A Wireless Sensor Network for Distributed Fault Management in Power Systems

Sandip Vijay*, *Member , IAENG, MIEEE, LMISTE;* S.C. Sharma, *Member, IAENG,MNSBE*

***Abstract*—This paper 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.**

***Index Terms*— Wireless sensors, time synchronization, fault management, Electrical System.**

1. INTRODUCTION

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 utilized to mitigate problems found in other components of the architecture. An example of this is the utilization of knowledge regarding the distribution network behavior during a fault, which is used to minimize 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 minimized .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 minimize 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 modeling, 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 modeled. 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 synchronization, 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.

Wireless Sensor Concept for Distributed Fault

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

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Sandip Vijay, B.Sc(Engg.), M.Tech., Member of IEEE, Life Member of ISTE, Member of NSBE (USA), Member of ISOC-Internet Society(USA), MIEANG, (snvijdpt@iitr.ernet.in) has more than twenty five international and national journal and proceedings publication in field of Wireless & Digital Communication and networks. He is serving Department of Electronics & Communication Engg. as a Professor of G.E.I.T. since more than three years. He has more than Eight years of experience in field of teaching and research. He has supervised twelve M.Tech Dissertation. Currently he is pursuing research work in Wireless Ad hoc Network at I.I.T., Roorkee under Ministry of HRD, Government of India fellowship. He has won several research awards in national and International conferences. He is the active reviewer of IEEE Sensor Journal. Currently, he is member of technical committee ACM- CS conferences of ICAIT 2008, Shenzhen, China (www.ICAIT.org) .

Kumar Manoj (**kumardpt@iitr.ernet.in**) has several international and national publication and proceedings in field of Wireless & Digital Communication and networks. National Conference on Emerging Technology In Computer Science has awarded him with Bronze medal for the best research paper in the year 2007. He is serving Department of Electronics & Communication Engg. of G.E.I.T. since more than three years. He has more than six years of experience in field of teaching and research. He has supervised several M.Tech Dissertation. Currently he is pursuing research work at I.I.T., Roorkee.

S.C .Sharma (scs60fpt@iitr.ernet.in**)** received M.Tech. (Electronics & Communication Engg. and Ph.D. (Electronics & Computer Engg.) in 1983 and 1992 respectively from IIT Roorkee (erstwhile University of Roorkee). He started his career as R & D Engineer in 1983 then joined teaching profession in Jan. 1984 in IIT-Roorkee and continuing till date. He has published over Seventy research papers in national and international journals/conferences and supervised more than 30 projects/dissertation of PG students. He has supervised several Ph.D. in the area of Computer Networking, Wireless Network, Computer Communication and continuing supervising Ph.D. in the same area. Currently, he is supervising Six Ph.D. Scholars. He has successfully completed several major research projects independently and many minor research projects related to Communication and SAW filter Design sponsored by Government of India. IIT-Roorkee has awarded him the Khosla annual research prize with best research paper in the year 2000. His many research papers has been awarded by National and International Committees

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 earth 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 paper presents a new wireless sensor concept for fault detection and location in radial electrical distribution networks. In *Section II*, 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 III* and *IV* respectively. A new fault management method is presented in *Section V* that also contains an assessment of different sampling means, their applicability and power dissipation. The paper concludes with a discussion in *Section VI*.

2. MOTIVATION FOR RESEARCH

2.1Review Stage

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. It was stated that it is necessary to develop a fault management concept where the energy dissipation of sensors is minimized 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 utilize time synchronization services . 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 (Sandip Vijay, 2006).

2.2Characteristics of Some Relevant Fault Management Issues in Power Systems: Middle Stage

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.

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 paper.

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 over-current relay (magnitude relay class), which trips when the input current magnitude exceeds a preprogrammed 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 over-current relays, but to enhance reliability, these are often combined with neutral over-voltage 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.

III. 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 minimization 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 paper.

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 synchronizing the sensor to the zero crossing of the measured signal and by taking a sample a ¼ period later (or ¼ and ¾ 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 section III and IV of this paper.

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.

Review & Characteristics of Developed Method

The technical requirements for developing a fault management concept in this paper are (see Sections II):

- Short circuits and earth faults shall be detected and located using only current measurements.

- The energy dissipation of a sensor shall be minimized. A sensor is therefore not continuously active and the sampling frequency is minimized.

- Sensors are not synchronized. 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 utilizing system information is developed instead.

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

.IV. 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. 1.1, where *PS* is the primary substation, *SX* are secondary substations and *NCC* denotes the network control center. The intended locations for wireless sensors are marked with Grey circles.

Ungrouped neutral		95% compensation	
Fault Resistance (Ω)	K	Fault Resistance (Ω)	K
0	46	0	37
100	51	100	37
5000	90	5000	37

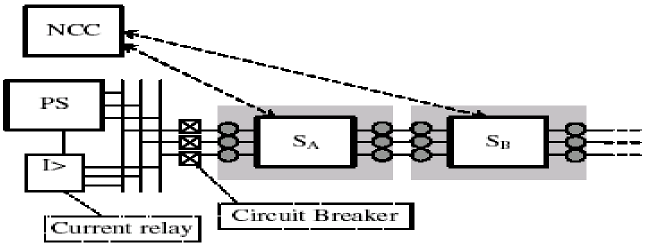

Fig. 1.1. A view of an example of the system hierarchy. *PS* stands for the primary substation, *SA SB*, and *SC* for secondary substations and *NCC* for the network control center.

In addition, the fault current amplitude expressed as *Δi(S)* can be calculated as:

$$\Delta i(S)=\sqrt{\{S[i(\alpha)]^2+S[i(\beta)]^2-2S[i(\alpha)]S[i(\beta)]\cos\phi\}} \quad (1)$$

Wireless sensors, formerly state-of-the-art, have been constructed to detect a fault in the power network. 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 center. Hence, the base stations collect the data from the sensor cells, make cell-wide computations and send the sensor data to neighboring base stations or to the network control center for further processing according to the behavior 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. 1.2 and the network with a compensated neutral in the lower part of Fig. 1.2. 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. 1.1). 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. 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. If zero crossing occurs at the time interval t_1,t_2, and t_3 the phase shift ø is given by :

$$Ø = f * 360 * [(t_3-t_2)-(t_2-t_1)] \quad (2)$$

Next the vector differences at subsequent sensor locations are subtracted from each other is given by the equation:

$$\begin{cases}\Delta^2(B_1,C_1)=\left|\Delta i(B_1)-\Delta i(C_1)\right|\\ \Delta^2(A_1,B_1)=\left|\Delta i(A_1)-\Delta i(B_1)\right|\\ \Delta^2(B_2,C_2)=\left|\Delta i(B_2)-\Delta i(C_2)\right|\\ \Delta^2(A_2,B_2)=\left|\Delta i(A_2)-\Delta i(B_2)\right|\\ \Delta^2(B_3,C_3)=\left|\Delta i(B_3)-\Delta i(C_3)\right|\\ \Delta^2(A_3,B_3)=\left|\Delta i(A_3)-\Delta i(B_3)\right|\end{cases} \quad (3)$$

The remaining value expresses the fault current that originates from the evenly distributed earth capacitances as depicted in Fig.1.2. 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.

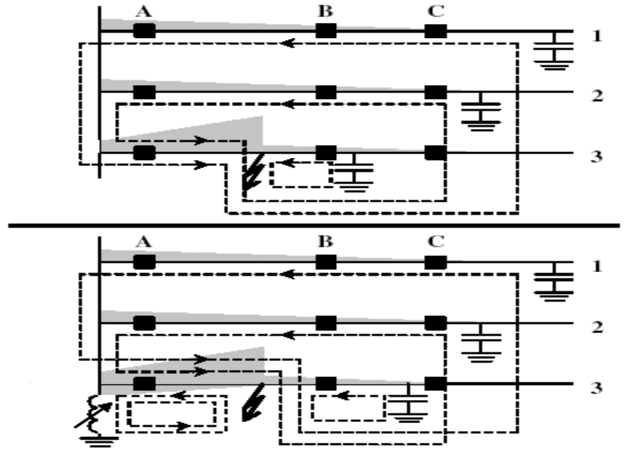

Fig. 1.2. Illustration giving an example of the location of sensors (black boxes), fault current path and direction (dotted lines) and the distribution of fault currents (amplitude given as gray areas) for a single phase to ground fault with ungrounded neutral (upper part) and compensated neutral (lower part) networks.

We have made some simulations with the EMTP-ATP power network simulator are also presented. 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 utilized, 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, (Sandip Vijay & S.C. Gupta, 2006) 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.

. V. 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 minimize 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. 1.1). 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 (1). 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.

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 and 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. 1.3. 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 A) 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 uncelebrated 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 analyzer. An example of the difference in measured current by a sensor and by the analyzer is shown in Fig. 1.5 for double peak.

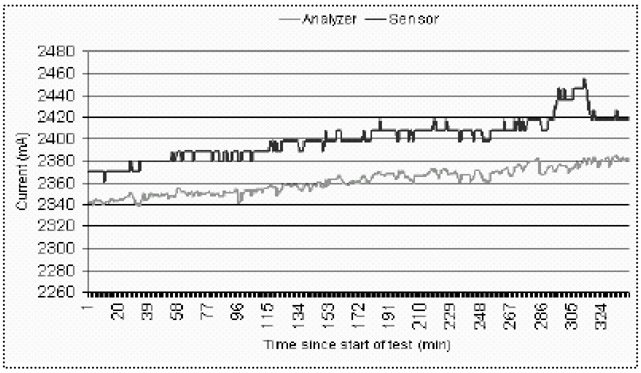

Fig. 1.3. Average current consumption of a prototype sensor with different sampling behavior and measurement periods.

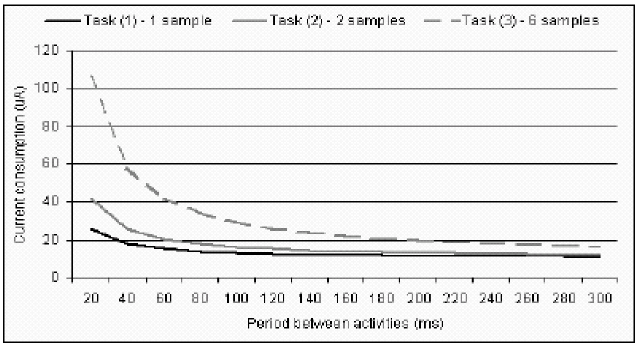

Fig. 1.4. Per minute current measured by a sensor (Sensor 0) and the analyzer during the test run of Task (1) at 10.11.2006.

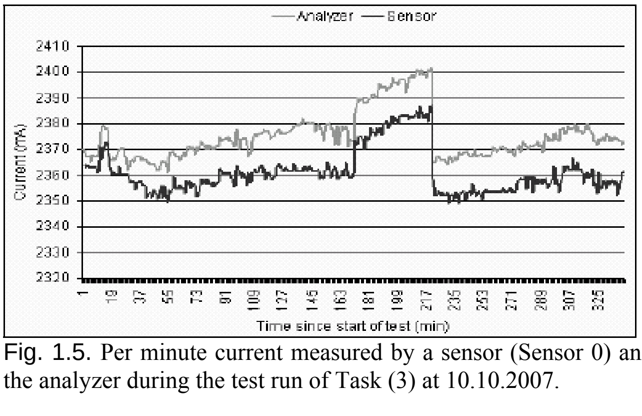

Fig. 1.5. Per minute current measured by a sensor (Sensor 0) and the analyzer during the test run of Task (3) at 10.10.2007.

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. 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.

.VI. DISCUSSION & FUTURE WORK

The developed fault management concept has two key features that should be emphasized. 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 synchronized 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 sensors 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 synchronizing 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. Synchronizing the sensors so that they measure the same fundamental period, although not every period, mitigates these problems. 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 optimization of the energy consumption of a sensor and can also be utilized when the activity of a sensor must be scaled according to the available energy resources. 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.

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