A Survey of Wireless Sensor Network Applications From a Power Utility's Distribution Perspective

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***Abstract*—The task of monitoring and controlling power distribution networks is very challenging given the huge number of assets involved and their wide geographic distribution; this frames a role for wireless sensor network (WSN) applications. This paper provides an overview of the highlights from a comprehensive survey commissioned by Eskom regarding the feasibility of WSNs on the transmission and distribution network; the aim is to direct power utility investment and research and development effort.**

Keywords-distributed; efficiency; electrical network; monitoring; real-time; sensor network; wireless.

I. Introduction

The basic function of the distribution network is to ensure that the utility supplies uninterrupted service to its customers while coping with the demand and maintaining an acceptable level of power quality. The utility now has the means to fulfill its basic function using widely distributed and massive wireless sensor networks (WSNs) due to dramatic reductions in costs combined with significant improvements in performance of sensors, computing and communications.

It is expected that the need for real-time monitoring, control and management of transmission and distribution (T&D) systems will greatly increase due to a number of reasons, including: theft of critical components; preventative maintenance and asset management in general; safety considerations; and the expected evolution of the grid towards a "Smart Grid" [1] matching distributed generation sources with increased demand (e.g. the impact of electric vehicles). The task of monitoring and controlling T&D networks given the huge scale of the number of assets involved and their wide geographic distribution is a very challenging problem [2].

Real-time monitoring and management systems can be realized by the utilization of various types of sensors and actuators (actors). WSNs [3] will help provide the required information to utilities to achieve the goal of dynamic efficiency. A wireless sensor combines sensing (and sometimes actuation) capabilities with computing and communications capabilities. The real-time information acquired from these sensors can be analyzed to diagnose problems early, serve as a basis for taking remedial action and thereby reduce service outages. This will reduce loss of revenue and minimize person hours required to locate and rectify faults.

There is strong evidence that WSNs do offer significant benefits in real-world T&D systems [4]. The aim of this paper is to direct power utility investment and research and development (R&D) effort in WSNs for the T&D grid.

A comprehensive literature study, covering academic as well as commercial literature, was undertaken by Eskom to understand the feasibility of WSNs on the Eskom grid. This paper provides an overview of that study regarding available technologies, products and issues excluding those related to grid stability and power routing.

The paper is structured as follows:

- The state-of-the-art in WSNs for the T&D grid is discussed with respect to: standards; a key patent; a key research paper; a key issue for critical infrastructure, i.e. security; and a key R&D program, i.e. the EPRI sensor program.
- Next, four important application areas are presented followed by a discussion of current limitations of WSN architecture as developed for T&D.
- Specific challenges to the deployment of WSNs in the T&D grid are then highlighted and finally a conclusion is provided.

II. STATE-OF-THE-ART IN WSNS FOR THE GRID

This section covers the key standards, patents, research, issues and R&D organizations relevant to a power utility interested in deploying WSN applications in its T&D network.

A. Standards and Inter-operability Issues

There are a number of standardization efforts underway with regards to different WSN components:

- Plug-and-play of smart transducers: IEEE 1451 [5].
- Clock synchronisation in measurement and control systems: IEEE 1588 [6].
- Network architecture: ISO/IEC 29182; ISO/IEC NP 20005; and ISO/IEC NP 30101 [7].
- Smartgrid interoperability: IEC 60870-6; IEC 61850; IEC 61968; IEC 61970; IEC 62056; IEC 62351; and IEC 62357 [8].
- Communication: IEEE P1777(TM); IEEE 802.11; IEEE 802.15.1; and IEEE 802.15.4 [9], [10].

B. Key Patent for a Collection of Sensors for Overhead Transmission Line (OHTL) Monitoring

A well-represented collection of sensors for monitoring OHTLs are included on this patented device [11] that measures conductor temperature, conductor vibration, the angle of inclination of the overhead conductor, current flowing in the conductor and voltage to ground. The device has a low-power mode in which parameters of the power line conductor are not measured. Upon detecting a change in an electrical or mechanical value of the power line conductor, the device measures parameters of the power line conductor for a predetermined length of time before returning to the low power mode.

C. Key Research Focus Areas

Recent research areas are mentioned in the seminal survey paper in [2].

- Overhead (OH) conductor sag measurement
- Conductor temperature profile measurement and dynamic thermal capacity
- Dynamic thermal rating systems
- Mechanical strength of towers and poles
- Conductor galloping
- Conductor contact with vegetation and animals
- Underground (UG) cable systems
- OH and UG Fault Circuit Indicators (FCI)
- Energy harvesting for powering distributed sensors

D. Security of WSN

Any system that provides functionality with regards to the monitoring and control of critical infrastructure should be subject to security controls. WSNs have the same broad security requirements as traditional networks with some unique security challenges [12]:

- Sensor nodes often have reduced energy, computation and communication capabilities, thus limiting the amount of resources that can be dedicated to security services.
- Sensor nodes are deployed in accessible areas, increasing the risk of physical attacks. In traditional networks, system critical devices are often physically secured and out of reach of an attacker.

Sensor nodes interact closely with their environment and depend on external input. This potentially introduces new security weaknesses where an attacker manipulates the input to influence the overall system.

E. Electric Power Research Institute Sensor Program

Electric Power Research Institute (EPRI) [13], [14] is by far the most actively involved in the development of sensing devices and systems for application in electric utility T&D systems. EPRI's R&D efforts are in the following areas: application of sensor information; sensor developments for transmission and substations; communication and sensor data collection; security; power harvesting [15]; and algorithms and data visualization.

III. KEY APPLICATION AREAS

This section covers four key application areas for WSN in the T&D grid (excluding grid stability and dynamic power routing applicable in a future smart grid environment). These compound areas were chosen based on a power utility's perspective of highest value to its T&D business.

A. Preventing Cable, Conductor and Lattice Theft

There continues to be frequent reports of cable theft, both of power cables and of telecommunication cables, from many parts of the world [16]. Cables, especially copper cables, are being stolen for the scrap value of their metal content and this has become an increasingly serious issue due to the rise in metal prices. In addition to cable theft, the stealing of lattice members (steel support structures) of the lower-end of the tower on the T&D network is a huge risk for utilities as evident in South Africa.

Outages due to damaged high voltage transmission lines and associated structures are time consuming to fix and cost billions of dollars in lost revenue. Business Against Crime (BAC) South Africa claims that the knock-on effects to the economy is, conservatively, ten times higher than the expenditure required for replacing stolen cables [17]. Therefore, in 2007, BAC estimated that South Africa loses in the order of $700 million a year due to theft of electricity, telecommunications and railway line cables [17]. Combating cable and lattice theft is a very challenging problem as transmission lines cross many kilometers of remote country through dedicated corridors with no effective means of physical security detection or protection [18].

The WSN role is to provide the pre-emptive system control to prevent regional outages. Currently, technology or physical surveillance devices exist that can perform this task (i.e. surveillance cameras, roving guards, intrusion detection systems), but these are impractical due to the high cost of implementation, maintenance, and operation [18].

B. Conductor Temperature and Low Hanging Conductors

Sagging in high voltage (HV) lines is mainly due to conductor temperature which in turn is a function of current loading. The monitoring of weather conditions is also related to conductor temperature monitoring.

Sagging in low and medium voltage lines is not due to temperature but rather due to tilting of the wooden poles arising from geological reasons. This type of sagging is predominant in rural areas and poses fatal hazards to man and animals.

A guideline for the evaluation of a system to operate HV transmission lines more efficiently while at the same time ensuring the security of system operation is given in [19].

C. Insulators: Partial Discharge and Leakage Current

Partial Discharge (PD) and leakage current monitoring is crucial for preventing or minimizing system failures due to the breakdown of cable insulation and insulators.

The benefits of on-line PD field measurements are that it is a predictive, non-intrusive [20] and non-destructive test that is relatively inexpensive when compared to off-line testing.

Some other desirable attributes of a PD measurement system that have been covered in literature are that it should provide the location [21] of the PD in real-time [22].

In medium and high voltage applications, a leakage current is the current that flows either through the body or over the surface of an insulator and may lead to flashover of the insulation. Hence, it is important to measure leakage current to determine mitigation strategies.

D. Fault Detection and Location Sensors

Traditionally, the short-circuit faults in power distribution lines were located by a trial and error method. This is time consuming, especially if it involves driving to remote locations, and newer more intelligent methods are required to quickly and accurately determine the location of the fault. Apart from location, other aspects important for fault-management are topology, type of earthing used and fault-resistance [2].

Various automatic means of implementing management functions for faults using WSNs exist and have demonstrated value in reducing outage times. The most important benefits provided by the fault location systems proposed are as follows: downtime reduction; operational costs reduction; and corrective maintenance optimization.

IV. WSN ARCHITECTURE FOR T&D

The literature study has not produced a sensor network architecture already deployed by an electric utility. The ISO/IEC JTC 1/WG 7 Working Group on Sensor Networks is working on some standards defining general sensor network architectures, but these are still under development [7]. Good guidelines on how to do an ad hoc design are in [23], [24].

If a WSN is practically deployed in the electric grid, it is most likely that a hierarchical data management architecture would be in place. Such architecture will allow for both localized data management for quick decision making and a centralized system for long term analysis.

A WSN data-management architecture is currently lacking. WSN literature often promotes the total exclusion of a human presence based on the notion that the nodes have localized intelligence and can therefore act immediately on events, or information, in their vicinity – a heralded benefit of WSNs.

V. CHALLENGES

In Section II. C., Key Research Focus Areas, a selection of research activities (with findings) as reported by research papers are listed; most require ongoing R&D culminating in marketable products. Furthermore, there are a number of research challenges not mentioned in Section II. C., including the following [25], [26]:

- *Sensor node development:* Topics to be addressed are resource constraints, reliability, low maintenance and operational cost, harsh environmental conditions, i.e., interference, highly caustic or corrosive environments, high humidity levels, vibrations, dirt and dust, or other conditions that challenge performance [26].
- *Networking and communications:* These include integration with Internet and other networks, low operation and maintenance cost, highly secure wireless communication using open standards to decrease costs and the human and other resources needed to operate a WSN. Cognitive radio approaches to WSN communications are an important area for T&D due to the harsh environment.
- *Architectures and protocols:* It is necessary to develop flexible and scalable architectures. A modular and hierarchical system can enhance the system flexibility, robustness, and reliability [26].
- *System integration:* System operators could easily be overwhelmed with sensor data from a massive WSN deployment and techniques for storing, processing and fusing such data is required. Methods for efficient data representation and advanced algorithms for data reduction have vast research scope [27]. Integration and interoperability with existing legacy solutions, such as SCADA, fieldbus and Ethernet-based systems, is required [26].
- *Real-time requirements.* Real-time requirements, include latency, network throughput, etc. In addition,

since sensor data are typically time sensitive, e.g., events in the electric power systems, it is important to receive the data in a timely manner in order to enable appropriate corrective action.

- *Quality of service (QoS):* QoS refers to the accuracy between the data reported to the sink node (the control centre) and what is actually occurring [28] taking into account specific application requirements and real-time requirements.
- *Security:* Security should be an essential feature in the design of WSNs to make the communication safe from external attacks and intrusion. WSNs pose some unique security challenges [12] and it is likely that some customization and further evaluation of any existing solutions would be required before deployment.
- *Reliability, availability and robustness* of all the above. Inevitable failures and malfunctions may cause severe contingencies in the power system and therefore fault-tolerant technologies and approaches are required [29].

Other open issues include optimal sensor node deployment, localization, interoperability between different industrial WSN manufacturers [26].

An appreciation for the potential scale of a WSN deployment and associated installation and maintenance challenges can be obtained by examining Fig. 1. Note, in particular, the number and different types of sensors indicated just for a narrow application focusing on the mechanical health of the transmission grid.

WSN implementation for distributed power delivery monitoring poses several technical challenges and issues and current capability does not meet the requirements. Academic/research papers on relevant topics indicate promising results, but in many cases remaining problems are identified and additional research proposed.

Mature WSN applications for T&D monitoring still needs to be developed. Complete 'off-the-shelf' solutions do not currently exist as current systems only appear to be in a development and test phase. Many commercial entities claim to have solutions, but on closer investigation it turns out that their solutions are made up of an integration of existing systems being marketed for other applications. A built-for-purpose sensor network architecture potentially offers the most benefits.

VI. Conclusion

This paper provided a generalized overview of an Eskom study on the feasibility of WSNs on its T&D grid excluding aspects related to grid stability and dynamic power routing. Four key WSN application areas to the utility were presented which covered: theft; sagging conductors; insulation breakdown; and fault detection and location.

There is strong evidence that WSNs do offer significant benefits in real-world T&D systems but there are several significant challenges with current implementations. Both the readiness of WSN technology and the existence of mature

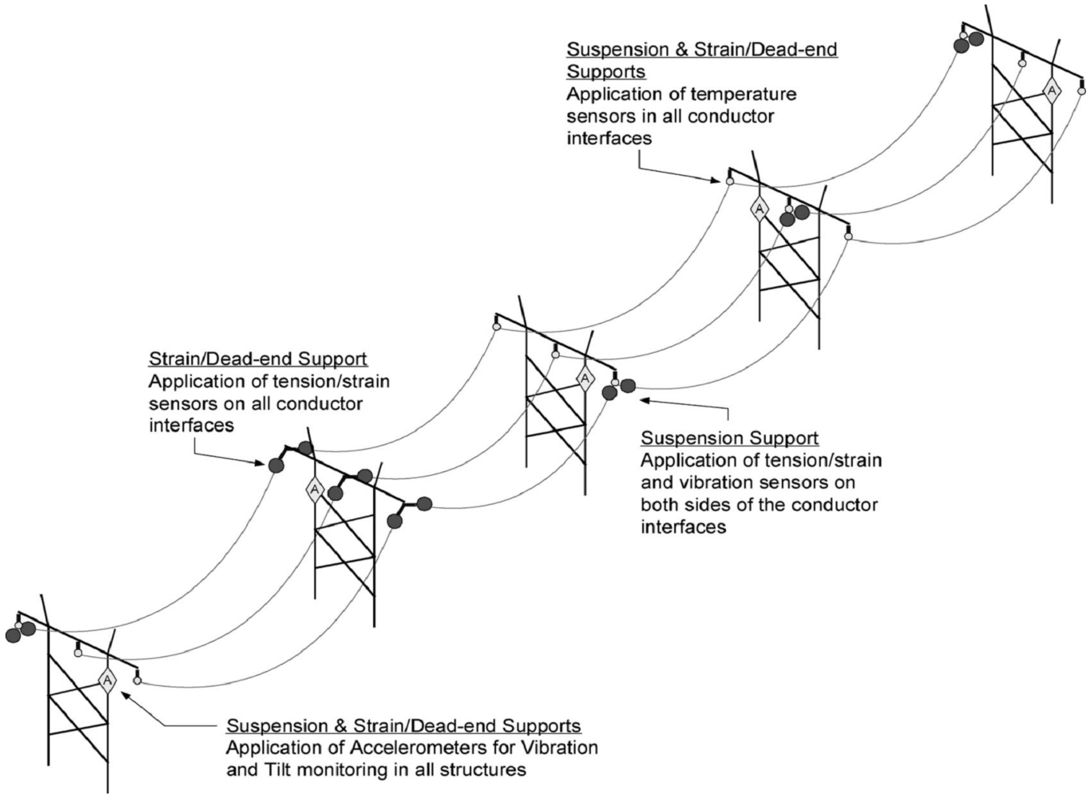

Figure 1. Conceptual placement of various sensors to monitor mechanical conditions pertaining to conductors and transmission structures [23]

WSN applications are lacking to confidently deploy in T&D networks currently. At this stage it is very hard to quantify the investment required by a utility to overcome these challenges in concert with the R&D community. However, nobody will disagree that huge amounts could be saved through the successful implementation of appropriate WSN monitoring and associated maintenance systems.

As utilities do not typically deploy "bleeding edge" technology, a close R&D partnership with research institutions and commercial entities to customize WSN solutions to a particular utility's T&D requirements is needed, especially focusing on the challenges highlighted in this paper.

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