland, the Technology Development Centre Tekes and the ABB Corporate Research Centre in Finland have mainly supported the work. This support is gratefully acknowledged.

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Espoo, September 2004

Mikael Nordman

Publications

This thesis consists of the present summary and the following publications, referred to as Publications I – VI.

- I M. Nordman, W. Kozlowski, and O. Vähämäki, A Method for Synchronising Low Cost Energy Aware Sensors used in Industrial Process Monitoring, 27 Annual Conference of the IEEE Industrial Electronics Society, Denver, Colorado, USA, Nov 28 – Dec 2, 2001, 7 pp.
- II M. Nordman, M. Lehtonen, and O. Vähämäki, Managing Concurrent Duties and Time of Wireless Sensors in Electrical Power Systems, IEEE Conference on Emerging Technologies and Factory Automation, Lisbon, Portugal, Sept 16 – 19, 2003, 8 pp.
- III M. Nordman, and M. Lehtonen, A Wireless Sensor Concept for Managing Electrical Distribution Networks, Accepted for publication in the proceedings of the IEEE PES Power Systems Conference & Exposition, New York, USA, Oct 10 – 13, 2004, 8 pp.
- IV M. Nordman, T. Nieminen, and M. Lehtonen, Characteristics of Wireless Sensors for Electrical Distribution Networks, IEEE Conference on Mechatronics & Robotics, Aachen, Germany, Sept 13 – 15, 2004, 7 pp.
- V M. Nordman, and M. Lehtonen, An Agent Concept for Managing Electrical Distribution Networks, Accepted for publication in the IEEE Transactions on Power Delivery, 2004, 9 pp.
- VI M. Nordman, and M. Lehtonen, Distributed Agent Based State Estimation for Electrical Distribution Networks, Accepted for publication in the IEEE Transactions on Power Systems, 2004, 8 pp.

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PUBLICATIONS I-VI

Acronyms

ADC	Analogue to Digital Converter
ANSI	American National Standards Institute
ASIC	Application-Specific Integrated Circuit
ASK	Amplitude-Shift Keyed
ATP	Alternative Transients Program
DA	Distribution Automation
DC	Direct Current
DEM	Distribution Energy Management system
DNP	Distributed Network Protocol
DSP	Digital Signal Processor
DSSS	Direct Sequence Spread Spectrum
EMTP	Electromagnetic Transient Program
EPRI	Electric Power Research Institute
FFT	Fast Fourier Transform
FHSS	Frequency Hopping Spread Spectrum
FIFO	First In First Out
FIR	Finite Impulse Response
FPGA	Field Programmable Gate Array
GPS	Global Positioning System
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISM	Industrial, Scientific, Medical
LED	Light Emitting Diode
MCU	Microcontroller Unit
MEMS	Micro-Electrical Mechanical Systems
NIS	Network Information System
NTP	Network Time Protocol
OOK	On-Off Keyed
PLC	Power-Line Communications
RBS	Reference Broadcast
RC	Resistor Capacitor
RF	Radio Frequency
RMS	Root Mean Square
SCADA	Supervisory Control And Data Acquisition
TCP	Transmission Control Protocol
UCA	Utility Communications Architecture
VAR	Volt Ampere Reactive

1 Introduction

Distribution automation (DA) refers to the efficient management of modern electrical distribution systems so that customer demand for safe and reliable access to electricity is satisfied. DA comprises a set of functions and a set of information systems that form the toolbox for network operation and management. Typical functions are the identification and analysis of network disturbances, substation control and distribution system state monitoring. Some typical information systems are the network information system (NIS), which is used for network planning, asset management and operation support, the distribution energy management system (DEM), which is used for energy acquisition optimisation and monitoring of energy consumption, and supervisory control and data acquisition (SCADA).

SCADA is the technology used to perform remote monitoring and control of DA equipment and processes in the power system. It has traditionally been based on a concept where the central host (generally called the master station) remotely monitors and controls field devices (the slave stations), which are geographically dispersed over a wide area. Communication in this system occurs over peer-to-peer links of different type (e.g. microwave, radio, dial-up telephone, and optic fibre), where the chosen type has been determined by the distance, location and cost of communicating with the remote site. Some typical SCADA protocols being used today are Modbus, ANSI X.3.28, IEC 60870-5-101 in the European and South American markets, and DNP3.0 in the North American and Australian markets.

Both manufacturers of DA equipment and utilities expect that the near future will bring changes in how communication between the network control centre and the field devices is organised (CIRED, 2003). Today, it is common to assess the applicability of TCP/IP (Transmission Control Protocol/Internet Protocol) as a protocol option in new installations. TCP/IP was developed by research groups in the USA in the late seventies and became during the next twenty years the de facto standard for communication between computers and information systems (Comer, 1995). TCP/IP is today used in all relevant telecommunication systems and is also considered to be the preferred platform for communication in large distributed control infrastructures.

Reduced equipment and engineering costs as well as improved interoperability are the main reasons for using TCP/IP in DA communications. With a common transport and network protocol, system integration and configuration become simpler (CIRED, 2003). However, because the life cycle of field devices and system components is substantially longer in power engineering than in telecommunications engineering, adaptation to TCP/IP will occur step by step. IEC 60870-5-104 is an example of this evolution. This is an IEC 60870 companion standard where the application layer data structures have been mapped on top of TCP. Eventually the aim is to extensively integrate TCP/IP and packet switching into all layers of the DA communication architecture. This development is further emphasised in the substation communication standard IEC 61850, which is a world-wide effort to develop a standard for the communication and object oriented data modelling of substation automation systems having TCP/IP as the preferred transfer protocol.

IEC 61850, derived from the Utility Communications Architecture (UCA) platform, is significant in other aspects as well. The standard provides a step towards a view of field devices as objects and object structures with common interfaces, properties and distributed functionality. The goal with this approach is to simplify system engineering and promote the harmonisation of information exchange between intelligent electronic devices (IEDs), which are responsible for various functions such as local monitoring, control, protection and diagnostics of the power system and its substations (CIGRE, 2003). Since the introduction of microprocessor based control devices, one of the strongest trends in DA has in fact been the increasing number of IEDs in the field. This has led to concerns about how to utilise, process and transfer between hosts the enormous amount of available information in a feasible and cost efficient way (Buse, 2003). In addition, centrally managed, these complex automation infrastructures, being a result of the interconnection of highly distributed intelligent control devices, pose a risk of generating widespread and cascading disturbances that the control centre is unable to handle (Amin, 2001).

According to (Wildberger, 1997) and (Amin, 2000), these problems can be mitigated by distributing control to different levels in the automation hierarchy and by delegating as much of the control to local IEDs as is practical and safe. There are many benefits with this approach. Local intelligence limits the information that is communicated to hosts outside the local control area, decision making is close to the phenomenon, and failures can be mitigated before their consequences are spread to other parts of the power network. Local and distributed intelligence also means that the SCADA computing facilities and the need for high data rate and reliable communication links become less critical.

IEDs with local intelligence are well suited for implementation as active objects (or agents) (Amin, 2001) (Amin, 2002) (Vishwanathan, 2001). These are, simply stated, objects that can sense the environment and take autonomous actions based on the input from, and knowledge about, the environment and the state of the system they belong to (Wildberger, 1997). In fact, protective relays and process controllers can be considered examples of active objects that participate in the management of the current power system. If development in computing and communications technology continues as in the past, the importance and role of these distributed, local and intelligent active controllers will significantly grow as well.

The increasing number of IEDs, local control and agent technology are not the only trends in advanced DA. At the bottom of the DA architecture, instrumentation transducers are becoming increasingly important and the number of such devices installed is constantly growing. Conventionally, sensors in the power system are used to measure, for example, voltage (by resistive or capacitive voltage divider), current (by iron core or air core coil), temperature, pressure and moisture (Luxa, 1998). Measurements have typically been transferred over point-to-point connections (4-20 mA, mV, 0-10 V, etc.) directly to the controllers.

A process bus concept based on fieldbus technology has replaced the point-to-point connections in newer substation installations (Gross, 2000). This significantly reduces the number of wires needed and makes the system more cost efficient and reliable.

Consequently, fieldbus technology has made an increasing number of sensor installations feasible in systems where a bus wire can be installed or the power line itself can be used for communication.

The continued rapid development in electronics, microcontroller performance and digital signal processing has made feasible both the conversion from analogue to digital data as well as basic data processing directly in the sensor before the information is transferred to the corresponding IED. In parallel with this technology evolution, advances in wireless communications technology have opened up opportunities to implement new industrial communication solutions at the process and system level. By combining wireless communication and low-power, low-cost digital signal processing, the concept of the intelligent wireless sensor is realised (Sinha, 2001). These wireless sensors are valuable in a number of applications. According to (Tang, 2002) for instance, medical diagnosis applications, environmental monitoring applications, and industrial applications are technology areas where wireless sensors will be used. In industrial and power systems, wireless sensors will become valuable for on-line condition monitoring (Brooks, 2001) and in the monitoring and control of machines and processes where signal cables are unfeasible and costly to install.

1.1 Scope of the Research Work

The scope of this research work is the applicability of wireless sensors and distributed local control in the management of electrical distribution networks. The general objective is to design an architecture primarily for state estimation and fault management applications that is composed of the following major components:

1. Methods that enhance the applicability of wireless sensors as an option for instrumentation and measurement in the architecture.
2. Models and methods for distributed management (primarily state estimation and fault management) in the architecture with respect to the region covered by a primary substation.

An illustration of the technical system considered and studied in this thesis is given in Fig. 1.1.

The first architecture component is related to research in wireless sensors. Intelligent wireless sensor research is a popular topic today and is gaining increasing attention in the academic community. This is exemplified in the work initiatives described by (Rabaey, 2000), (Pottie, 2000), and (Min, 2002), where research on optimisation, algorithms and components for wireless sensors are discussed. In addition, previous wireless sensor technology for power systems is described in, for example, (Fernandes, 1989) and (Moncorge, 1996). They give insight and a reference to the design and mechanics of wireless sensors for power system applications. Hence, extensive research in wireless sensors, both in general terms and from a power system perspective, has already been conducted (for a deeper discussion, see Chapter 2). This provides an opportunity to focus wireless sensor research in this thesis on system related aspects that are essential but have not gained attention in previous work.

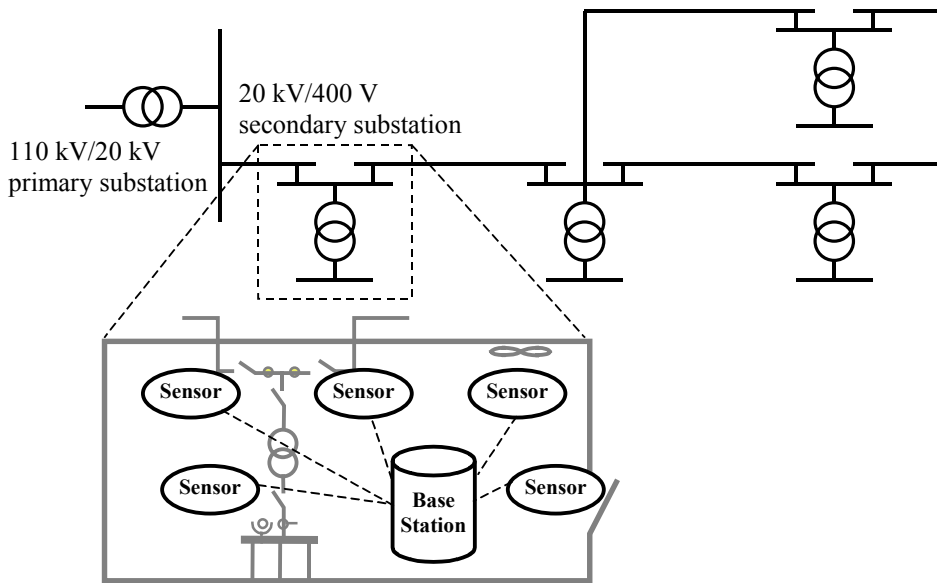


Fig. 1.1. An example of an electrical distribution subsystem suitable for the architectural framework considered in this thesis. Sensors in the secondary substation measure, e.g. transformer top-oil temperature, phase current and temperature of medium voltage conductors, voltage, status of the low voltage circuit breaker, door status and status of the cooling fan.

The first aspect is time management. Time synchronisation is an essential feature in the automation of industrial plants and distributed technical infrastructures, as the chronological order of events and co-ordination of tasks are crucial to achieving safe system operation. This thesis focuses on time management that can be used to synchronise wireless sensors organised in a cell with one base station acting as the clock master. The time synchronisation method is used when the phase angle is determined for individual sensors and when measurements are combined to provide information at the substation level. The research task was to develop a method with a synchronisation precision of tenths of an electrical degree for this environment (Phadke, 1994), corresponding to less than $50 \mu\text{s}$ in a standard European power system. However, the power drawn by the sensors implementing the method should also be minimised. This is an essential goal, as the main concerns with wireless sensor technology are the scarce energy resources available (Sinha, 2001). Instead of being powered by a cable, wireless sensors use batteries or harvest energy from the environment. These energy resources are generally limited (the reader is advised to see Chapter 2 for a deeper discussion on the energy harvesting and management problems with wireless sensors).

The second aspect is research into the applicability of wireless sensors in fault management that, according to (Antila, 2003), is a key function in the operation of electrical distribution networks with SCADA. In this thesis, a concept is developed for detecting short circuits as well as earth faults regardless of the type of network earthing being used. Current solutions are based on different hardware oriented technologies, see for example (Lindgren, 2003) and (Vähämäki, 2001). One task is to implement this functionality in a way that is more flexible and gives better possibilities to manage energy consumption than corresponding hardware solutions do. Another task is to determine which sampling methods are adequate. Fault management requires accurate

measuring, which consumes energy. Balance between the measurement accuracy and the energy consumed by a sensor shall be found in the context of the functions.

The second architecture component is devoted to research in the local control and distributed management of electrical distribution networks. The primary purpose is to consider distributed state estimation and fault management, which are essential functions in distribution automation (Antila, 2003). The region covered by a primary substation, the functionality and equipment it comprises, are taken as the main research reference, although the conceptual framework may be applied to other system levels as well. The goal is to develop a simple model that sets minimal requirements on the computational and communication effort needed to execute the distributed applications. Another goal is to minimise the interaction with the network control centre and to keep engineering and configuration effort to a minimum.

Amin, Heydt, and Wildberger have proposed to approach this problem area with agent technology and adaptive systems that use artificial intelligence and genetic algorithms to implement local decision making and optimisation (Amin, 2001) (Heydt, 2001) (Wildberger2, 1997). This is a technically attractive approach, which contains many theoretical and practical research challenges. However, the concept presumes a high level of system knowledge and local autonomy. This intelligent agent architecture is complex and technically very advanced. Contrary to this, a simpler, more controlled solution is introduced in this thesis. It provides an intermediate step between the systems of today and autonomous, intelligent agent based system architectures that will perhaps be implemented in the far future. An architecture having similar properties to the advanced proposals but using simpler agents with more deterministic behaviour offers a distributed computing platform that is also relatively easy to implement in currently available infrastructures and IEDs.

1.2 Motivation

In this section, the general reasons for using wireless sensors and the distributed, local management of distribution systems are discussed. The technical reasons for the developed methods and models are given in the beginning of the chapters describing them.

1.2.1 Motivation for wireless sensors

The motivation for using wireless sensors in power system instrumentation is generally twofold: economy and safety. From a system operation perspective, wireless sensors give an opportunity to safely and cost efficiently increase measurement coverage of the network, including locations where wiring is impossible. Hence, more extensive and accurate real-time information regarding the state of the system becomes available to the operator. This means that the components and the network can safely be run closer to their technical limits and that vital information for condition based maintenance of the network assets can be elicited.

According to (Antila, 2003), one of the biggest shortcomings in DA today is the lack of simple and cheap instrumentation solutions that are easy to implement and are

applicable in system refurbishment. For example, today the cost of instrumentation in a DA system with a high degree of automation is approximately 25% (Antila, 2003). According to (Sanderford, 2002) and (Scheible, 2002), the overall cost of installing and wiring a sensor exceeds the cost of the sensor by more than ten times. Using wireless communication, installation costs are significantly reduced (Brooks, 2001), no problems appear with damaged signalling cables that would need maintenance, and instrumentation is possible in applications where wiring is unfeasible. Typically these relate to rotating machines as well as medium and high voltage environments. In these environments isolation becomes a problem (Scheible, 2002) and maintenance activities can be dangerous. In addition, refurbishment and installation without de-energising the power network is possible. This favours wireless over power-line communications (PLC), although PLC has similar advantages to wireless technologies for sensor communication in industrial environments (Ahola, 2003).

1.2.2 Motivation for distributed and local system management

As discussed by (Shahidehpour, 2003), distributed processing is considered to be a method to enhance the performance and reliability of the computations needed in the execution of power system applications. When the number of remotely controlled points grows with the increasing grade of automation in the network, communication resources and the computational burden on the central SCADA computer are pushed to their limits. During a fault in the power system, both resources risk being saturated just when they are needed the most.

From a system viewpoint, well-designed and organised distributed and local computation can be regarded as more reliable and faster than corresponding solutions based on central computation (Shahidehpour, 2003). A broken controller or communication link affects, for example, only the performance of the local system. Reliability and speed are essential features, especially in fault detection and isolation where economic losses must be minimised and failures must be stopped from cascading. The level of automation needed to implement distributed fault management may seem high and costly. However, according to (Antila², 2003), when observed over a ten-year period this technical infrastructure is economically feasible in rural and large urban electrical distribution networks.

Consider also parallel and distributed state estimation, which has been discussed by, for example (Carvalho, 1998) and (Falcao, 1995). These discussions have focused on how to achieve a higher frequency in state estimation execution by utilising distributed SCADA resources. However, primary and secondary substations equipped with IEDs and communication capabilities can also participate in the execution of distributed state estimation tasks. Faster execution of the algorithm is perhaps not achieved, but local and decentralised state estimation at the substation level enhances reliability and robustness, as the state estimation can be performed on several system levels. The computational effort at the SCADA level is less significant and topological errors are easier to detect (Abur, 2002).

1.3 Research Methods

This work is interdisciplinary in nature and combines theory from different sciences. Power systems and power engineering is the fundamental science and theory giving the framework for developing components, methods and models. Phenomena from power systems engineering are also utilised to mitigate problems found in other components of the architecture. An example of this is the utilisation of knowledge regarding the distribution network behaviour during a fault, which is used to minimise the energy consumption of the distributed sensors participating in fault management. Instead of implementing fault detection and location strictly at the sensor level, the sensor level information is combined with information from the secondary substation level. This means that the computational burden is shared and energy dissipation of the sensors is minimised (see Chapter 4). Other relevant sciences for the development of wireless sensor methods are measurement and signal processing. These are used in the design of the sensor interface and play a role in the development of sampling means that minimise the energy drawn by individual sensors.

Communications and electronics are relevant to the development of time management for wireless sensors. Communications are also fundamental in the design of distributed and local state estimation and fault management methods. Combined with object modelling, computer science and probability theory, communications provides the framework in which distributed functions are broken down into local substation tasks, and their collaboration is defined.

The architecture is designed using a bottom-up approach. This means that the instrumentation and measurement level is considered first, after which the functions at the primary and secondary substation level are modelled. All developed methods and models are tested in a laboratory environment. Wireless sensor prototypes are designed for this purpose and they are used to test the developed time synchronisation, sampling and state estimation methods. Distributed fault management is tested with a small-scale model of a primary substation region that is designed with embedded controllers and electronics.

1.4 Contribution

In this thesis, methods and models for an architecture comprising wireless sensors for the distributed and local management of electrical distribution networks are proposed. To some extent, the architecture builds on existing technology, as wireless sensors and distributed functionality have previously been discussed in the power engineering society. The contribution of this thesis is visible in combining these areas into a new architecture and in the development of the following new architecture components:

- First, a time synchronisation algorithm for wireless sensor cells has been developed. It adapts to various synchronisation needs and minimises the energy consumed by a sensor participating in the synchronisation. This is a new concept that is particularly valuable when sensor measurements shall be merged. Merging measurements is required when phase angles and shifts in phase angles are determined for systems

where one sensor measures phase voltage and the other sensors measure phase current. These measurements must be related to each other in the time domain.

- Secondly, a new method was designed for detecting and locating faults in electrical distribution networks by combining measurements from distributed sensors at the substation level. This is an improvement to previous technology as the activity of individual sensors is optimised and the energy drawn by sensors is minimised. In addition, different sampling methods were assessed to determine the adequate sampling frequency, accuracy and energy dissipation of a sensor.
- Third, a conceptual model was developed primarily for distributed state estimation and fault management in a primary substation region. Secondary substations were determined as copies of a generic substation object while functionality was broken down into function copies that were allocated to the corresponding substation copies. In addition, a probabilistic method for local state estimation was designed and the information exchange needed in basic condition assessment, fault management and state estimation was determined. This generic concept presents a novel piece of scientific work that can be used as a framework for delegating tasks and access rights to local controllers in an area. In this concept, interaction with the network control centre and the configuration work are minimised.
- Fourth, a token passing mechanism was defined for distributed system management. This token is a novel concept that has two functions. First it is used as a mechanism to pass information between neighbouring substations. Simultaneously it forms the functionality at the primary substation level by merging data from locally executed functions into information representing the state of the whole region. Secondly, it is used to control execution of the distributed and local functions. Hence, it provides controlled and deterministic behaviour that is managed by the primary substation in its region.

Minimising the energy drawn by sensors while simultaneously enhancing their applicability in power system applications is an important achievement that has practical relevance. Wireless sensors used previously have been heavy and clumsy, mainly due to the energy harvesting mechanics and electronic parts (e.g. iron core winding surrounding the power line, see Chapter 2 for details). When the energy consumption is minimised (without degrading the applicability), these parts can be made lighter and one of the main concerns with wireless sensors is mitigated. In addition, when functionality is moved from hardware into software as enabled by the methods proposed in this thesis, the functionality is easier to adapt to different hardware platforms and to different energy harvesting capabilities. The sensor becomes more intelligent and is given the means to dynamically adapt to instantaneously available energy resources. This feature minimises the risk of the sensor being unavailable because of energy constraints.

The author's contribution is documented in the publications included in this thesis. The author is the originator of the proposed and developed architecture, methods and solutions, and he has written the publications. The co-authors have helped in verifying the correctness and the rationality of the ideas, and they have given valuable support in designing test systems and test cases.

1.5 Organisation of this Thesis

This thesis consists of five chapters and six publications. The publications are numbered with Roman numerals I-VI, and are included separately after the references. Chapter 1 gives an introduction to the research, its scope, motivation, and the contribution of the author. In Chapter 2, wireless sensors in power systems are discussed from different viewpoints. History, research trends, system components and applications are considered.

The first part of the scientific contribution is presented in Chapter 3, Publication I and Publication II. These form the time synchronisation algorithm that is the first component in the general architecture that this thesis embodies. The second part is presented in Chapter 4, Publication III and Publication IV. This contribution is the new approach to fault management with distributed wireless sensors. Not only the methodological framework is considered, but sampling methods are also assessed to determine the minimum sampling means and energy dissipation characteristics. The last part of the architecture is embodied in Chapter 5, Publication V and Publication VI. This part presents the conceptual framework for distributed and local condition assessment, fault management, and state estimation implemented with a token passing mechanism and distributed identical copies of both secondary substation objects and functions. In this part, the main emphasis is on the overall structure. Finally, Chapter 6 includes the summary and concluding remarks.

2 Characteristics of Wireless Sensors in Power Systems

During the last years, wireless sensor technology has become a popular research topic in many universities. This popularity is explained by at least two factors. First, according to the well-known Moore's law, the complexity of microelectronic chips is doubled every 18 months (Vieira, 2003). This development has made the design of low-cost and low-power electronic components and sensors feasible. Secondly, intelligence and surveillance have always been a central factor in the defence industry, and tiny, wireless sensors are regarded as a technology that may bring surveillance to new locations and new levels. This has motivated the defence industry, and also other industries, to grant university research groups substantial funding for developing wireless sensor concepts (Manges, 2000).

Section 2.1 presents a general review of the state of the art wireless sensor technology and research challenges. In Section 2.2, architectures, properties and the mechanical design of known wireless sensors used in the monitoring of power system quantities are discussed. Section 2.3 focuses on the assessment of wireless communication in the power system environment. This topic is relevant to gain confidence in the performance of wireless data transfer in environments with noise and disturbances typical to electrical distribution substations.

2.1 Review of Wireless Sensor Technology and Research Challenges

Wireless sensors are attractive in a broad range of applications. For example, environmental monitoring, medical diagnosis, smart buildings, security, and transportation are mentioned in (Estrin, 2001), (Shah, 2002), and (Tang, 2002). From an industrial engineering perspective, condition-based maintenance (Estrin, 2001), machine vibration (Brooks, 2001) and aircraft engine health management (Nickerson, 2000) denote some possible applications.

A wireless sensor is generally composed of four main components. These are the power supply, a radio communication interface, a microcontroller implementing the intelligence, and a sensor interface for sensing quantities of the environment. This general architecture is depicted in Fig. 2.1 (Vieira, 2003), where present research topics are also shown. These topics are studied in several international projects, e.g. Eyes in the European Union (Dulman, 2003), and uAMPS at MIT in the USA (Wentzloff, 2004).

Conventional wireless sensors have been assembled from commercial, of-the-shelf components. Currently available field-programmable gate arrays (FPGAs) consume too much energy to be attractive (Vieira, 2003) and application specific integrated circuits (ASICs) are regarded as expensive to develop as long as the potential market volume is unknown. However, wireless sensors based on FPGA, ASIC and also microscopic micro-electrical mechanical systems (MEMS) technology will be developed in the future and some prototypes are already available, see (Tang, 2002), for instance. These sensors will be smaller, consume less energy and be more intelligent than corresponding sensors build of commercially available components today.

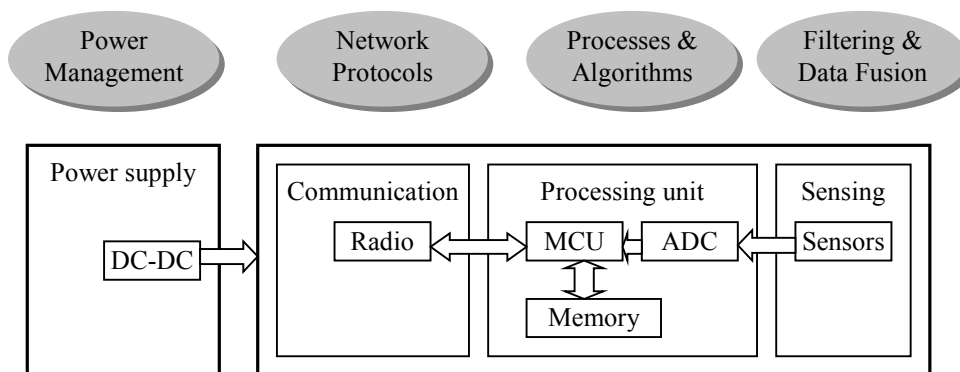


Fig. 2.1. An illustration of the main components of a wireless sensor and corresponding research challenges (redrawn from (Vieira, 2003)). MCU stands for MicroController Unit, ADC for Analogue to Digital Converter and DC-DC for DC-to-DC converter.

2.1.1 Power Management

A wireless sensor is self-powered. This means that it uses either a battery or energy extracted from the environment. A battery is used in many prototype implementations but it is neither a feasible nor a cost efficient solution in the highly distributed or embedded applications where the sensors eventually will be used. Possible energy sources are therefore sunlight, vibrations, wind, heat and magnetic fields (Rabaey, 2000) (Scheible, 2002). The applicability of these energy resources requires the power dissipation level of a sensor to be below $100 \mu\text{W}$ (Wentzloff, 2004). Power saving and management is thus the most important topic in wireless sensor research.

To meet the $100 \mu\text{W}$ requirement, energy optimisation shall be considered in all steps of the sensor development. Ultra-low power circuits must be used, system architecture and communication protocol have to be energy efficient, and a trade-off between functionality and power dissipation must be made. Additional energy saving is attained by shutting down the sensor whenever no events occur (Sinha, 2001). Hence, the radio device and the microcontroller are put into sleep mode when a task has been executed and are woken up again the next time an event occurs. To avoid events passing by unrecognised, a properly designed interrupt arrangement and short wake up time for the components are needed. See (Sinha, 2001) for a deeper discussion on shutdown strategies.

A wireless sensor is typically able to store energy extracted from the environment in a capacitor. Power management can be extended to handle both instantaneously extracted energy and energy that is available in storage. By determining the energy dissipation and the priority of executable tasks, energy aware scheduling algorithms can be designed (Nordman, 2003). These schedulers are valuable when the sensor must guarantee execution of critical tasks with a higher probability than non-critical tasks. For example, a wireless sensor participating in fault management and condition based monitoring of power systems, shall presumably prioritise measurements that are related to fault management. If proper energy aware scheduling is not available, there is a risk that tasks related to condition based maintenance (e.g. monitoring of partial discharges) consume the energy needed for fault detection and location.

2.1.2 Communications

The power consumption of a radio is determined by the modulation scheme, data rate and transmit power level (Vieira, 2003). To minimise the power dissipation of the radio component, it is kept in sleep mode (or shut down) between communications. This means that the sensor is mostly unreachable and to communicate, it must either agree on a communication schedule with its neighbours, or the system must accept that only sensors initiate communication.

The research on wireless sensor communication has mostly focused on low-power transceiver design (Chandrakasan, 2002) and protocols. For example, (Ye, 2002) has presented a medium access protocol for wireless sensors that proposes a periodic listen and sleep scheme and (Shah, 2002) has presented an energy aware routing protocol. Routing is especially important in large and distributed sensor networks where the path between a sensor and the receiver station may have to traverse several hops. These hops are normally other wireless sensors in the same network that consume energy when they listen for traffic and route packets forward.

2.1.3 Processing Unit & Sensor Interface

Sampling, analogue to digital conversion, filtering and processing draw energy. When developing wireless sensors, a trade-off should be made between the processing done in the sensor and the data transmitted to the receiving station for further processing. Pre-processing generally reduces the amount of data transmitted and thus communication energy dissipation, however, processing draws energy as well. Therefore, application properties, sensor components, how many samples are taken and how much processing is needed to extract the relevant information from the samples, determine the optimal trade-off. Although no generic approach can be given, it is clear that fewer samples and shorter duty cycles significantly reduce the average energy consumption. An important design property, therefore, is to minimise the information needed from sensors, use them only to extract the most important process data, and replace the missing system information with intelligence and functionality on a higher system level.

2.2 Wireless Sensor Technology in Power Systems

Wireless sensors have properties that make them attractive for monitoring and control applications in power systems. A wireless sensor does not need cabling, which is costly and problematic in harsh environments with constraints related to isolation and ground leakage currents. It can therefore be predicted that when wireless sensor technology becomes mature it will be used in a number of power system applications, e. g. in condition monitoring and on-line diagnostics. An industry sector where such applications already have been reported is aircraft and aerospace engineering (Harman, 2002) (Nickerson, 2001).

2.2.1 Wireless sensors for measuring quantities of power lines

A wireless sensor for measuring quantities in high-voltage overhead lines was presented in the late seventies by Leskovar (Leskovar, 1977). The objective with this invention

was to provide the means to accurately measure quantities and operational conditions of a high-voltage line, and transfer the measurements over a wireless link to a receiver. As with conventional sensors, this device measured voltage and current. However, another objective was to also measure the phase angle and temperature of the conductor, and detect transients and overload conditions.

In 1984 Fernandes concretised the idea further by inventing another wireless sensor for measuring quantities of an electrical power conductor (Fernandes, 1984). This invention was called the “donut” from its shape and it was mounted on the conductor with a hot stick. Hence, the sensor could be installed without de-energising the power line. This system architecture is shown in the left-hand side of Fig. 2.2 (Fernandes, 1989). It shows the intended location of the sensors and how they communicated with a receiving station, which had communication means for transferring the sensor readings to a remote control centre. The right hand side of Fig. 2.2 shows how the wireless sensors could be installed using a hot stick (from (Lau, 1995)).

These, and the next generation of power line wireless sensors presented in (Fernandes, 1987), (Lau, 1995), and (Lindgren, 2003), have a similar form and properties. Generally, they have a cylindrical housing, which contains the sensing instruments, electronics and radio for communication. They have a mechanical structure that makes it possible to install them upon energised power lines with a hot stick. The most common sensing instruments include a temperature probe, a current sensing coil (usually a Rogowski coil) and a pair of capacitor plates for measuring the conductor potential, i.e. the voltage. The electronics are responsible for sampling quantities, making calculations and forming messages for transmission by the radio to the receiving station, i.e. the base station. In addition, maximum, minimum and root mean square (RMS) voltage and current as well as the power factor are calculated and sent to the base station.

Power to operate the sensors is commonly derived from a winding on an iron core that surrounds the line conductor. Other power supplies that are proposed in the literature are photovoltaic cells and a capacitive connection formed by two surfaces being part of the sensor housing, see (Lau, 1995) and (Vähämäki², 2001) respectively. In some solutions a battery or capacitors ensure operability during outages.

The power that can be derived with an iron core winding depends on the magnetic properties of the core, the size, the number of turns in the winding and the load current. Continuous operation requires a rather large and heavy core, especially if the power consumption of the sensor has not been optimised. An example of this is given in (Lindgren, 2003), where the sensor weighs 2 kg and operates in a load current range of 5 A to 300 A. The power line is not designed to have such a big and heavy sensor hanging from the conductor. It creates a discontinuity in the mechanical construction of the power line and is affected by wind and ice formation. The sensor may change the line vibration and strength characteristics and thus the network operator interest in the device is diminished. A light and easily integrated sensor is for these reasons substantially more attractive. Realisation of this sensor requires that power management and functionality are well designed and optimised.

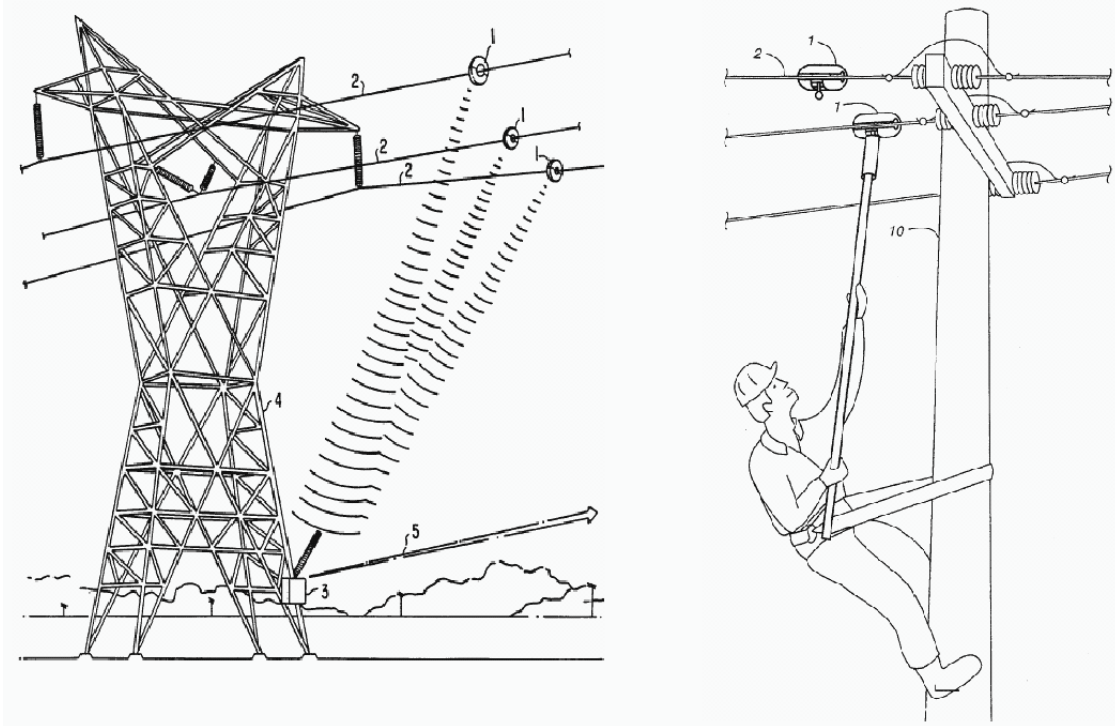


Fig. 2.2. Examples of wireless sensors in monitoring of power system quantities. The left-hand side shows a system architecture (Fernandes, 1989), with sensors (1) attached to the power conductors (2). The sensors communicate with a base station (3), which further sends data to the network control centre via link (5). The right-hand side illustrates how the sensors (1) are installed with a hot-stick (Lau, 1995).

Different constructions for power line sensors are depicted in Fig. 2.3. The sensor on the left is not wireless, instead utilising a cable for data transmission and to supply power. However, it provides a good example of how a light and small sensor for power systems can be integrated into equipment and components. Similar designs are found for cable terminations as well (Swanson, 2000). The other two sensors in Fig. 2.3 are wireless. They show constructions differing from conventional wireless sensors in power systems. The sensor in the centre of Fig. 2.3 uses a capacitive power supply, which means that it can be made lighter than a corresponding sensor with an iron core winding. However, it has a bigger size due to the layout of the surface plates forming the capacitances. The sensor at the right-hand side denotes the arrangement of an insulator with a plastic sleeve that is used to make line installation easier. The sensor can be integrated within the sleeve to form a construction combining the design of conventional wireless sensors and properties of the left-hand sensor in Fig. 2.3. To fit into the sleeve, the sensor must be substantially smaller than conventional ones. A capacitive power supply is thus not practical (the capacitances formed between the conductor, sensor and ground need a certain geometry, distance from each other and material to be applicable). Similarly, a large and heavy iron core winding will not fit into the end of the sleeve. This design is therefore a good example of a sensor with improved system integration properties compared to conventional arrangements, however, with constraints on the power supply. To physically fit within the dimensions given by the insulator, the power management and functionality of the sensor must be well optimised.

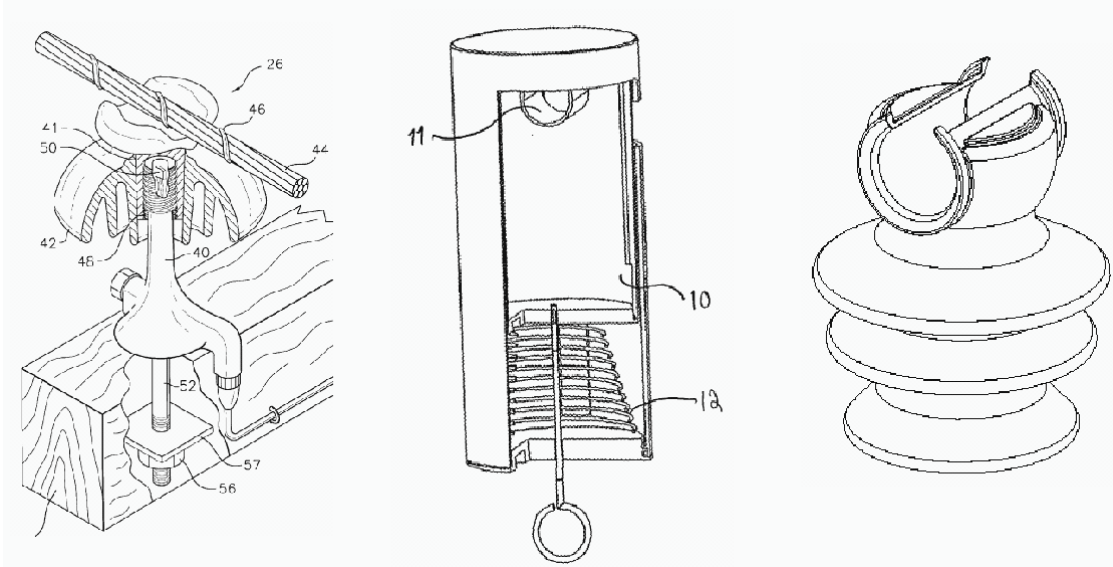


Fig. 2.3. Examples of different constructions for transmission and distribution line sensors. The left-hand sensor is integrated within the pin of an insulator and it communicates to the base station via a wire (Lindsey, 2000). The construction in the centre of the picture denotes a power supply arrangement for a wireless sensor, with an inner surface (10) and a metal-coated groove (11) forming the elements of a capacitive power supply and (12) being the spring keeping the construction tightly against the conductor (Vähämäki2, 2001). The right-hand construction denotes an insulator containing a plastic sleeve that is used to make line installations easier. A wireless sensor can be integrated within the sleeve so that one end contains the power coil winding; the other end contains the measurement arrangement and the sensor electronics are integrated within other parts of the sleeve (Hinkkuri, 2004).

2.2.2 Functionality

Fernandes, Lau and Vähämäki present three different means for how to measure quantities and detect abnormal conditions or faults (short circuits and earth faults) with wireless sensors in power systems. In (Fernandes2, 1984) and in (Fernandes, 1987), voltage and current are measured simultaneously and Fourier components are calculated from 9 up to 24 times per cycle. The phase angle is determined by the time difference between current and voltage waveform zero crossings provided by zero crossing detectors. The information is sent to the base station for further processing where, for example, real and reactive power are calculated and abnormal conditions are identified with different criteria. If this arrangement is to be used in fault management, it must frequently send the measurands to the base station for evaluation, and the sensors must be synchronised as well (Fernandes, 1987). This type of frequently operating application draws a great amount of energy, which makes the sensor construction heavy and bulky. In addition, voltage measurements must be calibrated for every installation to remove the impact of adjacent phase conductors.

In (Lau, 1995), a pre-configured trigger or threshold setting of the current sensing coil is used to indicate a fault. If the pre-configured level is exceeded, a hardware interrupt is generated. This interrupt switches on the microcontroller that makes further sampling and processing. The functional concept is very simple. The sensor samples data for a certain time to detect whether it has experienced a momentary interruption or a sustained outage. If a sustained outage is detected, the fault type is determined. If only

one sensor experiences an excessive current, it is assumed that an earth fault has occurred, and if two or three sensors experience an excessive current, it is assumed that a short circuit has occurred. This functionality can be extended with voltage detection. If the voltage drops below a threshold, an interrupt is generated and it is presumed that a fault may exist. The voltage characteristics for all three phases are examined to determine whether it is an outage, a deep voltage drop, or an open line.

(Lau, 1995), thus, uses threshold levels to detect faults. Configuring the right thresholds for different types of networks and network grounding is difficult and prone to errors. For example, setting thresholds for earth fault detection is a challenging task in networks with ungrounded or compensated neutral, where the earth fault current component can be much smaller than the load current component. Measuring voltage accurately is only possible with calibrated sensors where the impact of adjacent phase conductors has been removed.

In (Vähämäki, 2001), another hardware oriented solution for fault detection is proposed. It uses a specially designed measurement sensor in connection to one phase conductor to measure the phase angles of adjacent phases. With this information and with the absolute values of phase currents, the zero current can be determined. The zero current is used to detect and locate an earth fault.

The specially designed measurement sensor has current measuring coils in specific places at the sensor base. These are used to measure the current of one phase and to eliminate the effect of magnetic fields from the other phases. This arrangement is sensitive and does not provide a generic solution. In addition, the measuring coils set restrictions on acceptable layout, which limits the integration options within power system equipment and components.

2.3 Characteristics of Wireless Communication

There has traditionally been a lot of scepticism regarding the reliability and usability of wireless communication in industrial environments. For example, Ahola argues that there are problems related to propagation of the radio signal, attenuation and disturbances from power equipment (Ahola, 2003). There are, however, several independent studies that prove these problems to have only a minor affect on communication performance.

Wireless sensors typically operate at the ISM (industrial, scientific and medical) frequency bands. In Europe, popular ISM frequencies are 433 MHz, 868 MHz and 2,4 GHz. The maximum allowed transmit power and duty cycles are limited, for example, in the 433 MHz band to 10 mW and < 10 %, respectively (Ylisaukko-oja, 2000). Some transceivers use a simple on-off keyed (OOK) or amplitude-shift keyed (ASK) modulation, while others like IEEE 802.11 use the more advanced direct sequence spread spectrum (DSSS) or frequency hopping spread spectrum (FHSS) techniques. Bluetooth is probably the best known protocol operating at an ISM frequency today.

In an industrial environment most concerns relate to the harsh environment, with steel constructions causing reflections and multipath fading and electrical machines possibly

causing noise and interference (Brunsvik, 2000). Signal attenuation is another factor, which depends on the material in walls, floors and other objects. To determine the impact of these disturbances, tests have been performed in different industrial environments. Some results for IEEE 802.11 and Bluetooth are reported in (Brunsvik, 2000) and (Karasti, 2001).

According to the test assessments, IEEE 802.11 and Bluetooth perform well in an industrial environment. It is even so, that reflection from steel objects help in extending the radio coverage to places where dead zones would otherwise exist (Brunsvik, 2000). In addition, (Karasti, 2001) reports on the impact of an active inverter close to the radio transceiver. A small decrease in performance is noted. However, communication is not blocked by the noise signals generated by the device (Karasti, 2001).

Field surveys and tests of wireless communication in substations have been reported in (Kezunovic, 2002) and (Nordman, 2004) / Publication IV of this thesis. According to (Kezunovic, 2002), potential problems and disturbance sources for wireless communication are switching operations and discharges (high frequency impulse disturbances), other forms of electromagnetic interference, antenna gain and electrical isolation as well as changing environmental conditions (humidity, temperature, etc.). To assess the characteristics of these, field experiments were conducted with spread spectrum radios operating at 900 MHz and 2,4 GHz. Measurements were made for a period of 14 days, with both moving transceivers (on a wheel-chart) and fixed location transceivers in critical locations, for example, near a circuit breaker. The following results related to noise and communication devices in the substation were reported (Kezunovic, 2002):

- Noise level does not depend on ambient temperature.
- Load current, i.e. transformer loading has no relationship to noise level.
- The transformer temperature does not correlate with noise level.
- The physical structure of the substation may not allow the use of directional antennas. This is a potential problem.
- Surges initiated by the power system and ground leakage currents can damage the devices. Proper grounding and shielding must be taken care of.

To verify the applicability of simple OOK transceivers operating in the 433 MHz frequency band, tests have also been conducted in an indoor substation (Nordman, 2004). These tests are described in Publication IV and are thus only summarised here. It was noted that when the sensors were in the line of sight of the base station, the packet loss probability in the substation was equal to the packet loss probability in a standard office environment (for packets with a length of 15 bytes, the loss probability was approximately 0,5 %). In the case where a sensor was moved behind metallic objects, the packet loss probability increased significantly (to 2,3 %). The reason for this behaviour was, however, not further assessed. In addition, a packet was most likely to be discarded in the substation due to a bit error or synchronisation mismatch in the beginning of a packet.

Although more extensive tests and research should be made to verify communication characteristics in different locations and under changing conditions, the tests performed

show concrete examples of, and give confidence in, the applicability of wireless communication in substations and in industrial environments.

2.4 Discussion

Minimising the power consumption is the most important design aspect for wireless sensors. In addition to optimised components and functionality, “shut-down” and power management strategies are used. In wireless sensors for power systems, minimised energy dissipation is essential for the feasibility of integrating the sensor within equipment and components. A light, small sensor is easy to integrate and thus minimises the impact the sensors have on the power system reliability and operability. To achieve this goal, wireless sensors in power systems shall not operate continuously. They instead need properly designed “shut-down” strategies and the means to minimise the pre-processing done by the sensor. However, they must preserve functionality, i.e. the capability to participate in, for example, state estimation and fault management.

Conventional wireless sensors in power systems measure voltage with a pair of capacitive plates. These arrangements have two inconvenient properties. First, the impact of adjacent phases must be removed and the sensors must thus be calibrated. Secondly, if such sensors are used in the refurbishment of substations with cable networks, voltage measurements can not feasibly be implemented. It is prohibited to put any items on the sleeve of cable terminals or joints (in order not to affect electric field grading, which may cause partial discharges). The capacitor would thus have to hang in the air at a distance from the cable conductor. The other two parallel phases and the ground capacitance will then greatly affect the reliability and sensitivity of the measurement, even if the phenomenon is compensated with calibration. This is especially problematic in substations where the ground is more difficult to determine than in symmetrical overhead networks, see (Furukawa, 2000) for an example of the latter.

Hence, a wireless sensor concept that is energy optimised and works without voltage measurements, would be an attractive tool in new installations and especially in refurbishment. To be valuable, this concept must be capable of participating in at least state estimation and fault management.

3 Time Synchronisation of Wireless Sensors in Power Systems

Time synchronisation in distributed systems has been studied in many research projects during the last thirty years. The paper presented by Lamport (Lamport, 1978) has been the landmark for many studies and inventions, especially for those focusing on computer clock synchronisation. Following Lamport, many other methods have been developed for time and synchronisation maintenance in microprocessor based systems, see (Cristian, 1989), (Mills, 1991), and (Patt, 1994) for a limited number of examples. The most well known protocol today is the Network Time Protocol (NTP) proposed by Mills in 1991 and used all around the world in communication networks supporting the TCP/IP protocol (Mills, 1991).

In this chapter time management of wireless sensors in power systems is considered. First, the motivation is given for developing a time synchronisation method, particularly for state estimation calculations, as part of this thesis. Next, common error sources are listed and some key requirements and applications of time synchronisation in power systems are discussed. In Section 3.3 various currently available time management concepts for wireless sensor networks are briefly reviewed. The developed time synchronisation method is presented and assessed in Section 3.4. Section 3.5 concludes the chapter with a discussion.

3.1 Motivation

In the proposed architecture, time synchronisation is intended as an auxiliary activity, primarily in state estimation. Consider the layout of a secondary substation depicted in Fig. 3.1. Sensors I_1 , I_2 , and I_3 measure the phase current in one phase. Sensor U measures the corresponding phase voltage. An advantage of this arrangement is that only one sensor (the voltage sensor) must be integrated and calibrated to remove the impact from adjacent phases. If the substation power lines are of overhead or single-phase cable type, the current sensors are simply put around the lines or cable sheaths respectively (note that with cables the sheath earthing must be drawn back through the current measurement coil). Refurbishment will thus be easy. Furthermore, if single-phase cables are used, only the voltage sensor must be integrated within the terminal to avoid partial discharges. Only if three-phase cables are used will this arrangement be problematic to implement and may require integration of all sensors within the terminals or joints

In state estimation calculations the power factor and thus the phase angles provide important information. In a system similar to the one presented in Fig. 3.1, this means that sensors must be synchronised or they must have a common time reference to pinpoint voltage and current zero crossings and to derive phase angles. Enabling the calculation of phase angles is therefore the main objective for developing a time synchronisation method in this thesis.

Although state estimation is the considered application, time synchronisation can be used in many other power system functions as well. It can be used to determine the order of events, to assess load imbalance and to calculate zero sequence current and voltage, which are useful in advanced fault detection and location.

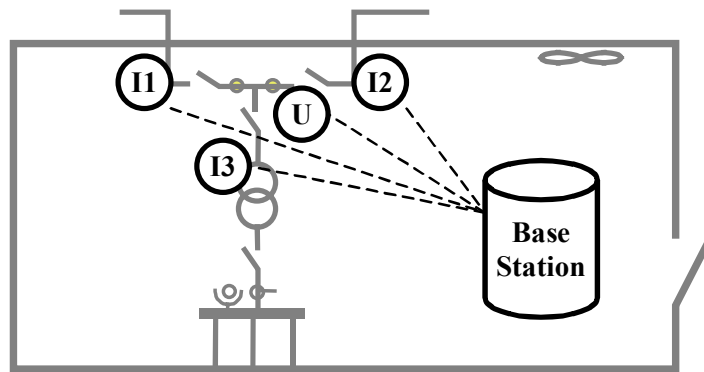


Fig. 3.1. An example of a secondary substation, which has current measurements in all branches and voltage measurement in only one branch. This instrumentation layout does not need extensive calibration and thus makes refurbishment easy. Sensors I_1 , I_2 , and I_3 measure the current in one phase. Sensor U measures the corresponding voltage. The layout for the other phases is assumed similar.

3.2 Common Error Sources in Time Management

Common error sources in the time management of distributed systems can be divided into local factors and system factors. A node in the system has a local clock that normally is driven by a quartz crystal oscillator, although some simple nodes may use an RC oscillator instead. The quality of the local clock depends on its frequency stability, i.e. the ability to keep constant frequency over time. The clock frequency is affected by environmental factors, for example voltage, ambient temperature, magnetic fields, and age. The stability is commonly accepted to be within one part in 10^9 to 10^{11} . In addition, two local clocks will typically drift apart between 0,1 and 10 seconds per day. (Elson, 2003)

The dominant system factor affecting the performance of time synchronisation is the communication process. When a clock server sends a synchronisation message to clients, the message delivery delay will affect the accuracy achieved. According to (Kopetz, 1989), the delay is composed of the send time (message assembly and send request procedure), access time (channel access), propagation time and receive time (message processing at the receiving host). The impact of these can be minimised by statistical means, averaging round-trip delays or by estimation procedures, for instance.

3.3 Characteristics of Some Relevant Time Synchronisation Issues in Power Systems

Time synchronisation requirements in power systems depend on the applications and the application domain. For example, remote monitoring and control applications have lower requirements on synchronisation accuracy than substation automation applications. Other examples are functions using only the chronological order of events. These functions have lower synchronisation requirements than functions needing to know the exact time of events (e.g. in fault location using travelling waves).

Wireless sensors in power systems are typically located in an arrangement that can be characterised as a cell with a base station receiving data from the sensors, see Fig. 3.1.

In this system, the base station is responsible for time synchronisation with other IEDs and with remote SCADA computers. These time management applications and methods are generally out of the scope of this thesis, but the Global Positioning System (GPS), because of its importance, is briefly discussed next.

3.3.1 Examples of GPS in power system applications

GPS, initiated by the U.S. Department of Defence in 1978, was primarily intended for navigational purposes but the information provided by the GPS satellites can also be used in time management. A GPS receiver simply extracts two items, a pulse and a message containing the date and time of the previously received pulse, to accomplish this functionality, see (Gale, 1994).

GPS time synchronisation has been suggested in a number of power system applications. For example, (Burnett, 1994) proposes using GPS in synchronised phasor measurements, which is a technology to track power system dynamic phenomena in real time and to enhance monitoring, control and protection functions. Another application of GPS is fault analysis based on travelling waves. Travelling waves occur during a fault and the fault location can be determined by examining the time difference between arrivals of the surge and its reflections at one end of a transmission line. In addition, if measurement devices at both ends of the line are accurately synchronised, the time difference in arrival of the surge at the different ends can be used to locate the fault. Because the wave moves in the line with an approximate speed of $300 \text{ m}/\mu\text{s}$, a very accurate synchronisation is needed.

As a third example, (Shahidehpour, 2003) proposes GPS for synchronising distributed multi-agent systems. This approach, based on the work done by Amin and Wildberger (Amin, 2001) (Wildberger2, 1997) and discussed in this thesis as well (see Chapter 1 and Chapter 5), anticipates that competing and co-operating autonomous agents will be used in the future to manage technically advanced power systems. GPS satellites will then offer synchronisation services to the agents so that distributed measurements and control actions can be co-ordinated and be given a common time reference.

3.3.2 Required synchronisation accuracy for wireless sensor applications

In (Phadke, 1994), the required accuracy of synchronisation for state estimation and different fault location functions is discussed. In state estimation, the estimate of phase angles is normally accurate to tenths of an electrical degree even though one degree also can be considered sufficient in many applications (Phadke, 1994). In a European electrical distribution system, this requirement is transferred into a synchronisation accuracy of $10 - 50 \mu\text{s}$.

The required accuracy of synchronisation in fault management depends on the fault detection and location application. If sensors are used to accurately provide the information for calculating the zero sequence current (and voltage if possible), the sensors on single phases must be synchronised to concurrently measure the phase currents. In this application, the required synchronisation accuracy does not have to be better than the accuracy of the magnitude measurements. If the sensors use standard

analogue to digital converters, typically with 12-bit resolution, the 1-bit resolution is approximately 0,02 %. This corresponds to an accuracy of 0,1 electrical degree, i.e. approximately 5 μ s in a European power system. Lower accuracy will give rise to an error in the calculations. However, according to (Lehtonen, 1996), the maximum phase displacement allowed for protective current transformers is an electrical degree (accuracy class 5P). Transforming this limit to wireless sensors attached to phase conductors, the relative accuracy for a group of sensors will be one electrical degree. Hence, the sensors forming the sum current of the three phases must be synchronised to each other within approximately 50 μ s (this level also applies to alternative fault management methods, see (Vähämäki, 2001)).

If, on the other hand, travelling waves are used for fault location, an accuracy of 1 μ s is adequate (Phadke, 1994). However, this application requires advanced transducers and is therefore not considered feasible in currently available systems where low cost and low power wireless instrumentation sensors can be implemented.

3.4 Time Management in Wireless Sensor Networks

Time management in wireless sensor networks is a new research area, which in 2001 was approached by (Elson, 2001) and (Nordman, 2001). The motivation for developing new time synchronisation methods for wireless sensors is that conventional approaches using GPS and NTP have been found impractical and not energy optimised. For example, some problems with GPS are that it is expensive, has high power dissipation, requires line of sight to the satellites and can be jammed by the U.S. army (Elson, 2003) (Sichitiu, 2003) (Kusy, 2004). The main problems with NTP are that, due to energy constraints, wireless sensor receivers can not continuously listen for synchronisation messages (Elson, 2001), and that the communication delay in wireless sensor networks is to a large extent non-deterministic, i.e. round trip delays can not reliably be determined (Kusy, 2004). NTP on the other hand assumes that communication resources are frequently available and that communication delays are close to deterministic.

Hence, new time synchronisation methods applicable in wireless sensor networks must be developed. The main goals with these are very low power consumption, flexibility, minimised communication between nodes, and low synchronisation error. In (Elson, 2003) a scheme called Reference Broadcast (RBS) is introduced. This method uses a reference message that is transmitted from a server node to two client nodes. The clients record the time that they received the message and exchange this information to find the difference in their local clocks. Hence, this method is used to synchronise the clients with each other and not with the server. Tests performed with RBS using an 11 Mbit IEEE 802.11 network, show that the synchronisation error with this method is approximately 7 μ s (Elson, 2003), and tests performed with wireless sensors show an error of approximately 30 μ s (Kusy, 2004). In addition, in (Elson, 2001), Elson proposes another method called post-facto synchronisation. In this method, the sensors are normally unsynchronised and only when an event is detected the local time is recorded. Later when a master node sends out a synchronisation pulse, the arrival time of this pulse is used as a reference to the time locally elapsed since the event occurred. Hence, it is assumed that the event occurred at a time equal to the duration since the

occurrence of the event subtracted from the arrival time of the synchronisation pulse. Basically the same approach is reported in (Nordman, 2001) as well.

Some other time synchronisation schemes for wireless sensor networks have been presented in (Ganeriwal, 2003), (Greunen, 2003), (Sichitiu, 2003) and (Kusy, 2004). Of these, the methods developed in (Ganeriwal, 2003) and in (Kusy, 2004) have been extensively tested with wireless sensors and show a synchronisation error of approximately 20 μ s. Unfortunately, the research works mentioned in this section do not present figures of the energy consumed by wireless sensors implementing the proposed methods. It is therefore difficult to assess how well these methods meet the requirement of low power dissipation in addition to the requirement of low synchronisation error.

3.5 Review & Characteristics of Developed Method

The technical requirements for developing a time synchronisation algorithm in this thesis are thus the following:

- It shall be used to determine phase angles when separate sensors measure phase voltage and phase current. The phase angles are used in state estimation calculations, and the required synchronisation level is therefore 10 – 50 μ s.
- Power consumption of the algorithm shall be minimised.

The proposed method and the achieved results are discussed next. Details and a more thorough description are given in Publications I and II.

3.5.1 Method

According to the above requirements two statements can be made. First, it is not necessary to synchronise the sensors with the absolute time of the base station. Phase angles can be derived if synchronisation is achieved between the measuring sensors and the role of the base station is only to provide a relative time reference pulse. This synchronisation method, discussed in (Nordman, 2001) and (Elson, 2002), is very accurate as the send time and access time delays can be ignored. Secondly, the sensors must have the means to receive the relative time reference from the base station. This can be done with a radio receiver, whose active time must be minimised to save energy.

Initially it is assumed that a sensor has a periodic behaviour, i.e. it sleeps by default and periodically wakes up to do a measurement task. A clock (presumably external to the microcontroller as the microcontroller clock is normally shut off during sleep) controls this periodic behaviour. Once in each period it generates an interrupt that wakes the sensor up from the sleep mode and activates a task (the measurement task).

Synchronisation between sensors can be achieved by replacing the clock interrupt with an interrupt generated as a response to a synchronisation pulse received by the radio receiver from the base station. The problem with this is that the sensors must continuously keep their receivers active, which leads to unacceptable high power dissipation. As described in Publication II, the receivers can be replaced with low power radio detectors (RF detectors), but these also have a rather high energy consumption and

are in addition difficult to exactly calibrate. Hence, continuously active, they may generate false interrupts as responses to high frequency and high power noise pulses appearing in the power system environment.

There is therefore a motivation to minimise the active time of the receivers (radio receiver or RF detector) by co-ordinating the transmission of the synchronisation pulse from the base station with the periodic interrupts of the sensors local clocks. The following algorithm constituting three steps does this (for details and technical variables, see Publications I and II).

In the first step the aim is that the base station learns the periodic behaviour of the sensors and sets up a common period in the sensor cell. It is assumed that individual sensors may initially have different period length, determined by their local clock interrupt cycle. The period of one sensor in the cell shall be chosen as the reference to which the other sensors must adjust their own period. For example, a sensor may initially measure a quantity with a period of 100 ms while another sensor may measure the same quantity with a period of 80 ms. The base station decides that the period shall be 100 ms and requests the second sensor to extend its period by 20 ms. A common reference period for the cell is thus determined and the base station will use this period extended by a short guard time (denoted margin in Publication II) as the period for the transmission of synchronisation pulses in step three (see below).

In the second step the aim is to co-ordinate the periods of different sensors. Initially the measurement tasks are arbitrarily distributed in time and they should be adjusted to occur concurrently for every sensor. This is an iterative process that is driven by the base station determining the instant in time when it will send out a reference pulse and the duration between these pulses (based on the period agreed in the previous step). According to this, the base station requests the sensors to move the occurrence of their next task forward or backward in time. In this iterative process the sensors will gradually synchronise the initiation of their tasks to the common time reference. For example, if a sensor does a task at time instants 0, 100, 200, 300, ... and another sensor does a task at time instants 20, 120, 220, 320, ... the base station can request the first sensor to move the occurrence of its task 20 units forward in time. An approximate synchronisation is thus achieved in this step.

In the third step, the actual synchronisation is implemented. When coming to this step, the sensors are approximately synchronised, have a common period and act according to the following scheme. When a sensor is woken up by the local clock interrupt, it turns on its receiver (or RF detector) and goes back to sleep. Next, when the receiver detects a signal on the radio channel (the synchronisation pulse from the base station having a slightly longer period due to the guard time), it interrupts the microcontroller that resets its periodic clock and executes the task. Hence, to minimise the active time of the receiver and thus the energy consumption, a two-layer interrupt structure is utilised. First the local clock interrupt is handled and then the interrupt from the synchronisation pulse (delayed by the guard time) is handled. This process is illustrated in Fig. 3.2.

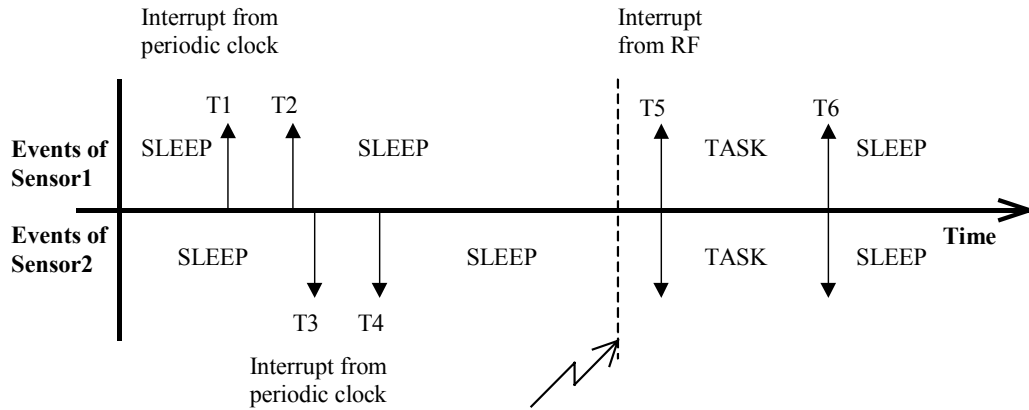


Fig. 3.2. An example where two sensors have been synchronised to the same signal from the base station and how they perform a concurrent duty. Events above the time axis show events of Sensor 1, events below the time axis show events of Sensor 2. At time $T1$, Sensor 1 is woken up by the internal clock interrupt and turns on its radio detector at $T2$. Similarly Sensor 2 is woken up by its internal clock interrupt at $T3$ and turns on its radio detector at $T4$. The dotted line shows when the base station sends out the synchronisation pulse, which is received by both sensors. As a response they start their task at $T5$. At time $T6$ the concurrent duty is done. Note that the guard time seen by Sensor 1 is basically the duration between $T2$ and $T5$, and for Sensor 2 is the duration between $T4$ and $T5$. Slightly different drifts in their local clocks cause the difference in guard time between the sensors.

The algorithm was originally developed for sensor cells with arbitrary behaviour (a worst case assumption). It can therefore be presumed that the first step will not be necessary in every application. For example, in a power system the sensors will probably have the same task period. Furthermore, if the method is used to derive phase angles, the synchronisation pulse will not be used to trigger execution of concurrent tasks. Instead, it will be used to relate voltage and current zero crossings to each other in time. The pulse will act as a time reference for the local clocks only, and the sensors can measure the time elapsed between the reception of the pulse and the next zero crossing. On the other hand, if the method is used to accurately determine the zero sequence current or voltage, the synchronisation method can be used to trigger concurrent sampling of different phases.

3.5.2 Analysis

The time synchronisation method was tested with two sensors and a base station. Here a short summary of the most important test results is given, see Publication II for a more extensive report.

Three tests, A, B, and C were executed with the sensors. A common period was agreed upon (in this case 10 seconds), and then the base station synchronised the tasks of the sensors. When the synchronisation pulse period was set up and the sensors were approximately synchronised, the continuous scheme given in the third step above was initiated. Fig. 3.3 depicts the duration from which the base station sent out a synchronisation pulse until a sensor was interrupted. Hence, this duration contains the transmitter delay, the propagation delay (can basically be ignored) and the delay in the receiver, which in this case was an RF detector, see Publication II for design details. The achieved average delay of $14 \mu\text{s}$ is in line with the results measured in other similar tests, see Section 3.4.

In Fig. 3.4, the synchronisation error between the two sensors is denoted (it depicts the difference in time between the sensors starting execution of a task in response to the interrupt from a synchronisation pulse). The average error is only 2,2 μs , which is an excellent result. This corresponds to 0,04 electrical degrees and thus meets most of the requirements given for power system applications in Section 3.3.2.

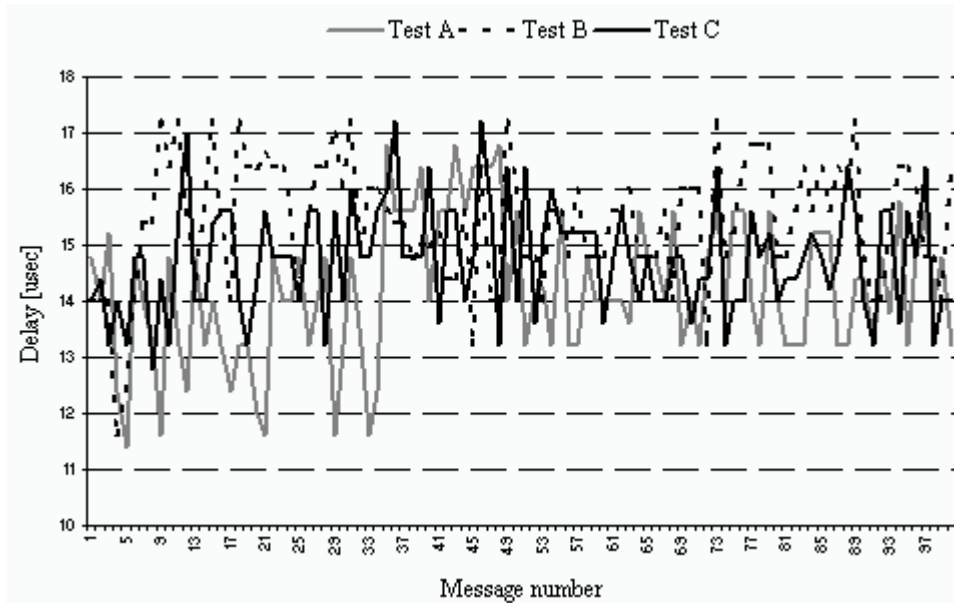


Fig. 3.3. Results of three tests where the duration from which the base station sent out the synchronisation pulse until a sensor was interrupted is measured. In Fig. 3.2 this is denoted as the time from the dotted line to $T5$. The x-axis gives the message number and the y-axis is the delay given in μs . 100 synchronisation pulses were sent for every test.

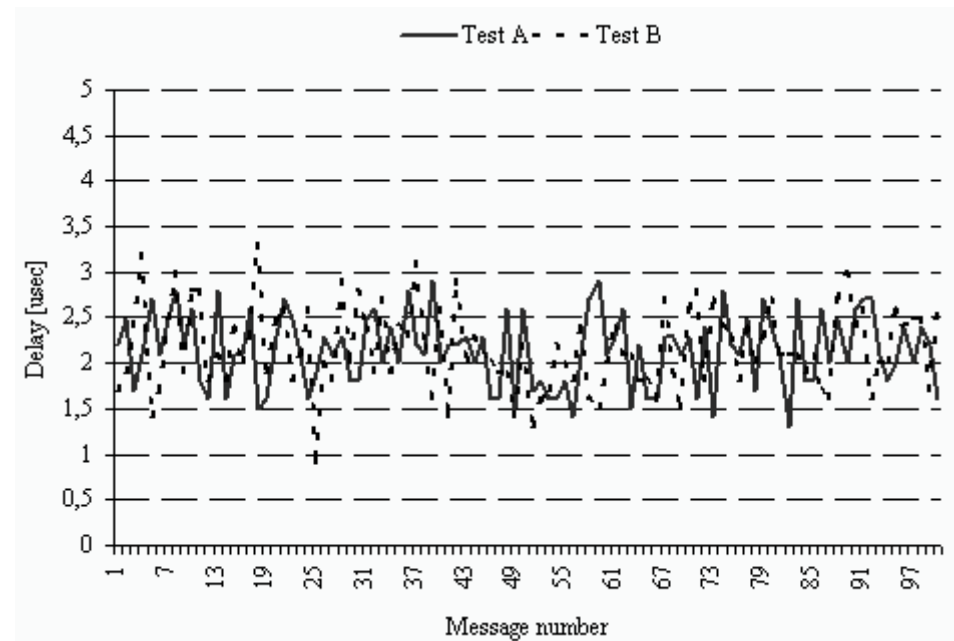


Fig. 3.4. Results of two tests giving the synchronisation error between two sensors. In Fig. 3.2 this depicts the difference in time that the event $T5$ is registered at Sensor 1 and at Sensor 2. The x-axis gives the message number and the y-axis is the delay given in μs . 100 synchronisation pulses were sent for every test.

The energy consumption depends on the electronics used to implement the method and on the period between tasks. In Publication II, a period of 10 seconds is used in some tests and the energy consumed by the synchronisation method is decreased by a factor of 500 compared to the case where the RF detector would be continuously active. However, in state estimation a more realistic period between measurements is 100 ms – 1000 ms. Accordingly, this reduces activity and power consumption by a factor of 5 – 50, which is a significant improvement compared to the case where only RF detector interrupts would be used.

3.6 Discussion

The developed time synchronisation method has two key features that should be emphasised. First, it uses a radio synchronisation pulse generated by the base station to provide a relative time reference for the sensors. Because the sensors experience the same send and access delays in the base station transceiver, these can be ignored and the overall synchronisation delay is only composed of the propagation delay and the receiver delay. The propagation delay can also be ignored as, in principle, it is approximately equal for all sensors. Hence, synchronisation error originates from the different delays in sensor receivers, which are affected by the receiver hardware and the interrupt mechanisms of the microcontroller. The variations in these factors between sensors are very small, and it is therefore possible to achieve a very good synchronisation between sensors. In the synchronisation of computer systems this method is not new, but for synchronising concurrent tasks in wireless sensor cells it was first introduced by the author in (Nordman, 2001) and developed in Publications I and II.

Secondly, transceivers have high power consumption. An applicable and feasible time synchronisation method requires minimisation of the power dissipation. A two-layer interrupt structure is used to achieve this goal. The sensors have their own local clocks that periodically interrupt the microcontroller to execute a task. This periodic behaviour is co-ordinated in the cell so that the duration between the clock interrupts of individual sensors and the interrupt generated as a response to the synchronisation pulse from the base station is minimised. Due to the guard time the period of the synchronisation pulse is always slightly longer than the clock periods of the sensors, i.e. the clock interrupts will occur before the receiver interrupt. This method significantly reduces the active time of the receiver and thus the power consumption of the sensors as well. Originally, this approach was first proposed for wireless sensor cells in (Nordman, 2001) and was developed further in Publications I and II.

Compared to other time synchronisation schemes for wireless sensor networks, the proposed method differs in the utilisation of the two-layer interrupt structure. The advantage of this approach is that energy dissipation is minimised and the method adapts to the periodic behaviour of the sensors. It works equally well for periods of 100 ms and for periods of 20 seconds, for instance. The actual energy dissipation is only determined by the length of the guard time needed to ensure that local clock interrupts occur before the synchronisation pulse is received from the base station. However, the guard time is also the weakness of the method. If it is too short there is a risk that the synchronisation pulse will be sent out before all sensors have activated their receiver

interrupts. In that case, these sensors will not receive the interrupt and will lose synchronisation, which must then be re-established. If on the other hand the guard time is too long, the method will not be energy efficient.

According to the test results, the method meets the specified synchronisation requirements of state estimation. Generally, the synchronisation pulse can be used as a time reference for the local clock of a sensor, which can measure the duration between a synchronisation pulse and the current or voltage zero crossing. In this case, the accuracy will not only be affected by the receiver time delay but also by the drift in local clocks, see Section 3.2. Although clocks may drift apart some seconds per day, the error per measurement period and thus per synchronisation period (one second according to (Phadke, 1988)) will not exceed the bounds of 10 – 50 μs set for state estimation applications.

An alternative application would be to locally record the time a zero crossing occurs and add this information to a message sent by the sensor to the base station. This approach is problematic because local time information must be attached to the message. This method has, in addition to drifts in local clocks, errors in the message handling, send and access processes as well as in the handling of the received message at the base station. These delays are non-deterministic and more significant than the synchronisation error of 2,2 μs achieved with the proposed method.

The developed method is thus recommended in state estimation calculations. For fault management applications the guard time may, however, cause a reliability problem. As previously discussed, synchronisation may be lost if the guard time is not correct. This is not critical in state estimation but may be critical in fault detection and location (lost synchronisation makes calculations of the zero sequence current impossible and a fault may therefore pass by undetected). It is therefore of interest to develop an alternative fault management application where the sensors do not require a time synchronisation service. Such an application can be more robust and needs less intelligence than a corresponding application implementing and utilising time synchronisation.

4 A Wireless Sensor Concept for Distributed Fault Management

As discussed in Chapter 2, wireless sensors that have been previously state-of-the-art have been intended for fault detection and location applications. Various means of how to implement fault management functions have accordingly been invented and proposed. These wireless sensor applications are valuable in reducing outage time in radial electrical distribution networks, especially in networks with many branches.

Short circuit faults are relatively easy to detect and locate in radial networks because the fault current is almost always significantly higher than the load current. Earth faults, on the other hand, are more problematic because the fault current component is small and depends on several factors in the environment. Generally, the properties of managing earth faults depend on the network topology, fault location, fault resistance and the type of earthing being used. In networks with an ungrounded neutral, the earth fault current depends mostly on the currents flowing through the earth capacitances of the sound phases and on the fault resistance. According to (Lehtonen, 1996), in the case of 20 kV overhead lines, the earth fault current corresponding to zero fault resistance is approximately 0,07 A/km. In networks with a compensated neutral (Petersen coil), the earth fault current is significantly reduced because the compensation coil is used to compensate the capacitive fault currents. Only a small fault current part remains due to resistance in the system (Welfonder, 2000). Typically, however, compensation is not perfect and the network is slightly under- or overcompensated. Hence, it can be expected that the fault current in a compensated network is approximately 5 to 10 % of the fault current in networks with an ungrounded neutral, i.e. at maximum 0,007 A/km for 20 kV overhead lines and zero fault resistance. Solidly earthed distribution networks are also used, especially in the USA. According to (Lehtonen, 1996) the fault current varies in these systems largely with the fault location and the fault resistance. It can in some cases be almost equal to short circuit fault currents. In that case, the earth fault is relatively easy to detect and locate.

This chapter presents a new wireless sensor concept for fault detection and location in radial electrical distribution networks. In Section 4.1, the motivation and requirements for developing a new fault management method and for taking the chosen technical approach are given. Some background information and characteristics of relevance to the subject as well as an introduction to important measurement principles are given in Sections 4.2 and 4.3 respectively. A new fault management method is presented in Section 4.4 that also contains an assessment of different sampling means, their applicability and power dissipation. The chapter concludes with a discussion in Section 4.5.

4.1 Motivation

The major technical motivation for developing a new fault management concept instead of using the previously proposals is to enhance the integration of wireless sensors within power system equipment. This issue has been discussed in Sections 2.2 and 2.4 of this thesis, where it was stated that it is necessary to develop a fault management concept where the energy dissipation of sensors is minimised and voltage measurements are not used. That is, the technical goal is to develop a simple short circuit and earth fault

detection and location method using distributed wireless sensors that measure only phase current, have low power consumption and do not utilise time synchronisation services (as dealt with in Section 3.6). There is also a business motivation: to better manage service downtime, which according to (Clift, 2003) can be significantly cut with wireless fault finding applications. Wireless sensors installed in the branches of remotely monitored (and presumably controlled) switching stations or secondary substations, indicate in which branch the fault has occurred. Combining this information with the data received from fault distance calculations at the substation makes fast and efficient fault isolation and power restoration to the healthy feeders and branches possible.

4.2 Characteristics of Some Relevant Fault Management Issues in Power Systems

The most common fault type in an electrical distribution network is a single phase to earth fault (Hänninen, 2001). Typically, the fault is detected by a directional protective relay in the substation, which trips if the zero sequence current, the neutral voltage, and the phase shift between these violate the configured settings (Lehtonen, 1996). The fault location is determined by splitting the feeder into sections and by testing in which section the fault occurs. This is a time consuming task, especially if the switches are manually operated. It is therefore essential to use fault indicators to determine the faulty branch in areas where a short interruption time is important to the customers.

4.2.1 Some conventional fault indicators

Most common fault indicators are short circuit indicators. The early design consists of a yoke (the magnetic field strength surrounding the conductor is used to discriminate between load and short circuits) and a display system. The display system can be mechanical (e.g. a rotor showing the fault direction), based on fluids (red colour in the fault direction), or using a light emitting diode (LED), for instance.

Some combined short circuit and earth fault indicators have also been proposed. One example, presented in (CIRED, 1998), has an LED indicating the direction of a short circuit and a metal strip wound around the phases, which forms the sum current that indicates a possible earth fault. In overhead line networks another principle is used. The indicator is mounted some meters below the conductors. A coil is then used to measure short circuit currents and the magnetic field produced by the zero sequence current to determine earth faults. Another solution is to use wireless sensors, as proposed in this thesis.

4.2.2 Short circuit and earth fault detection and location

A fault in the electrical distribution network is managed at a substation, with a protection system that basically consists of a circuit breaker, a protective relays and some auxiliary equipment (measurement transducers) (Kaufmann, 1990).

The accuracy and availability of fault location and detection functions have improved a lot since the first attempts to develop computer based relaying algorithms in the 1960's. According to (Phadke, 1988), relays can be classified into a number of groups. These

are magnitude relays (responding to the magnitude of the input), directional relays (responding to the phase angle between inputs), differential relays (responding to the magnitude of the algebraic sum of the inputs), and ratio relays (which respond to the ratio of two input signals expressed as phasors).

Short circuits are typically detected at the substation with an overcurrent relay (magnitude relay class), which trips when the input current magnitude exceeds a pre-programmed limit. By measuring the fundamental frequency quantities, the fault distance can be estimated, however, with the reservation that several possible fault locations will be obtained for feeders with many branches (Lehtonen, 1992). The fault distance calculation is implemented with different techniques. The simplest solution is to compare the measured short circuit current to the calculated one. More advanced methods are based on the estimation of faulty line length reactance by forming a differential equation model of the line or by deriving the Fourier components of the measured quantities, i.e. voltage and current (Phadke, 1988) (Lehtonen2, 1992). The main factors affecting the performance of short circuit location and distance computation are errors in the measurement transformers, variations in network component impedance, and impact of the load current. See (Lehtonen2, 1992) for some results achieved with distance computations in networks with short circuits.

Earth faults can be detected with zero sequence overcurrent relays, but to enhance reliability, these are often combined with neutral overvoltage relays. This arrangement is normally replaced with directional relays that in addition to zero sequence current and neutral voltage determine the phase shift between these measurands, see (Lehtonen, 1996).

In power systems with ungrounded or compensated neutral, the rated frequency earth fault current component is usually too small for reliable fault distance estimation applications (Eberl, 2000). The earth fault initial transient has instead proven to be the most common and promising approach (Chaari, 1995) (Lehtonen, 1992) (Hänninen, 1999). Hence, several different algorithms have been developed for the analysis and derivation of required information in distance estimation based on this initial transient phenomenon. Examples of developed methods are differential equation algorithms, Fourier analysis, curve fitting and artificial neural networks, see for example (Hänninen, 2001) for a deeper discussion. However, there are still many technical problems related to sampling rate and errors due to load impedance, parameter identification and measurement transformer accuracy that affect the reliability and applicability of distance estimation using transient methods. See (Hänninen, 2001) for some results of distance estimation in networks with earth fault.

4.3 Measurement principles

Some basic signal processing principles are applicable for measuring quantities associated with a power line. Here, simple peak sampling and the Fourier algorithm are considered because these methods do not require extensive sampling, which is impractical in wireless sensors with limited energy resources. If energy minimisation would not be the major design constraint, dedicated digital signal processors (DSPs), discrete Fourier analysis (or fast Fourier analysis, FFT) and finite impulse response

(FIR) filtering could be used. However, standard DSP controllers available today have rather high power consumption (Wang, 2002) and are therefore not discussed in this thesis.

The intention with simple peak sampling is to measure the signal magnitude with one or two samples taken at the peak (or peaks) of the fundamental frequency. This method is easy to implement by synchronising the sensor to the zero crossing of the measured signal and by taking a sample a $\frac{1}{4}$ period later (or $\frac{1}{4}$ and $\frac{3}{4}$ periods later). The accuracy of this method depends on the stability of the fundamental frequency, the quantization error and non-linearity of the analogue to digital converter and on the design of the amplifier-filter circuit (Carlson, 1987) (Phadke, 1988). These error factors are further discussed in (Phadke, 1988), for instance and in Publications III and IV of this thesis.

The Fourier algorithm is a well-known method to extract the fundamental frequency components from a number of samples taken during a period. If the measured signal contains only the fundamental component and its higher harmonics, the amplitude and the phase angle can be determined from the sine and cosine terms of the signal, see (Voipio, 1976). Advantages with the Fourier algorithm are that it is not very sensitive to quantization errors of the analogue to digital converter, and it rejects components of the harmonics. However, if the sampling rate is low, the Fourier algorithm needs an anti-aliasing filter to remove image frequencies. Further discussion on using the Fourier algorithm in fault management applications is given in Publications III and IV.

4.4 Review & Characteristics of Developed Method

The technical requirements for developing a fault management concept in this thesis are (see Sections 2.4 and 3.6):

- Short circuits and earth faults shall be detected and located using only current measurements.
- The energy dissipation of a sensor shall be minimised. A sensor is therefore not continuously active and the sampling frequency is minimised.
- Sensors are not synchronised.

These requirements imply that the zero sequence current, the neutral voltage and the phase angle between these will not be available for the fault management applications. An alternative approach utilising system information is developed instead.

The proposed method and the achieved results are discussed next. Details and a more thorough description are given in Publications III and IV.

4.4.1 Fault Management Method

System aspects are of major importance in the new fault management concept. An example of the system architecture considered is depicted in Fig. 4.1, where *PS* is the primary substation, *S_x* are secondary substations and *NCC* denotes the network control centre. The intended locations for wireless sensors are marked with grey circles.

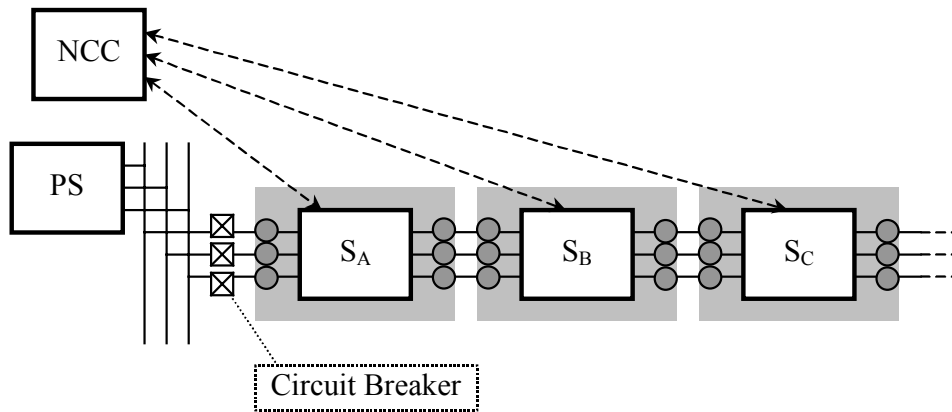


Fig. 4.1. A view of an example of the system hierarchy. PS stands for the primary substation, S_A , S_B , and S_C for secondary substations and NCC for the network control center.

Wireless sensors, formerly state-of-the-art, have been constructed to detect a fault in the power network (see Chapter 2). This approach means that a sensor must be equipped with triggering levels either in the electronics or in the software. The levels are difficult to set and the fault detection functions require almost continuous operation, which consumes energy. In the proposed system, another approach is taken. A sensor is not responsible for detecting a fault. Instead it has only one triggering level, which is determined as the measurement of a zero load current. If practically zero load current is measured, the sensor assumes that the circuit breaker has been opened as the consequence of a fault. As a response to this event, a sensor sends the contents of a buffer to the base station.

The buffer is a simple FIFO buffer of length N , in which the periodically measured values of a quantity are stored. The requirement set for the length of the buffer is simply that it should be big enough to contain values measured before and during the fault. Hence, the tripping time of the circuit breaker and the duration of a measurement period in a sensor determine the length. The content of the buffer is used to calculate the fault location. The calculations occur at the base stations located at the secondary substations or in the network control centre. Hence, the base stations collect the data from the sensor cells, make cell-wide computations and send the sensor data to neighbouring base stations or to the network control centre for further processing according to the behaviour described next.

The location of a short circuit is determined by comparing the current measured during a fault at different sensor locations. Sensors located at the faulty phases between the primary substation and the fault location measure significantly higher currents during the fault than the other sensors. It can even be expected that the measurement arrangements of these sensors are saturated and they give only the maximum current value that can be measured. Correctly designed, the other sensors (on healthy lines and sections) give a current value that is below the saturation level.

Earth faults are located according to the following method. Consider the network with an ungrounded neutral in the upper part of Fig. 4.2 and the network with a compensated neutral in the lower part of Fig. 4.2. The figure shows the three phases of a power line,

depicted 1, 2, and 3. Sensors are the black boxes at locations *A*, *B*, and *C* (compare to Fig. 4.1). The dotted lines denote the direction of the fault currents. The grey areas show the distribution of the fault current amplitude that originates from the evenly distributed earth capacitances of phase wires. The fault current at each sensor location is first determined. This is achieved by calculating the vector difference of the current measured before the fault and the current measured during the fault, see Equation (2) of Publication III. The current magnitude before and during the fault and the phase shift between these is measured. The phase shift is derived as follows. The time elapsed between the periodic wake up of a sensor (determined by its internal clock) and the next zero crossing is recorded for every measurement period. The difference in this duration measured before and during a fault is consequently used to derive the phase shift, see Equation (9) and Fig. 4 of Publication III for details.

Next the vector differences at subsequent sensor locations are subtracted from each other, see Equation (3) of Publication III. The remaining value expresses the fault current that originates from the evenly distributed earth capacitances as depicted in Fig. 4.2. This value, or more exactly the trend of this value between subsequent line sections, is approximately the same for all sections except the one where the fault is located. At this location the trend is broken (basically because the length of the network behind the fault is normally much shorter than the rest of the network). Therefore, by comparing the trend between all sensor locations the faulty line section is identified.

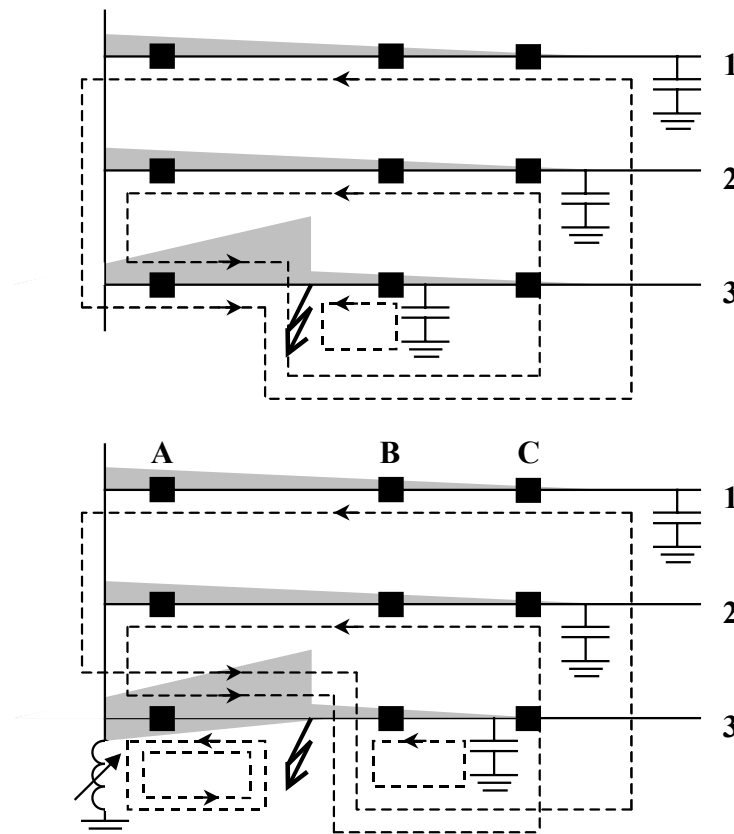


Fig. 4.2. Illustration giving an example of the location of sensors (black boxes), fault current path and direction (dotted lines) and the distribution of fault currents (amplitude given as gray areas) for a single phase to ground fault with ungrounded neutral (upper part) and compensated neutral (lower part) networks.

The method and measurement principles are thoroughly described in Publication III where some simulations made with the EMTP-ATP power network simulator are also presented. Furthermore, sensor extensions and characteristics related to the subject are proposed in Publication IV. Generally, the method will perform well when the network behind the fault is essentially shorter than the rest of the network. In addition, because the trends in the fault current are utilised, a network with an ungrounded neutral and a small fault resistance will give better performance than a network with a compensated neutral or a fault with high fault resistance, for instance. Conceptually, the method offers the means to detect and locate faults with sensors that are simpler than previous ones. The sensors are not responsible for detecting the occurrence of faults or for autonomously determining the fault location. The sensor hardware and software can thus be simplified compared to previous arrangements. Nevertheless, the sensors provide key data to the next upper system level (i.e. the base stations), which can run the fault management functionality instead.

4.4.2 Analysis

There are two main factors that affect the accuracy and the power consumption of the developed method. These are the period between measurement activities and the measurement principle being used.

Ideally a sensor measures the phase current magnitude (and phase shift) every fundamental frequency period. However, because of the need to minimise energy dissipation this is not always possible and the period must sometimes be extended. As the method uses measurements taken before and during a fault, there is a maximum allowable length for the period between measurements. For example, because the sensor must take a measurement during the fault the period between measurements must be shorter than the time it takes to trip and open the circuit breaker at the primary substation (see Fig. 4.1). In modern power systems a maximum period length of 100 ms is feasible. If the current is not measured every fundamental frequency period, the performance of the method is also slightly degraded. Changes in the load current occurring just before or during an earth fault will affect the results of the calculations made in Equation (2), Equation (3) and Equation (4) of Publication III. In the worst case the right fault location will not be found. The probability for this to occur is determined by the period between measurements, the accuracy of the measurement principle and the network topology, power demand and customer base. Hence, it varies on a case by case basis and exact figures can therefore not be given.

As discussed in Section 4.3, simple peak sampling and the Fourier algorithm are considered applicable measurement principles in the concept. The performance of these was assessed in a test system, described in Publication IV. The following measurement principles were tested:

Task (1) – peak sampling

Sleep; wake up at the interrupt from the load current zero crossing; sleep for 90 electrical degrees; sample the current amplitude; return to sleep.

Task (2) – double peak sampling

Sleep; wake up at the interrupt from the load current zero crossing; sleep for 90 electrical degrees; sample the current amplitude; go back to sleep; wake up at the next zero crossing; sleep for 90 electrical degrees; sample the current amplitude; calculate the average of the first and second sample; return to sleep.

Task (3) – Simple Fourier algorithm

Sleep; wake up at the interrupt from the load current zero crossing; wake up at 30, 90, 150, 210, 270, and 330 electrical degrees and sample the current, otherwise sleep; return to sleep.

First, the current drawn by each task was evaluated for different periods between measurements. The results are denoted in Fig. 4.3. The Fourier algorithm using 6 samples (an absolute realistic minimum) consumed, due to the higher activity (despite the low number of samples), significantly more current than the simpler peak sampling methods. With the peak sampling methods, the sleep current (10 μA) dominated the current consumption when the period between measurements was longer than 60 ms. With the Fourier algorithm, the average current consumption was almost always dominated by the current drawn in active mode.

Next, the accuracy of the measurement principles was assessed with uncalibrated sensors in 9 tests lasting 6 hours each. The sensors sampled the phase current with a measurement period of 80 ms. The measured current was averaged for every minute and compared to the average minute current measured by an analyser. An example of the difference in measured current by a sensor and by the analyser is shown in Fig. 4.4 for double peak sampling (see Publication IV for more results).

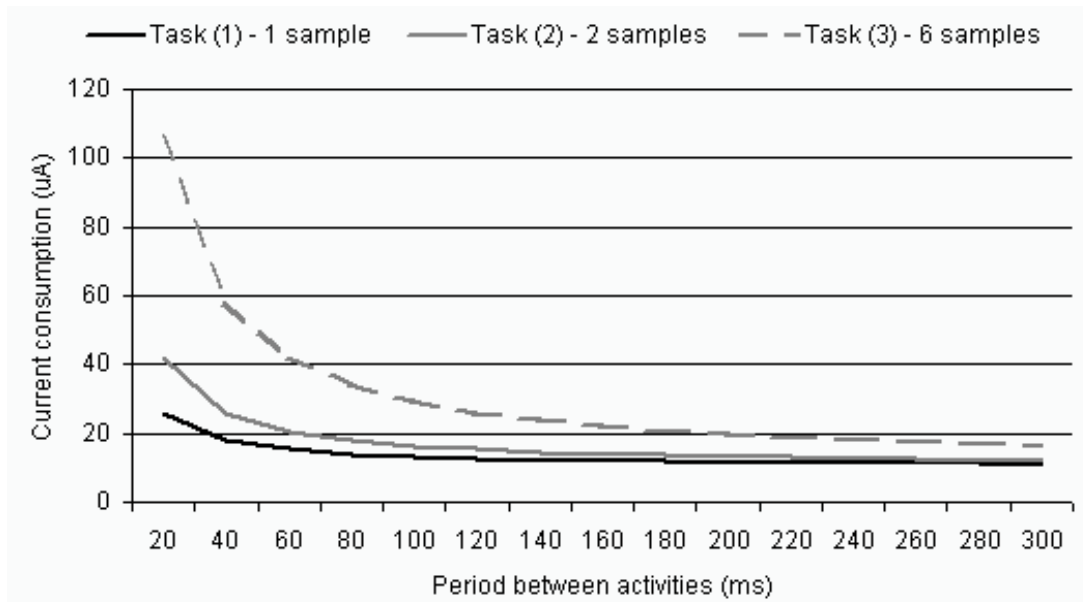


Fig. 4.3. Average current consumption of a prototype sensor with different sampling behavior and measurement periods.

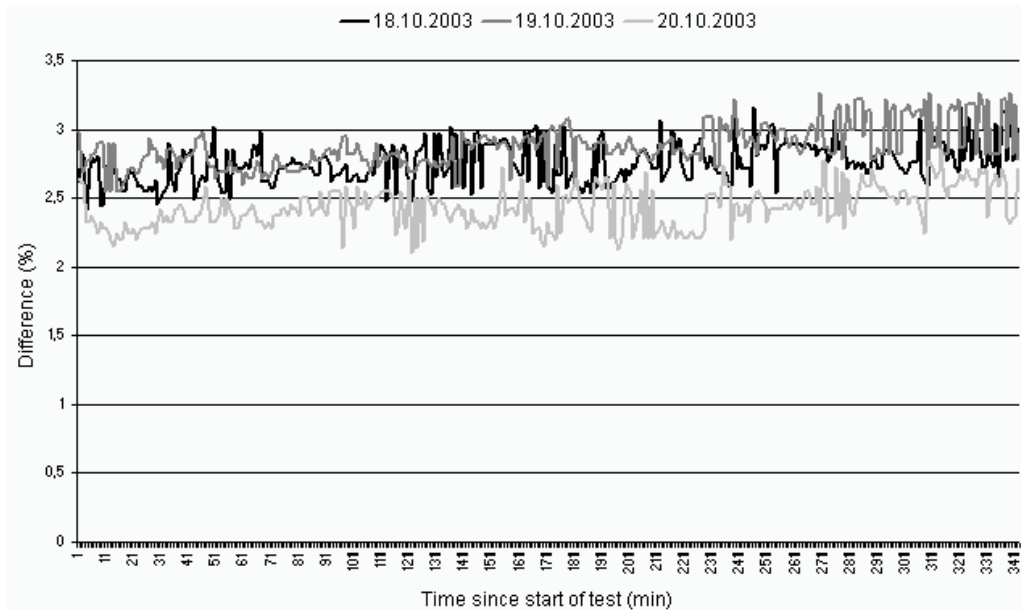


Fig. 4.4. The per minute difference in measured current by the sensor and by the analyser for three tests of Task (2). During the tests (lasting 6 hours) a small trend in terms of a growing error can be noted, especially in the test made 19.10.2003. This was assumed to originate from some instability in the analogue amplifier being used.

When comparing the measurement principles it was concluded that the double peak sampling principle seems most feasible. The single and double peak sampling methods are more energy efficient than the Fourier algorithm. According to the tests, the double peak sampling method is more accurate than single peak sampling, which has a deviation from the mean error that exceeds 1 % in several cases (see Publication IV). Double peak sampling on the other hand, is rather stable around the mean error (which will be mitigated during calibration), and deviates between only 0,5 – 1 % from the mean. Hence, when calibrated, it meets the accuracy requirement for protective current transformers of accuracy class 5P (Lehtonen, 1996) and can therefore be considered adequate for fault management application and also for state estimation calculations.

4.5 Discussion

The developed fault management concept has two key features that should be emphasised. First, sensors do not detect faults. They react instead to an event that is itself a consequence of the opening of the circuit breaker at the primary substation. This makes it possible to develop much simpler sensor electronics and intelligence (especially triggering levels) than before, which consequently leads to a simpler and more robust solution. Secondly, faults are located by comparing trends in the phase current in subsequent locations. Hence, sensors do not necessarily have to be synchronised and they are not responsible for identifying the fault location. The base stations communicating and calculating the data provided from the sensors implement this functionality instead. Conceptually, emphasis is thus put on simplifying the sensor arrangement by moving intelligence to another system level and by including in the concept the information that is available at the primary substation and other locations in the network.

The proposed arrangement enables detection and location of short circuits and earth faults in a radial electrical distribution network, with the reservation, however, that high resistance earth faults and some earth faults in compensated networks may pass by undetected. This is simply because the fault current in these cases can be so small that the resolution of standard analogue to digital converters and signal processing means may not be sufficient to distinguish the fault current component from the load current. In addition, as long as the circuit breaker has not been opened, the sensors will not react to a fault; i.e. developing faults will not be identified until they are detected by the protection system at the substation.

Furthermore, it is proposed that the sensors do not have to measure quantities (presumably phase current) every fundamental frequency period. To save energy, the period between measurements can be extended. Without synchronising the sensors the accuracy of the method may, however, be degraded with this approach. If changes in the load current occur between measurements made by different sensors, the trend calculations can be erroneous and can give false information regarding the fault location. Synchronising the sensors so that they measure the same fundamental period, although not every period, mitigates these problems. The synchronisation can be provided by the method proposed in Chapter 3 and GPS, for instance.

The proposed method has only been simulated and calculated analytically. It has not been tested in a real system installation and is therefore not yet fully verified. However, different measurement principles have been tested and they show that in most cases it is sufficient to measure the average of two subsequent peak values instead of using the more energy consuming Fourier approach. This is a valuable piece of information concerning the optimisation of the energy consumption of a sensor and can also be utilised when the activity of a sensor must be scaled according to the available energy resources, see (Nordman, 2003).

The developed concept can thus be implemented with very simple wireless sensors where the intelligence is moved to another system level, which combines the information produced by individual sensors in an intelligent way. This concept requires a data and communication architecture above the sensors that handles communication between base stations (at the secondary substations) and with the primary substation. This architecture is not only necessary for implementation of the fault management concept but also in general to manage the vast amount of data produced by wireless sensors distributed in the electrical distribution network.

5 A Distributed Concept for Managing Electrical Distribution Networks

Today, the number of sensors and the degree of automation in electrical distribution networks are constantly growing. This development is driven by factors like market deregulation (enhanced asset management and optimisation), advances in digital technology (cheap controllers and instruments) and structures of the modern society (customer expectations for high power quality and short interruptions). To manage and extract important information from the vast amount of data being produced, expert systems and other advanced information technology tools are used.

During recent years another approach has been evolving that proposes using competing and co-operating adaptive software agents to implement local automation functions for power system monitoring and control. In this concept, operations are executed locally in distributed, intelligent and autonomous controllers, however, so that they conform to global optimisation criteria and so that only essential information is communicated between the controller nodes (Shahidehpour, 2003) (ABB, 2003). Amin and Wildberger at the U.S. Electric Power Research Institute (EPRI) have mainly initiated this work, see (Amin, 2000) (Wildberger, 1997), and it is currently being further developed in a U.S. national research program (Goodman, 2002).

In this chapter a new architecture is presented for distributed computing and management in electrical distribution networks. First, the motivation is given for the technical solution, also emphasising the differences with the earlier proposed models. In Section 5.2, background information of relevant technologies used in the architecture is reviewed. This is followed in Section 5.3 by a description of the developed components and how they are used to implement functions in the architecture. Three major functions are presented in the concept. These are condition assessment, fault management and state estimation. The performance of these functions in relation to the developed architecture is assessed and analysed. The chapter concludes with a discussion on the proposed methods and models.

5.1 Motivation

Using local and distributed monitoring and control can prevent possible saturation of the communication system and the central computational resources of the SCADA in electrical distribution networks having a high degree of automation. The previously suggested concepts have been based on intelligent and autonomous agents that are complex and technically very advanced. Although such solutions may be feasible in future systems, they are challenging to adapt in the currently available environment. Contrary to previous work, a simple and well-controlled solution is thereby proposed in this thesis. This solution provides the means to delegate functions to different levels in the distribution automation system and to execute local functions and corresponding activities in a controlled way. This approach simplifies and enhances the robustness of the distributed processing concept compared to solutions based on autonomous agent architectures.

Another motivation for developing the architecture is to seamlessly integrate and enhance the utilisation of wireless communication and wireless sensors in distribution automation. As considered in Chapter 4, the architecture presented in this thesis presumes that wireless sensors are distributed throughout the power system. It is feasible to process the data from these sensors as close to the system processes as possible. A simple and cost effective infrastructure is needed to support this functionality. In addition, with the vast amount of sensors in remotely controlled and monitored substations, engineering and system maintenance will be resource consuming. It is therefore motivated to provide a solution that minimises these activities. The proposed architecture provides the means to achieve this.

5.2 Characteristics of Relevant Technologies

There are several technical building blocks in the developed architecture for distributed and local management. Here, a short review of three relevant technologies is given. These are state of the art object oriented standards in power system automation (relevant when modelling substation resources), agent technology (determines the framework for implementing local intelligence), and distributed state estimation, which is technically the most advanced and most challenging to theoretically implement in the proposed architecture.

5.2.1 Object oriented technology in modern power system automation

An approach to enhance the reusability and configuration flexibility of software for intelligent electronic devices in industrial systems is to consider them and the functionality they support as software components (or objects). For example, in substation automation an instrument transformer, a circuit breaker, a protective relay or a part of the protection functionality (e.g. earth fault protection combining measurement and control objects) can be modelled as software objects with attributes, functions and communication capabilities. A first attempt to extensively define these object models was the Utility Communications Architecture (UCA) project initiated in 1988 (Gilbert, 1998). This project not only defined the device objects but it also proposed a unified communication protocol stack for applications in power systems. Based on this communication architecture a global effort was later made to define a general object oriented standard for communications, devices and applications in substation automation. This is today referred to as the IEC 61850 standard (IEC, 1999). See (Preiss, 2003) and (Nordman2, 2003) for an introduction to the standard and its application domain.

Although IEC 61850 has been primarily intended for substation automation, it is expected that in the future it will provide a general platform for communication and device modelling in distribution automation as well (CIGRE, 2002). In addition, the modelling practice is also considered in a larger context, for example, in the definition of devices and their interaction for applications of distributed energy resources like wind power plants or fuel cells (EPRI, 2003).

5.2.2 Agent technology in power systems

A local agent in computer science terms means a computer program that takes independent actions based on events in the surrounding environment (Coury, 2001). Generally it is assumed that an agent is intelligent and that the intelligence is implemented using artificial intelligence, expert systems or genetic algorithms, for instance.

Although no unambiguous definition of an agent in the industrial context has been given, some definitions can be found in the literature. For example, Buse discusses an agent in an industrial system as an entity that can react to changes in the environment and that can operate autonomously in a goal-oriented way (Buse, 2003). Amin proposes that an agent collaborates with other agents, is adaptive, and can act without human intervention (Amin, 2002). Parunak gives the lowest common denominator, considering the agent to have data and code encapsulated in the form of software objects, its own thread of control, and the ability to execute autonomously without being externally invoked (Parunak, 1998). Hence, the definition of an agent in the industrial environment is similar to the general definition given in computer science.

Several research groups have made studies using advanced agents in power system applications. For example, agent technology concepts for power system stability (Hui, 2002), power restoration (Nagata, 2002), adaptive relaying (Coury, 2001), circuit breaker maintenance (Kezunovic2, 2002) and substation automation (Buse, 2003), have been developed. In addition, an extensive agent architecture for distribution automation and demand side management is proposed in (Hägg, 1995). Generally, these concepts are based on distributed artificial intelligence and interacting multi agent concepts.

5.2.3 Distributed state estimation

The main purpose of state estimation is to provide a reliable, accurate and complete set of data for real-time monitoring and control applications in the power system. By processing the available measurements in combination with knowledge of the network topology and line model parameters, a quite exact view of the state of the system can be obtained, also for areas without real-time measurements. These locations are instead estimated with load models that are verified in the process with measurements from other locations (Lehtonen, 2002).

According to (Shahidehpour, 2003), state estimation can be divided into four main steps: network topology analysis (determines the network structure), observability analysis (determines whether the measurements provide necessary coverage), state estimation computing (assesses the network state) and bad data detection (identification of measurands that are incorrect). The most fundamental analytical state estimation method is based on weighted least square estimation where the mathematical relations between state variables and measurements are formed and calculated in an iterative process. See (Baran, 1994) and (Celik, 1995) for a deeper discussion and for a review of the fundamental equations and mathematical relations.

Distributed processing is considered a tool that enhances the reliability and performance of the computations needed in the state estimation process (Carvallo, 1998) (Falcao, 1995). In distributed state estimation, the conventional theoretical framework is similar to that used in centrally managed state computations but the system is virtually divided into a number of areas that have their own SCADA resources and their own state estimation processes.

In topology analysis, each SCADA will first analyse its own area and pass the derived local information to a node that acts as the information collector. The role of this node is to merge the collected information and to analyse the boundaries of adjacent areas to form the network topology of the entire system. The observability analysis process is basically similar. Each SCADA analyses its own area and sends the required data to the information collector node. For the network to be observable all areas should be observable (i.e. form a minimum spanning tree of the measurements) and they should be interconnected with observable boundary measurements. Hence, if some boundary line is unobservable, the entire system becomes unobservable. State estimation computations and bad data detection also follow the same basic process. That is, state estimation computations and bad data analysis are local iterative processes that are executed autonomously in every area. The required boundary line information (state variables) is determined by interacting with the local processes of adjacent areas. Merging the information in some collector node finally derives the state of the entire network. The state estimation process is thoroughly described in (Shahidehpour, 2003).

Hence, distributed state estimation has thus far been considered at the network control centre level where every area comprises several primary substations and covers large geographical regions. Distributed state estimation can, however, be located closer to the physical process so that primary substations manage state estimation calculations in their own regions. This approach can enhance the accuracy and robustness of state estimation as the calculations are performed close to the physical process and on several system levels (primary substation region and network control centre region, for instance).

5.3 Review & Characteristics of Developed Architecture

The technical requirements for developing a distributed architecture for management of electrical distribution systems as proposed in this thesis, are the following:

- The architecture shall primarily consider the region covered by a primary substation. Although the developed architecture can be applied in other power system subsystems as well, it is from a conceptual point of view natural to limit the scope and the functionality to a clearly limited subsystem. In this case the primary substation region is chosen.
- The primary substation shall manage region wide functionality so that activities are executed in a controlled way.
- Functionality shall be implemented as close to the physical process as possible. This means that the role and intelligence of the intelligent electronic devices in secondary substations are emphasised and increased.

- Implementation of distributed functions shall enable the use of different communication means. Adjacent secondary substations must at least be able to collaborate but the type of communication used (packet switched radio, fibre optic local area network, etc.) has no major impact on the implementation or performance of a function.
- Time synchronisation is not mandatory but preferred. That is, it is not assumed that region wide time synchronisation (e.g. GPS) is available, but the accuracy and robustness of the applications is better when this service is supported.

The developed concept is based on some key components, the general architecture framework, the distributed condition assessment, fault management and state estimation functions, and a token passing mechanism that controls execution of local activities having an impact on the system performance at the primary substation level. The proposed architecture and the achieved results are discussed next. Details and more thorough descriptions are given in Publications V and VI.

5.3.1 Architecture framework and components

In the considered concept, the framework boundaries are determined according to the region that is covered by a primary substation. The main components are thus the primary substation controller, secondary substation controllers and communications. The system is depicted in the left-hand side of Fig. 5.1. This region is also the environment where the distributed functions are executed. Control is determined by two features, the information access model and the token passing mechanism (see next section).

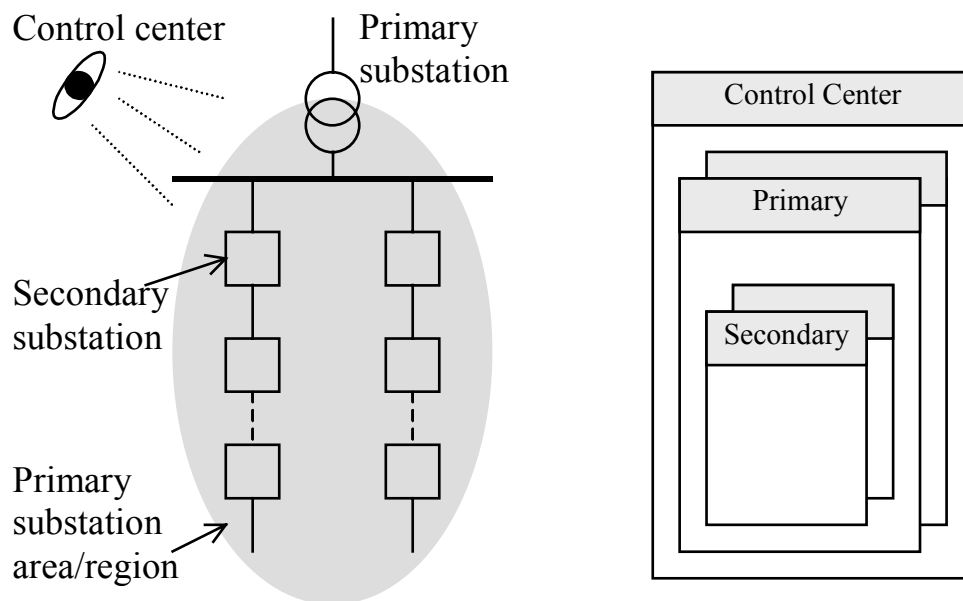


Fig. 5.1. On the left is a view of the considered system framework, which mainly contains the primary substation and the secondary substations of its feeders. The corresponding information access model is depicted on the right-hand side.

The role of the information access model is to provide the means for delegating permissions to execute functions and related activities on different levels in the automation system constituting the network control centre level, the primary substation level and the secondary substation level, see the right-hand side of Fig. 5.1. For example, the network control centre has the most extensive information in the distribution network, and is therefore the most capable of executing system wide functions. However, permissions can be delegated to another level, which becomes responsible for executing the delegated tasks in its context. If the responsibility for fault management is delegated to the primary substation and for some reason fails, it decides to move the initiative back up to the control centre. The control centre has a broader network view and presumably better capabilities to manage the fault by remote control. In the architecture the meaning of the information access model is thus to provide a tool that defines which level is allowed to perform an action and how failures to perform an action on that level should logically be handled.

The secondary substations in the region are defined as copies of a general secondary substation object, see Fig 5.2. The substation object knows its adjacent neighbours and how to communicate with them. These neighbours determine the boundaries of the knowledge a secondary substation has about the system architecture. The object has two relevant entities: a set of classes representing the substation hardware and intelligence that is capable of executing activities representing the object behaviour. The intelligence is conceptually modelled as an (software) agent that operates on inputs from the environment (local sensors or data from neighbours). The agent participates in region wide functions by collaborating with neighbour agents and by executing its local activities. The functions (discussed later in this chapter) are designed so that the agent intelligence can be implemented with simple and conventional methods but solutions based on advanced artificial intelligence can be used as well.

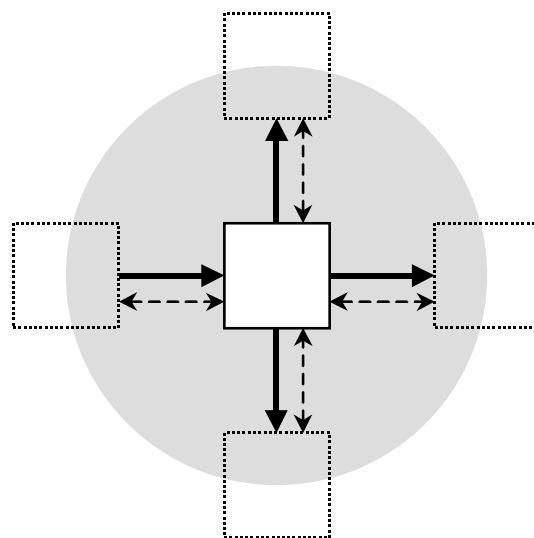


Fig. 5.2. The external view of a secondary substation and some neighbouring substations that can be reached by the communication media. Black arrows depict the power flow direction (radial network assumed) and dashed arrows express the necessary communication paths.

The functions are locally present as copies of general functions. For example, in distributed state estimation, each secondary substation will perform its own local state estimation process, which is handled by the substation agent. Region wide state estimation is realised by merging the results and data of these local processes. The merging process is implemented with the token, which controls the collaboration between adjacent substations. For a definition and deeper discussion on the major substation classes and the agent intelligence, see Publication V.

5.3.2 Token

The token provides the tool for controlling critical activities of the distributed functions in the primary substation region. It can be compared to a token in a token ring telecommunications network. However, in this architecture the token contains more intelligence and information. In addition to permissions it also has the means to pass data between substations in the region.

Under steady state conditions, the primary substation controls the token passing procedure, but in case of an exception in some local substation (a severe violation of some technical limit), the substation may spontaneously initiate communication as well (see the condition assessment in Publication V). However, normal collaboration starts by the primary substation sending out a token to the closest secondary substation. This token contains permission to execute some actions. It can be modelled as a three-tuple $\langle P, F, S \rangle$, where P denotes the permission to take action, F the associated function identification, and S the host delegating the permission. In addition, it contains process information relevant to the function being executed.

When a substation receives a token it executes some associated local actions permitted by the token, attaches local information to it and passes it forward to some of its neighbours according to a collaboration scheme of the executed function. When the token has traversed the substations in the region, it is recursively returned back to the primary substation. Fig. 5.3 shows an example of a simple interaction sequence.

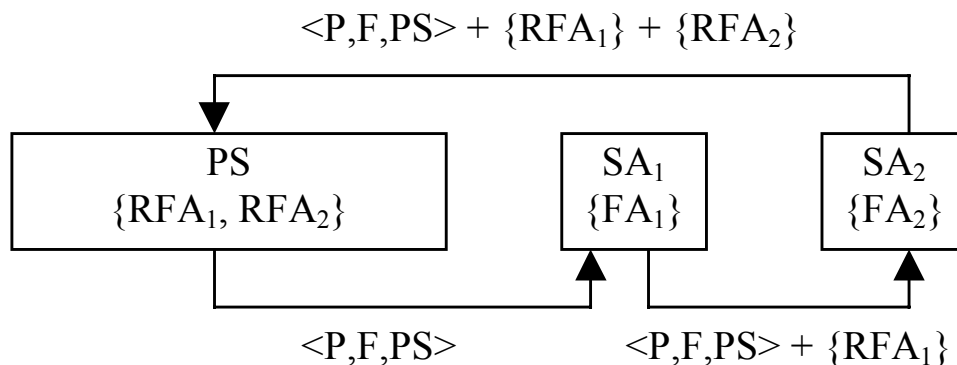


Fig. 5.3. An example illustrating the execution of distributed functionality. *PS* stands for Primary Substation and *SA* for Secondary substation Agent. *FA* is the locally executed Function by the Agent and *RFA* is the Result (data) from the local Function corresponding to the activities performed as a response to the arrival of a token denoted $\langle P, F, PS \rangle$.

If there is a loop in the network (due to, for example, reconfiguration), the token must know when to return (to the primary substation) and where it has been (in which secondary substations). The token keeps a list of visited substations and can thus avoid visiting and executing actions multiple times in a substation. In addition, if the token reaches an opposite circuit breaker at the primary substation, it knows it has been in a loop and returns back to its origin.

In the next sections, the roles of the secondary substation agent and the token in distributed condition assessment, fault management and state estimation are discussed. Examples are given on how the token passing mechanism is used to control and execute these distributed functions in the primary substation region. Extensive description and details on the implementation concepts are given in Publication V (condition assessment and fault management) and Publication VI (state estimation).

5.3.3 Condition assessment

Basic condition assessment is rather trivial to implement in the architecture. In this function the local agents are given a scheme describing how they shall act to different inputs from sensors. Because the secondary substations and associated functions are modelled as copies of a general substation and function respectively, all agents in the primary substation region will primarily be given the same scheme. The scheme can simply be a table describing the reporting behaviour for different risk levels and the technical limits of components corresponding to these levels. Alternatively, it can consist of advanced condition monitoring and diagnostics functions with specified triggering levels for different alarms, for instance. Locally the substation agent operates autonomously; it reads data from the sensors and assesses the data according to the technical limits and reporting behaviour.

The primary substation periodically sends out a reporting token in the area. The aim of this token is to collect status reports from the substations. Hence, when a secondary substation agent receives the token, it adds the substation identification and the requested data (e.g. 10-minute average values of interesting quantities) to it. After this, the agent passes the token to an adjacent substation. This process continues until all secondary substations in the region have been visited by the token. The token is then returned back to the primary substation. However, if some data in a secondary substation deviates from the expected value and violates some limit, the local agent is permitted to spontaneously take action and send an alarm token to the primary substation. The reporting behaviour depends in this case on the parameter settings and the determined reporting interval.

5.3.4 Fault management

Fault management is triggered in the primary substation when protective relays trip and a circuit breaker is opened due to a permanent or persistent fault. When this occurs, the primary substation agent initiates a fault management token, which it sends to the closest secondary substation in the direction of the fault current. When the local agent in the secondary substation receives the token, it enters fault management mode. The contents of the token and the status of the local fault indicators are analysed. Based on

this analysis, the agent determines whether the fault is before the substation, whether the fault is at the substation or behind it. In the last case, the secondary substation agent attaches its fault indicator information to the token and passes it forward to the next secondary substation according to the direction given by the local fault indicators. This process continues until the faulty line segment is found.

When the fault has been found, the adjacent secondary substations collaborate to isolate it. This action is permitted by the token and without the token the substations are not allowed to operate their local switches. If the fault isolation process is successful, the token is passed back to the primary substation with necessary information on the switching operations that have been performed.

Next the primary substation tries to close the circuit breaker. If it succeeds, it is assumed that the fault has been isolated and the primary substation can proceed with the fault management process. In the general case, there are some healthy line sections behind the fault, which must be energised. If a backup path exists, it is therefore activated. If not, the control centre is informed that fault isolation has been made and where the fault location is (between which substations). However, when a backup supply is available, the agent sends out a new token asking which secondary substations need power. Substations along the backup line that are without power but are not affected by the fault and are not without power because of a service break, will add their identification to the token. When the faulty segment is reached, the token is recursively returned back to the primary substation. In this process the affected secondary substation agents perform switching operations (permitted by the token), making power restoration possible. When the primary substation receives the token back, it connects power to the backup path and sends the new network topology and configuration to the control centre.

The reliability of the fault management process can also be upgraded by combining the token passing mechanism with local measurements. For example, if a secondary substation agent receives the fault management token but the substation voltage is not zero, a mismatch in the information is detected and the secondary substation agent will return the token with this information to the primary substation. If the protective relays trip when the primary substation tries to close the circuit breaker upon receiving a successful fault isolation token back, it is concluded that the fault isolation either failed or that there are other faults in the primary substation region. In these cases, the situation is considered too complex for the primary substation and its permissions are exceeded (it has not enough knowledge about the network). According to the information access model depicted in Fig. 5.1, the initiative is moved up to the control centre. Hence, the risk of taking erroneous actions and causing a cascading failure due to limited system knowledge is mitigated.

It is shown in Publication V that the developed fault management concept is especially valuable in electrical distribution networks with a high degree of automation (remote terminal units, automatic switching capabilities, and fault indicators installed) that use packet switched radio networks for communication. Compared to centralised control in the control centre the proposed distributed concept makes significant savings in

communication hops used. These savings mean that the following benefits with packet switched communication networks are achieved:

- Shorter duration of the fault isolation process due to less communication. This leads to smaller outage costs.
- Communication and packet retransmissions are minimised and possible communication bottlenecks are mitigated.

From a communication technology perspective enhanced usability of the packet switched radio networks is thus achieved. This communication technology has an important role in many large technical infrastructures. It is a robust and cost efficient solution that also has routing capabilities, which makes the construction of redundant communication networks feasible.

5.3.5 State estimation

The analysis of the proposed state estimation method made in the next section requires that some of the equations derived in Publication VI be repeated here. A more complete set of equations is found in Publication VI.

In state estimation the primary substation agent has two roles. First, it periodically initialises a token and sends it to the closest secondary substation. This activity is part of the periodic state estimation process. Secondly, it compares the measured load with the load obtained from load class models. If measured and expected load behaviour significantly differ, the agent assumes an exception in the monitored region and sends out an extra token to collect information about the exception (e.g. changes due to switching, production or consumption imbalance).

The periodically initiated token has two purposes. First, it is used in network topology and observability analysis. When the token reaches a secondary substation, the substation identification and data from sensors are added to the token message. When the token has traversed the network it contains a tree structure depicting the valid network topology. If the data received with the token forms a minimum spanning tree (i.e. there is enough valid data from substations and boundary buses so that potentially missing or estimated measurements can be recovered by real-time and pseudo-measurements from other sensors or from neighbouring substations), the primary substation agent considers the region to be observable. Secondly, the token is used in state estimation computing and bad data detection. When a secondary substation agent sends the token to an adjacent secondary substation agent it includes information regarding the correctness of the measurements in the substation as well as the data from the boundary line sensors. This information is used in the bad data detection process of the substation receiving the token next.

To illustrate the steps in distributed state estimation the following example utilising current phasor measurements is discussed. Consider the secondary substation B in Fig. 5.4, with adjacent substations marked as A , C and D , and (wireless) sensors marked as grey circles numbered from 0 to 8. The local agent continuously records data from sensors 1, 2, 3, 4, 7 and 8 and calculates 10-minute moving averages for each. If, for a

sensor J at time T when the token arrives, the 10-minute moving average value of a current phasor is denoted $M_J(T)$, the following relations are computed (see also Publication VI):

$$\begin{cases} \Delta I_B(T) = M_1(T) - M_2(T) - M_3(T) - M_4(T) \\ \Delta I_{A,B}(T) = M_0(T - \Delta T) - M_1(T) \end{cases} \quad (5.1)$$

The term $M_0(T - \Delta T)$ in (5.1) denotes data that is received from A in the token, and ΔT expresses the communication and processing delay between A and B . Every time the token arrives at a substation the computed $\Delta I_B(T)$ and $\Delta I_{A,B}(T)$ are stored as elements in a database (the history database). Hence, the database will contain a set of data elements of $\Delta I_B(T)$, denoted ΔI_B and a set of data elements of $\Delta I_{A,B}(T)$ denoted $\Delta I_{A,B}$. Both these data sets have a mean μ (thus considered for all elements in a set) and a variance σ^2 . Because measurements are assumed to contain random errors (noise in instruments, sampling and analogue to digital conversion) the distribution of a data set is assumed to conform to the Normal distribution (see also Fig. 12 in Publication VI).

In state estimation computations the least square estimate of the 10-minute averages (e.g. of current phasors) is calculated and sent in the periodic token to the primary substation. If some measurement is missing or discarded in the bad data analysis, it is replaced by a pseudo-measurement that is obtained from type load class models. See Equation (4) in Publication VI for details.

Bad data analysis utilises the data sets stored in the history database. Simply, when the token arrives, the computed data in (5.1) is compared to the corresponding data in the history database. Consequently, the distribution of ΔI_B with mean μ_B and variance σ_B^2 (derived from the elements stored as the data set in the database) is used to assess the correctness of the $\Delta I_B(T)$ computed when the token arrives at time T . The following criterion is derived (because the historical data is presumed to be normally distributed):

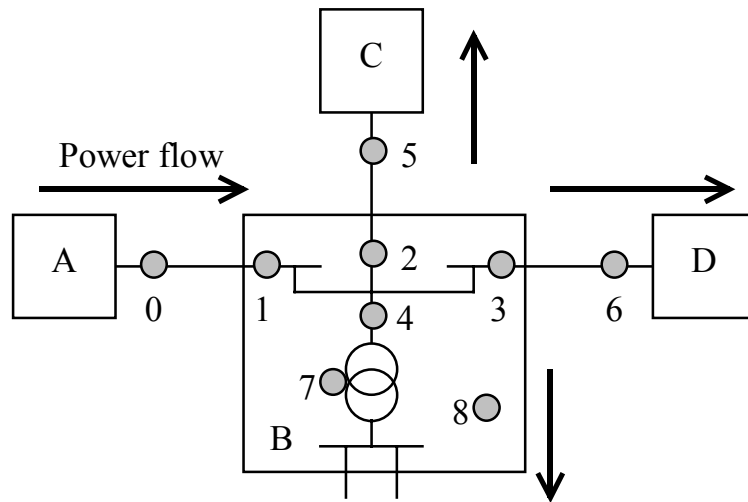


Fig. 5.4. An example of a substation, its neighbours and sensors that are used in the state estimation process. Black arrows depict the power flow and the grey circles are the sensors.

$$\mu_B - 2,58\sigma_B \leq \Delta I_B(T) \leq \mu_B + 2,58\sigma_B \quad (5.2)$$

Hence, if $\Delta I_B(T)$ falls within 99 % of the long time average behaviour, it is presumed correct, otherwise it is assumed to possibly contain bad data, which shall be identified. To simplify the concept it is assumed that only one incorrect measurement can occur. The incorrect measurement is identified by utilising information provided by adjacent substations. According to the state estimation process, the databases of C and D contain this information and thus the parameters of the (Normal) distribution for $\Delta I_{B,C}$ and $\Delta I_{B,D}$, which are transmitted to B on request. $\Delta I_{B,C}(T)$ and $\Delta I_{B,D}(T)$ are also calculated and requested from C and D using the token. In addition B has formed $\Delta I_{B,B}$ and $\Delta I_{B,B}(T)$ from measurements available in the substation (transformer top-oil temperature, current of adjacent phases or temperature of cables). With this information the probability $P_{X,Y}$ of $\Delta I_{X,Y}(T)$ (X and Y are substation identification characters) in relation to $\Delta I_{X,Y}$ with mean $\mu_{X,Y}$ and variance $\sigma_{X,Y}^2$ is determined:

$$P_{X,Y} = 2\Phi\left(\frac{|\mu_{X,Y} - \Delta I_{X,Y}(T)|}{\sqrt{\sigma_{X,Y}^2}}\right) - 1 \quad (5.3)$$

The further the data is from its mean, the greater is the probability in (5.3). The probability is used to rank the data (higher probability implies a higher likelihood of being incorrect). The incorrect data (thus sensor) is furthermore determined by applying the Bayesian theorem on the probabilities derived by (5.3). See Publication VI for details.

5.3.6 Analysis of bad data detection method

The probabilistic bad data detection method was studied and verified in the form of a case study in Publication VI. Here, an analysis of the consequences of (5.1), (5.2) and (5.3) is given.

The bad data detection method is constructed to compare long term behaviour (historical data) with the data measured during the last token period. The distribution of historical data is assumed to conform to the Normal distribution (with corresponding mean and variance). In addition to conventional error sources (analogue to digital conversion and instrument disturbances) the magnitude of the variances of ΔI_B , $\Delta I_{A,B}$, $\Delta I_{B,B}$, $\Delta I_{B,C}$ and $\Delta I_{B,D}$ depend on the measurement method, availability of time synchronisation and communication delay.

If magnitude is measured instead of phasor the variance of the data in (5.1) grows. Using magnitude measurements is realised when unsynchronised and wireless current sensors lacking voltage measurement capabilities are used in the state estimation calculations (see discussions on the time synchronisation of wireless sensors in Chapter 3). In this case the phase angle is estimated using, for example, load models, which will give an error that depends on the relation of the estimated value to the value of the real phase angle. Furthermore, random communication delays or lack of global time synchronisation (e.g. GPS) increase the variances in the data formed from the

measurements from different substations ($\Delta I_{A,B}$ for instance). These larger variances affect the accuracy of the second relation in (5.1).

A large variance in the data set weakens the reliability of (5.2). Because the variance is considered for data sets that periodically have been calculated from several measurands ($M_J(T)$, where J is 1 to 4) a large variance in separate measurands will increase the probability of not detecting bad data. For example, if the measurands in the data set normally have large variances, bad data generated by one erroneous sensor may not be detected if the other measurements are simultaneously close to their historical mean value. Hence, (5.2) as such is not totally unambiguous and more sophisticated criteria can be developed for current phasor measurements, temperature measurements and voltage measurements, for instance. This does not, however, change the conceptual approach proposed for the distributed state estimation process.

When applying the probabilistic method in (5.3) in conjunction with the Bayesian theorem, problems may arise in the selectivity of the method. If there is no significant difference in $\Phi()$ for different $\Delta I_{X,Y}(T)$, the Bayesian theorem will not give an unambiguous result. Hence, good selectivity of the method requires that the error is significant. This means that the magnitude and sometimes also the duration of a disturbance will affect the calculations. For example, as seen in the case study in Publication VI, it may take several minutes from the beginning of a disturbance until it is recognised by the method. This partly depends on the fact that moving averages are calculated and partly because the probabilistic method needs a good selectivity. So a short disturbance with a great magnitude can pass by unrecognised. It is therefore feasible to give maximum limits to the separate measurands that are continuously assessed. If a limit is exceeded the substation agent can take immediate action and inform the primary substation about the problem (similar to condition assessment). It is also interesting to note that the time when bad data is detected depends on the token arrival time. In the case study in Publication VI, the bad data criterion was violated 4 minutes after the disturbance began. If the token arrives during these first 4 minutes, the disturbance is not recognised and bad data detection is postponed until the next periodic token arrives. The token period thus also affects the performance and accuracy achieved with the method.

5.4 Discussion

The general benefits of the proposed concept in the management of technically advanced electrical distribution networks are:

- Engineering complexity is mitigated. The secondary substation copy, its local agent intelligence and the local function concepts are introduced, which permit a system operator to set up a simple configuration that is valid for all substations in the primary substation region.
- Information and communication saturation is mitigated with local system management. In general this is not a new idea but the proposed concept has two new features. First, an information access model is introduced that forms a tool to logically manage permission related to the execution of functions and activities at different levels in the automation hierarchy. Secondly, a token concept is introduced

that provides the means to execute the distributed and local functions in a controlled way. For example, the token controls permissions to perform certain actions that can be hazardous if they are only locally controlled. An example of this is switching operations related to fault management. In addition, the token is used to prioritise functions so that if, for example, state estimation is running when a fault occurs, the fault management token is allowed to take control over the state estimation token. With this feature the token method clarifies the execution of distributed functions and prevents functions from competing with each other (which could be a potential problem with autonomous agents).

The benefits of the concept in fault management relate to minimisation of the communication used and the robustness of the system. According to the information access model, fault management can be executed by the primary substation in its local region. However, if it fails the initiative will be moved up to the control centre, which can analyse the case within its wider system perspective and manage the fault with normal remote control operations. Hence, it is a double layer concept, which adds redundancy to the decision making during the fault management process.

The developed state estimation functionality is assessed on a conceptual level. In particular, the token passing mechanism is essential in the architecture. It has a natural role in topology and observability analysis but its role in bad data detection should also be emphasised. Regardless of the relations and criteria formed in a substation for assessing the correctness of sensor measurements, the token provides the means to merge adjacent state estimation processes at the boundary lines. It forms a chain of measurements and approved data that is used in adjacent substations to check the conformance of their local data. With this method, most of the periodic state estimation data is kept in the primary substation region and is not periodically sent from secondary substations to the control centre. Hence, if, for example, packet switched radio networks are used, the communication needed to perform state estimation will basically be minimised according to the same principles as discussed in the case of fault management.

The state estimation process has been exemplified by deriving relations and criteria for current phasor measurements. In a substation other relations can also be formed that have the same purpose, i.e. to validate the correctness of measurands. Regardless of these, the reliability of the state estimation calculations and bad data detection process is enhanced with well-synchronised sensors (in substations and between substations). The impact of time synchronisation, different types of relations and criteria, as well as the impact of different variances in the data has, however, not been practically assessed in the context of this thesis. The focus has instead been on the architecture and its components.

One major motivation for developing the proposed concept is to provide a distributed computing platform for wireless sensors in the electrical distribution network. Fault management and state estimation using wireless sensors are given special attention in this thesis. According to the discussion in Chapter 4, fault location with simple wireless sensors needs the means to communicate current measurements between adjacent substations in a controlled way. This is supported in the developed concept. Similarly,

state estimation needs distributed communication capabilities to send process data between substations. These capabilities are part of the proposed architecture. The state estimation reliability can be further enhanced with the time synchronisation method proposed in Chapter 3.

6 Conclusions

The recent developments in microelectronics and wireless communication have made the development of wireless sensors for the monitoring of different industrial processes possible. These wireless sensor solutions are valuable in power engineering where the harsh environment sets hard requirements on cabling, safety and cost optimisation. Previously developed wireless sensors for power system monitoring have unfortunately been poorly integrated within the power system equipment and automation system. This has limited the applicability of these sensors in the domain.

Nevertheless, the number of sensors and monitoring units in the power system is constantly growing. This has led to discussions on whether the data produced should be processed close to the physical process and on what automation level decision-making should occur. Several solutions have been proposed that generally utilise sophisticated agent technology to realise the local process intelligence. These concepts are technically advanced and the current power system may not conform to the technical requirements of these arrangements.

The general objective of this thesis was therefore to develop an architecture supporting the use of wireless sensors and distributed functions in the management of electrical distribution networks. In particular, the applicability of wireless sensors in distributed fault management and state estimation was considered essential to the research and development work. The theoretical framework chosen was based on the assumption that by distributing functions to different levels in the distribution automation system, and by developing supporting functions for the sensors, the size, energy consumption, functionality and thus integration of the sensors within the power system could be optimised. This assumption led to the identification and development of new components that have not been addressed in previous work. The process also led to the design of the generic architecture discussed in this thesis. The major new components and the main scientific contribution of this thesis are thus embodied in the following:

- First, a new time synchronisation method was developed. It is based on the co-ordination of two interrupt sources, an internal clock interrupt in the sensor and a synchronised interrupt generated by a signal received from a master station, for example, a base station used to collect the data from the sensors. With this approach, the energy drawn for time synchronisation purposes is minimised because the time the sensor listens for synchronisation pulses is minimised. However, the synchronisation accuracy achieved meets the requirements of some tenths of an electrical degree specified for the considered architecture. This new time synchronisation method is mainly useful in architectures where phase angles need to be determined in state estimation computations. Nevertheless, it can also be useful in advanced fault management where concurrent sampling is used to determine the zero sequence current and neutral voltage.
- Secondly, a new fault detection and location method was developed. The main purpose was to develop a concept where sensors executing tasks asynchronously and measuring only phase current can still provide the necessary data for detection and location of short circuits and earth faults in uncompensated and compensated

distribution networks. The concept is based on detecting a fault by recognising when the circuit breaker in the primary substation is opened due to a fault. Faults are located by comparing the current measured before and during a fault at different places in the networks. With this approach the sensor electronics and logical behaviour can be simplified, which minimises the energy dissipation of each sensor executing the functions. In addition, various measurement principles were tested to determine which measurement approach has sufficient accuracy and a feasibly low energy consumption to be used in the application. According to the tests made with sensor prototypes, sampling two subsequent peak values seems the most feasible approach.

- Third, a new architecture for the distributed management of electrical distribution networks was developed. The main purpose was to provide the means to integrate wireless sensors within the automation concept and to mitigate possible communication and computation saturation at the control centre. The proposed concept is based on a generic substation object and copies of this particular object, local and distributed functions, an information access model, and a token passing mechanism that provides permissions to execute certain activities related to functions at the primary substation level in a local and controlled way. Within this concept, distributed fault management and state estimation were primarily developed. Assessment of the architecture shows that it is especially valuable in technically advanced distribution networks where the communication is implemented with, for example, packet switched radio networks.

The overall architecture presented in this thesis is also a scientific contribution of relevance. It determines a generic concept for integrating distributed and simple instruments (here wireless sensors) and distributed functions within distribution automation processes in a controlled way. Control is essential when functions are assigned to local processes and, without control, confidence in the distributed system is diminished. However, distributed functions that are locally executed close to the physical process have several benefits. In this thesis, the developed fault management concept where communication in the automation system is realised with, for example, packet switched radio networks is one example. The communication needed in distributed fault management is significantly reduced compared to a similar system based on central control. Hence, with the proposed approach, the outage time can be reduced and the communication robustness can be improved.

In this thesis, the focus has been on concepts, architectures, methods and models. Therefore, although the developed components have been tested and their behaviour has been verified with prototypes in laboratory environments, more system testing would be valuable (emphasis has been on verifying the conceptual approach and not the long time behaviour under different system conditions and in different system configurations). Building a prototype system of the architecture and testing it thoroughly is thus a future activity of practical relevance.

In the research and development activities that have been conducted, new subjects and solutions for future theoretical research have been identified. Future research activities could be focused on the following subjects:

- Enhanced selectivity of the fault detection and location method by using probabilistic methods to determine the faulty line segment when only measurements with moderate accuracy are available.
- Detection and location algorithms for the management of high resistance earth faults.
- Development of the substation copy and token passing concepts to embed other types of distribution automation functions (topology optimisation, Volt/VAR control and demand management) within the architecture.
- Enhanced state estimation algorithms in the architecture using more sophisticated criteria and probabilistic methods.

More generally, the architecture discussed in this thesis can be considered to provide an opening for future computer and communications research in distributed energy systems. A distributed computing platform that is simple and robust will be useful in the development of technically advanced control systems for autonomous as well as interconnected distribution regions where energy production and consumption constantly have to be monitored and controlled with sensors and supervisory systems.

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