

NSF PROJECT ECS-0601423:

Power Line Sensor Nets for Enhancing Line Reliability and Utilization

FOURTH AND FINAL PROGRESS REPORT: April 2010

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A. Introduction

The project commenced in May 2006 and has had a one-year no-cost extension.

The main objective of this research has been to develop a distributed Power Line Sensor Network (PLSN) to provide continuous on-line monitoring of the geographically dispersed power grid by using hundreds of thousands of low-cost, autonomous, smart, and communication-enabled Power Line Sensor (PLS) modules in order to improve the utilization and reliability of the existing power system [1].

The proposed PLSN specifically targets the use of passive sensing techniques, focusing on monitoring and predicting the real-time dynamic capacity of a specific span of a power line under present weather conditions by using computational intelligence technologies. An ancillary function is to detect the presence of incipient failures along overhead power lines via monitoring and characterizing the electromagnetic fields around overhead conductors.

A **first report** was submitted in January 2007. The first report

- summarized a survey that was conducted to review recent sensing technology developments in power grid monitoring, as well as the existing communications technologies for power system applications. The ZigBee Wireless Sensor Network (WSN) technology has been chosen to provide the communication backbone for the proposed PLSN, because the technology is uniquely characterized for its flexibility, inherent intelligence, fault tolerance, high sensing fidelity, low-cost, and rapid deployment, which is an ideal solution for wide area and cost effective monitoring systems;
- described the initial work on investigating the underlying technologies to implement the proposed Power Line Sensor Network (PLSN), including the evaluation and prediction of real-time dynamic thermal rating (RDTR) of overhead power lines by using artificial intelligence technologies;
- described early work on investigating the underlying technologies about vicinity monitoring of overhead power conductors via measuring and analyzing the electromagnetic (EM) field around overhead power lines.

A **second report** was submitted in March 2008 for the period from February 2007 to February 2008, which included results centered on the following major thrusts:

- Modeling the thermal behavior of overhead power conductors in the presence of different ambient weather conditions and electrical conditions.
- Detailing the principles by which the heat removal capability of overhead conductors can be estimated based on only current and temperature measurements. With the proposed Power Line Sensor (PLS) module as the platform, a Multilayer Perceptron Neural Network (MLPN) based scheme is used to estimate two weather-related parameters in real time, and tracking the time-varying ambient weather condition, which is used to predict the line thermal capacity at the span where the PLS module is mounted.
- Exploring principles by which Electric field (E-fields) around overhead conductors can be used to estimate both the voltage of the line, as well as clearance of the line to the ground; establishing a mathematical space-phasor based model of each conductor's E-field in a 3-phase overhead power line system.
- Understanding the limits of ad-hoc sensor network communication devices operating in a high electrical noise environment, particularly in the presence of corona discharge noise.
- Integration of multiple functions for a PLS prototype module, including the design and fabrication of a preliminary prototype unit to demonstrate its basic operating characteristics, and to provide a platform to demonstrate the advanced functionality.

A **third report** was submitted in April 2009 for the period March 2008 to March 2009, which summarized activities and findings centered in the following thrusts:

- Using an Echo State Networks (ESN) based model to identify overhead power line segment thermal dynamics under different weather conditions, and thus to predict conductor thermal behavior under the present weather conditions. This method removes the need for an analytical conductor thermal model. The direct prediction of conductor temperature can be achieved by the well-trained ESN identifier, and thus help to evaluate the line dynamic thermal rating.
- The ESN identifier replaces the analytical conductor thermal model that is generally required by both conventional methods and the MLPN based method when establishing the dynamic thermal rating of an overhead line. The dynamic thermal behavior of the conductor identified by the ESN model can effectively reflect the heat-removal capability of the conductor caused by any cooling effects, i.e. convective cooling, radiative cooling and/or evaporative cooling (omitted in both the conventional methods and the MLPN method). This removes the difficulty in measuring and quantifying the meteorological parameters especially associated with the evaporative cooling effect.
- Exploring principles by which Electromagnetic (EM) energy wave propagation along overhead power lines can be used to detect the shunt impedance variation along power lines, in order to detect and locate the presence of incipient faults in the vicinity of PLS modules.
- Building a first prototype PLS device to evaluate the behavior of the PLS module on a power line carrying high current; setting up a laboratory PLSN in the Intelligent Power Infrastructure Consortium (IPIC) lab at Georgia Tech to evaluate the system performance;

B. Progress during the One Year of No-Cost Extension from April 2009 to April 2010.

1. ***Real-Time Dynamic Thermal Rating Evaluation of Overhead Power Lines based on Online Adaptation of Echo State Networks***

1.1 *Overhead Power Lines Dynamic Thermal Ratings*

The fact that the inherent conservatism in conventional overhead line ratings result in underutilization of the power grid has been widely recognized by utilities [13] [14]. To assist utilities in utilizing the overhead power lines more effectively and thus to optimize the utilization of the existing system, it is important to know the actual current capacity or capability of lines down to a 'per span' level of granularity. Specially, during contingencies, when a particular line may have to be overloaded for a short period of time before a new generator can be dispatched, it is important for the control room operator to know by what percentage the current in that particular may be increased and for how long. The maximum allowable short-term overload capability of a line is normally called the *Real-time Dynamic Thermal Rating* (RDTR) of the line.

Formulation of the RDTR requires the accurate assessment of the ambient weather conditions along the line (either directly measured or indirectly inferred), and an accurate prediction of conductor temperature ahead of time under different ambient weather conditions. Traditional methods normally require direct measurements of the weather conditions, in order to quantify various meteorological parameters, and to establish a complex analytical model for overhead conductor thermal dynamics. Such methods are often expensive, complex and difficult for real-time implementation.

1.2 *Online Adaptation of ESN based Thermal Dynamics Identifier*

To overcome the above difficulties, a novel strategy of using an Echo State Network (ESN) (type of neural network) has been developed to directly identify the non-linear dynamics of the conductor thermal behavior, under various weather conditions. The well-trained ESN identifier replaces the analytical conductor thermal model that is required by both conventional methods and the MLPN based method (as proposed and developed in the second year of the project) when establishing the line dynamic thermal rating. The ESN identifier can be directly used to predict the conductor temperature subject to various conductor overload conditions, and in turn helps evaluate the line dynamic thermal rating.

Similarly to the MLPN based method, this ESN based method also requires only there real-time measurements, i.e. conductor temperature, ambient temperature and conductor current, as inputs that can be obtained from the PLS module [7]. However, the ESN method is advantageous compared to the MLPN based method in the following aspects:

As an alternative form of a Recurrent Neural Network (RNN), the ESN is a promising tool to identify non-linear dynamical systems [18], while MLPNs are successful in solving static mapping problems. Even though MLPNs have been used to identify dynamic systems in many applications [19], they do not effectively capture the dynamics of a system and the prediction of the system transient behavior can be obtained only one step ahead. The ESN, on the other hand, is able to learn the

complete transient behavior of a dynamic system, e.g. the overhead conductor thermal behavior studied in this research. If an ESN model is applied to identify the conductor thermal dynamics, the need for an analytical conductor thermal model is removed, so is the need for prior knowledge of the conductor's properties. On the other hand, an analytical model with prior knowledge is still required by the MLPN method. Besides, the dynamic thermal behavior of the conductor identified by the ESN model can effectively reflect the heat-removal capability of the conductor caused by any cooling effects, i.e. convective cooling, radiative cooling and/or evaporative cooling (omitted in both the conventional methods and the MLPN method). This relieves the difficulty in measuring and quantifying the meteorological parameters especially associated with the evaporative cooling effect. Moreover, the training of an ESN is simply a linear regression task [20], which is much simpler than the generalized back propagation (BP) algorithm needed in the MLPN method and makes it a promising solution for real-time implementation.

The research in the third year of the project has demonstrated the usefulness of the proposed ESN model as an identifier for conductor thermal dynamics under various ambient weather conditions; the ESN's ability to predict conductor temperature up to 40 minutes ahead of time was also validated with acceptable accuracy when compared to calculations based on the IEEE Std. 738 thermal dynamics model [15]. The ESN-based identification was, however, conducted in an offline batch learning mode.

The research in the fourth year extended that earlier work by comprehensively investigating the ESN's ability to adapt itself to time-varying ambient weather conditions on a continuous base in real time. Figure 1 shows the online adaptation scheme of the ESN identifier for overhead conductor thermal dynamics. As shown in the figure, an ESN Identifier is used to identify the actual conductor thermal dynamics (Ref. [5] provides a more detailed introduction about the overhead conductor thermal dynamics). The ESN model takes conductor current, I , and ambient temperature, T_a , as inputs (directly measured from the PLS module) and the estimated conductor temperature T_c^* as output. During the system identification, the network function $f_{ESN_Idf}(\cdot)$ is trained to maintain a minimized error between T_c^* and the actual conductor temperature T_c , and continuously adapts itself to any time-varying changes in the conductor thermal dynamics caused by the weather condition variations.

At any instant of time, once the ESN_Idf is updated, the most recent weights are exported to another ESN model, denoted as ESN_Pred (of the same structure as ESN_Idf). The ESN_Pred, $f_{ESN_Pred}(\cdot)$, then runs independently and functions as a conductor temperature predictor driven by a set of different, assumed overload conditions of the conductor, and in turn helps evaluate the dynamic line rating. More details and results are available in the complete paper [10] at the end of this report.

The ESN training algorithm is essentially a linear regression problem. This allows the ESN to continuously adapt itself to any changes in conductor ambient weather conditions without too much computation required, which makes it an attractive solution to real-time implementation. However, online adaptation of ESNs has its own issues and challenges, especially the network's stability. In this research, a Sliding-Window (SW) based online adaptive learning algorithm is developed to overcome this stability problem [10].

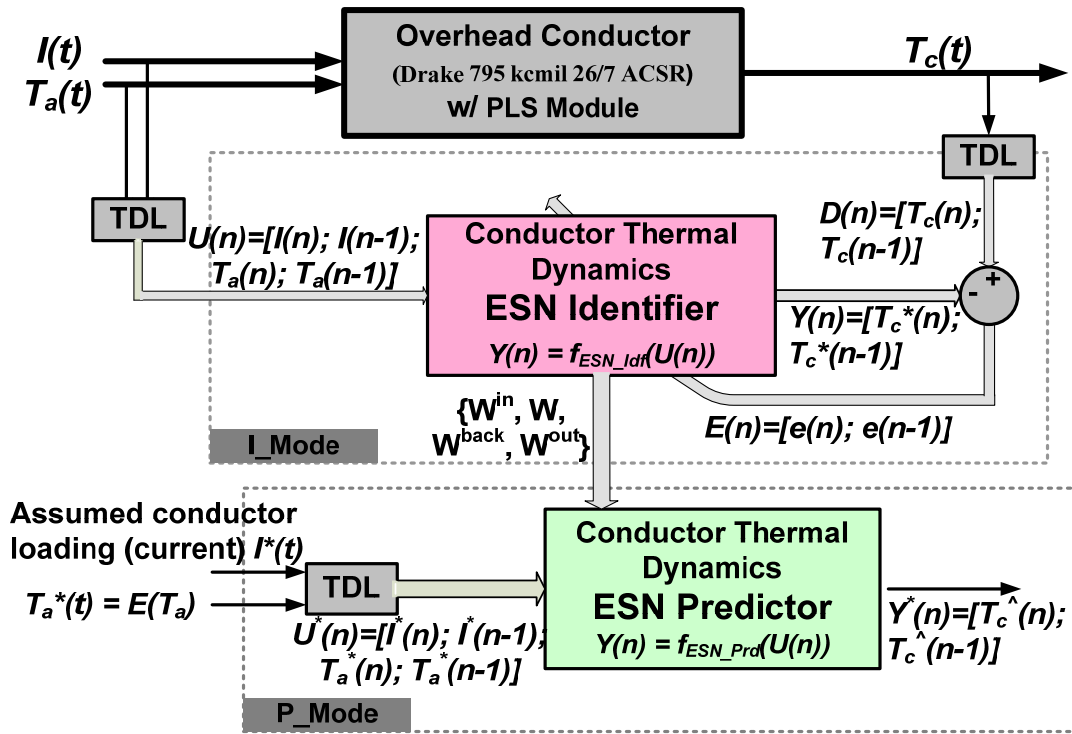


Fig. 1. Online Adaptation of ESN Identification for Overhead Power Conductor Dynamics.

1.3 Real-time Dynamic Thermal Rating Evaluation

The performance of the ESN online adaptation has been validated in both simulation and experimental environments. The results show that the ESN model is able to identify the conductor thermal dynamics, adapt itself to time-varying ambient weather conditions, and thus help evaluate the safe operating margin (thermal rating) of a line under the present ambient condition on a continuous base.

A 795 kcmil 26/7 ACSR (Drake) conductor has been evaluated as the base case. Figure 2 shows the experimental test set-up for the thermal testing of the Drake conductor. The set-up is powered through a 0-480 V feeder of controlled voltage. A step-down transformer, with a turns ratio of 10:1, is used to provide increased current on the secondary side. The ACSR Drake conductor closes the loop on the secondary with an inductive load of 120 μ H connected in series, and the system is capable of delivering up to 1500 A of continuous current through the conductor. A PLS module is clamped around the ACSR Drake conductor as shown in Fig. 2. Ref. [7] provides a more detailed description about the PLS module functionalities.

Inside the PLS module, three sensors are mounted to continuously monitor conductor temperature, ambient temperatures, and conductor current, which form the inputs to the ESN identifier. A Texas Instrument TMS320F2812 DSP inside the PLS module implements local computation for the ESN based adaptive conductor thermal dynamics identification and the RDTR evaluation in real-time. To introduce the time-varying

weather conditions, a wind-tunnel has been build to generate wind passing across the conductor with varying velocities, ranging from 3 ft/s to 18 ft/s.

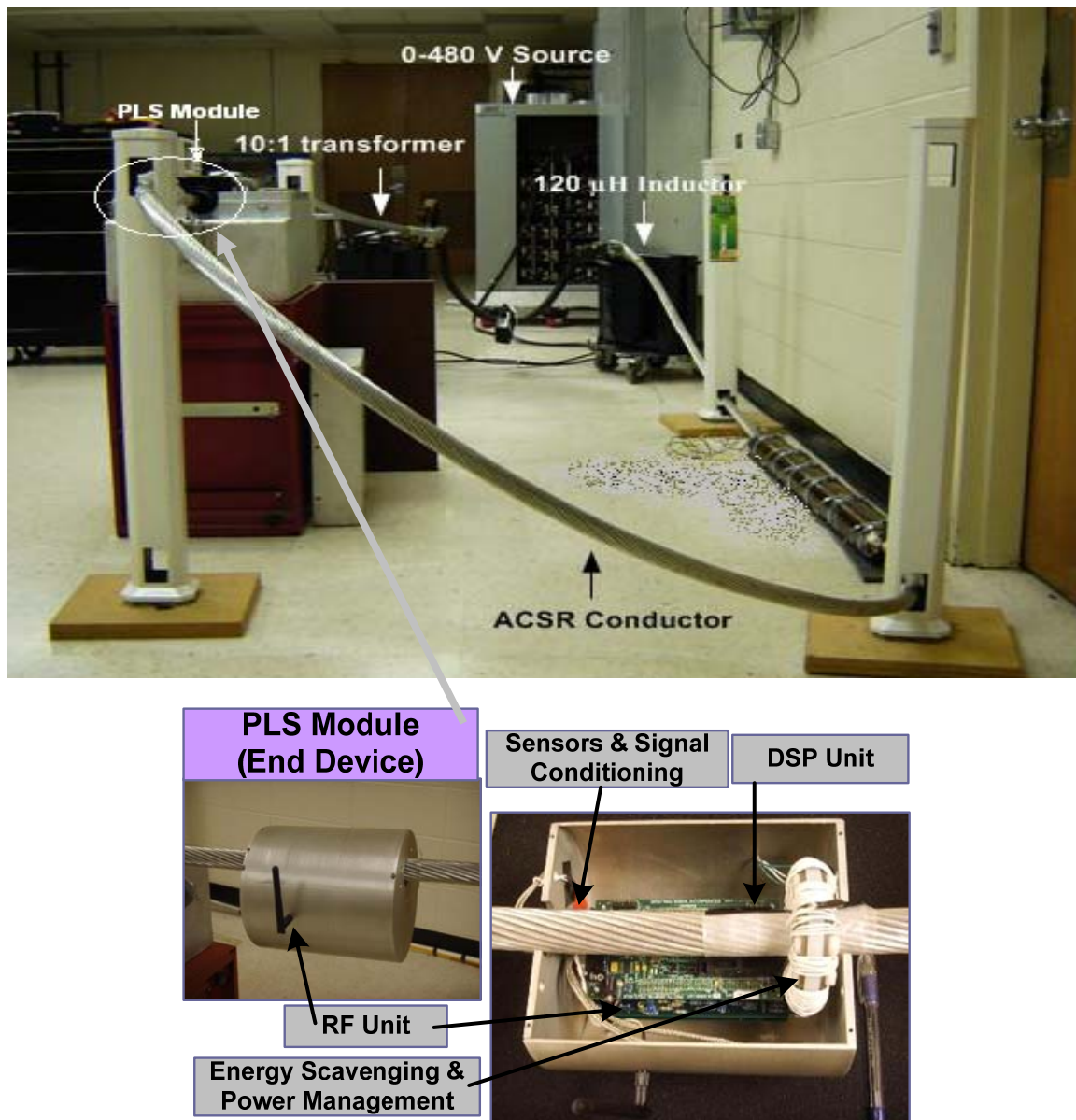


Fig. 2. IPIC Lab set-up for experimental testing.

Figures 3, 4, and 5 demonstrate the performance of the ESN based method to evaluate the real-time dynamic thermal rating of conductors under time-varying weather conditions in simulation environments. More details and results are available in the complete paper [10] at the end of this report. Figure 3 shows a set of time-varying weather conditions and loading conditions of the conductor for a period of two days. The ESN identifier is then continuously trained based on the proposed Sliding-Window (SW)-based learning algorithm for a period of two days. The continuously updated ESN identifier functions as a conductor temperature predictor under time-varying weather

conditions and in turn helps evaluate the I-T thermal limit curve (line dynamic thermal rating).

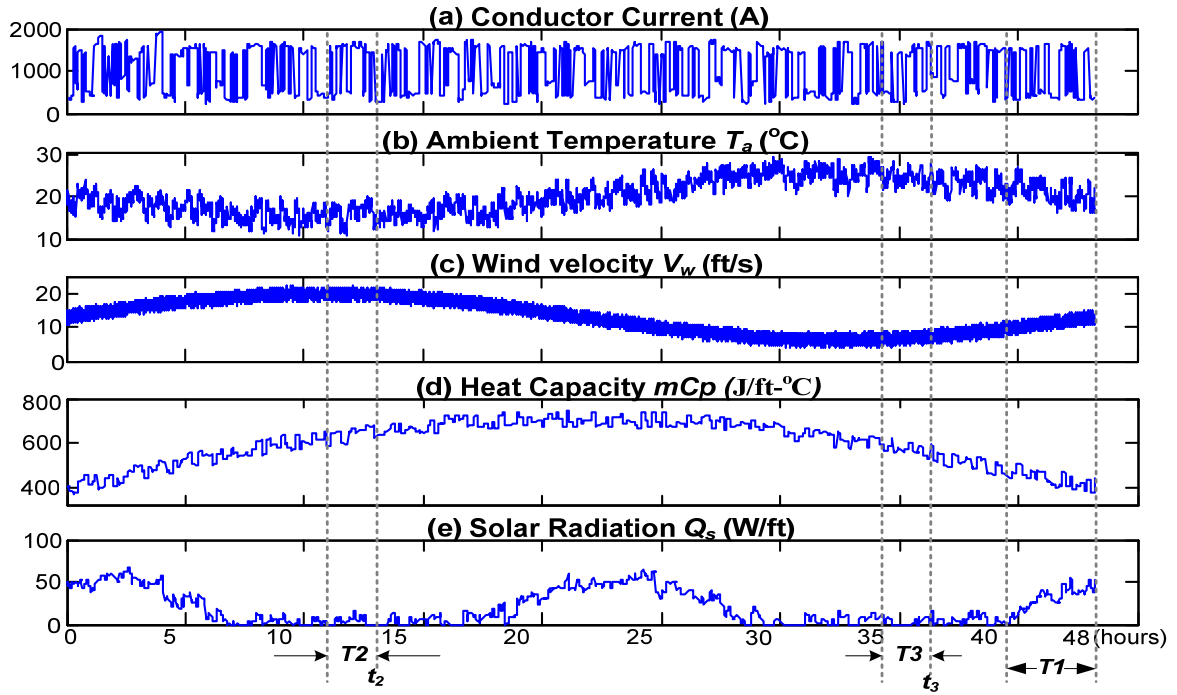


Fig. 3. Time-varying weather and loading conditions of the conductor for two days, including Joule heat gain; ambient temperature T_a ; wind velocity; conductor heat capacity; and solar radiation.

Figure 4 shows how the I-T thermal limit curve is updated continuously through time based on the weather and loading conditions as depicted in Fig. 3. For demonstration purposes, the examples shown in the figure are the curves as updated every 5 hours. The I-T curve is continuously sent from the local PLS module to a control center providing the operator with an effective guideline to determine the maximum allowable short term overload capacity under the latest ambient conditions for the line segment where the PLS module is mounted.

Figure 5 shows continuous profiles of the Real-time Dynamic Thermal Rating (RDTR), I_{dyn} , over an overload duration of 15 minutes (Fig. 5 (a)) and 25 minutes (Fig. 5 (b)). Comparing $I_{dyn}@25\text{minutes}$ to $I_{dyn}@15\text{minutes}$ in Fig. 5 reveals that the shorter the overload duration, the more the maximum allowable short-term overload current is allowed to flow through the conductor. This additional short-term capacity of the conductor is especially meaningful, when an emergency happens and the utility needs to temporally overload a particular line for a short duration. This short-term safe operating margin of a line can help the operator make an optimized load management decision and utilize the lines more effectively.

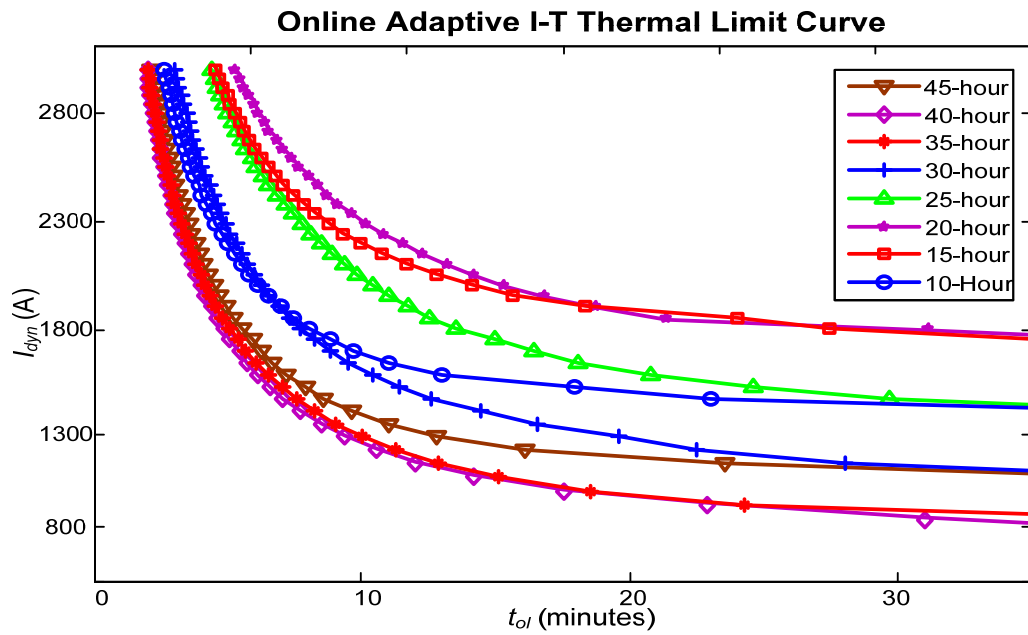


Fig. 4. I-T thermal limit curve updating through time.

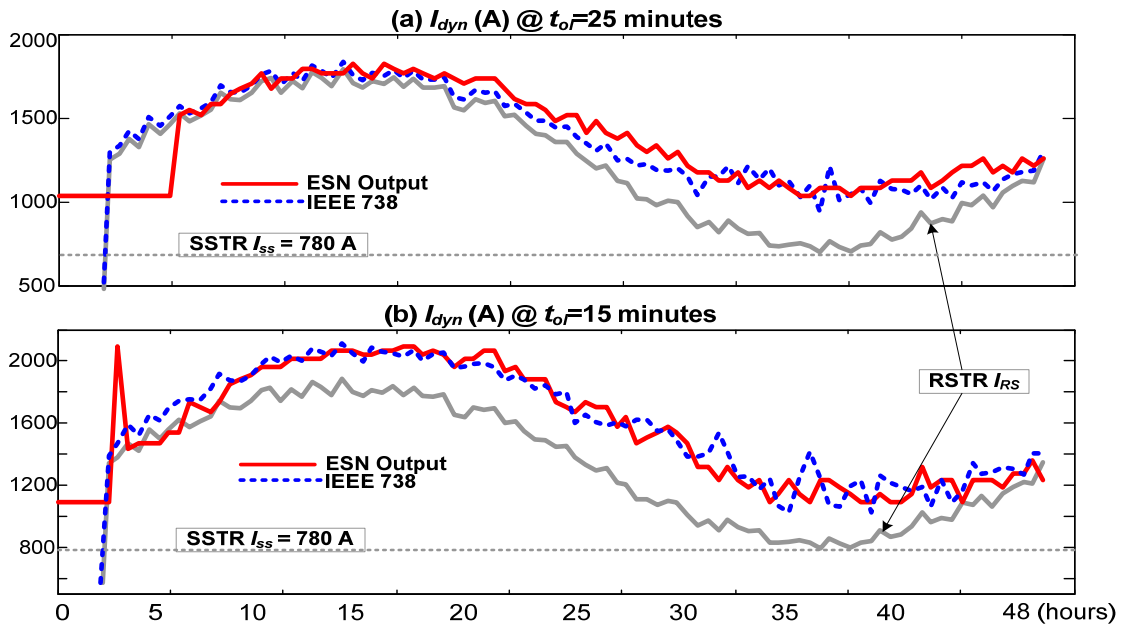


Fig. 5. Real-time dynamic thermal rating over an allotted overload duration: $t_{oI} = 25$ minutes; $t_{oI} = 15$ minutes.

2. Multiple Displacement Current Measurement to Detect the Conductor-to-Ground Clearance and Conductor Voltage

2.1 Power Line Vicinity Monitoring via Electric Field Analysis

Sensing and characterizing local Electromagnetic field (EM) signatures around overhead line conductors are additional useful auxiliary functions to implement on the proposed low-cost, distributed and massively deployed PLSN for power grid monitoring. Such EM sensing technologies potentially assess the local healthiness of power lines and predict incipient faults of lines, such as proximity of tree limbs, or violation of conductor-to-ground clearance. This kind of information, although extremely useful, is however normally not available to system operators and maintenance crews except by costly and slow manual inspection.

For overhead lines, there is a strong electromagnetic (EM) field around the line conductors, which are affected by insulation conditions between conductors and ground [16]. There has recently been much interest to develop sensing technologies to detect and characterize local EM signatures around line conductors, and thus to detect the healthiness of power lines and to predict incipient faults as discussed above. Driven by this motivation, a new sensing technique has been developed, by which an unprecedented sensitivity in line health condition monitoring can be achieved.

2.2 Multiple Displacement Current Sensor

For this function of the PLSN, a novel *Multiple Displacement Current Sensor* (mDCS), as a part of the PLS module, has been proposed and developed to capture the spatial mapping of the E-field distribution around the overhead conductor where the mDCS is mounted, and thus to detect the presence of incipient insulator failure between the conductor and the ground, and/or other conducting objects in vicinity of the line.

Figure 6 shows the cross-sectional view of a 3-phase overhead power line system, where an mDCS is clamped around phase conductor C, and is electrically connected to C. The mDCS consists of six capacitors that are 60° apart from one another, and are clamped together forming a cylinder as shown in Fig. 6. The inner layer of the mDCS has the same potential as surface of conductor C. The induced electric charge on the mDCS surface is thus affected in the same way as the induced charge on conductor C due to the conductor voltage and the conductor environment, such as conductor separation, conductor-to-ground clearance, and proximity of tree limbs, etc.

2.3 Space Phasor Model of Electric Field Distribution around Overhead Conductors and DQ-axis Decomposition

The E-field distribution around overhead conductors is affected by both conductor voltage and line geometry variations, such as conductor-to-ground clearance, or proximity of tree limbs to conductors. The analysis of the E-field distribution around the conductor captured by the mDCS enables the separation of the capacitive coupling

effects between the conductor and its adjacent conducting objects in different directions, and thus allows independent and accurate measurements of both conductor voltage and line geometry variations.

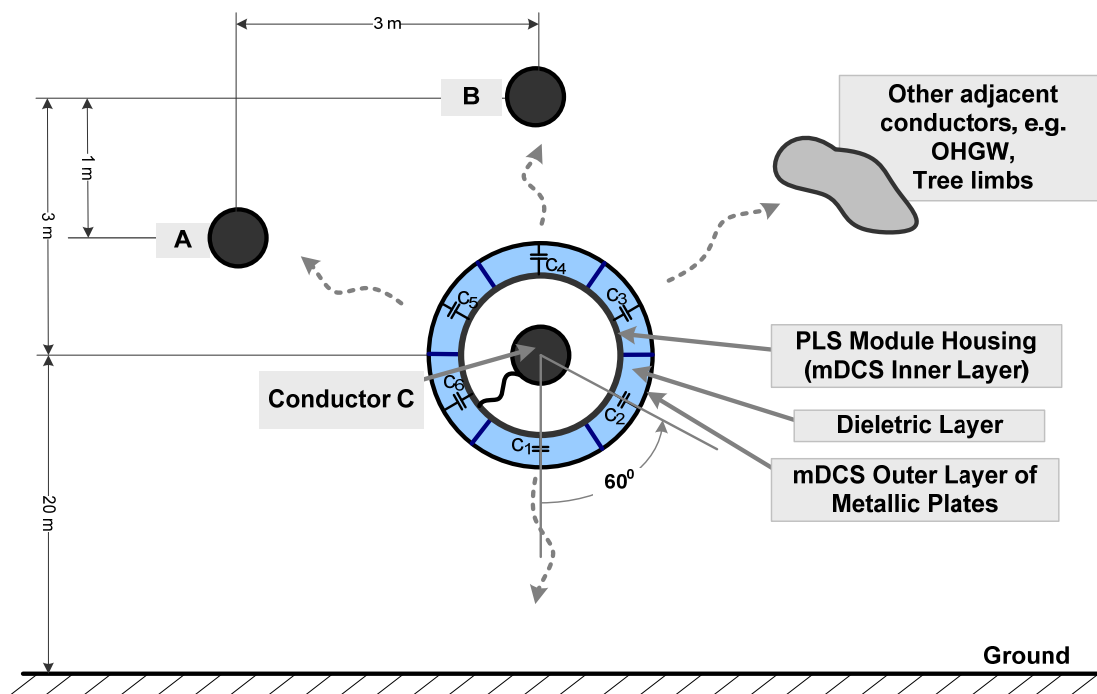


Fig. 6 Multiple Displacement Sensor (mDCS) as a part of the PLS Module mounted around a Overhead Conductor

An original, new concept of *Distributed Capacitance Density* (D_{cap}) between two conductors has been introduced to help establish a Space Phasor model of E-field distribution around overhead conductors. A DQ-axis decomposition technique is used to separate the capacitive coupling effects between the conductor, where the mDCS is mounted, and other adjacent conducting objects in different directions. The decomposed DQ-axis components are thus used to enable the independent measurement of both conductor-to-ground clearance and conductor voltage. Figure 7 shows the block diagram of the information extraction procedure.

The mDCS sensing scheme is a passive sensing solution. It only requires a simple capacitor add-on to the existing PLS module, which is low cost, robust, and easy to implement. The performance of the mDCS sensing scheme has been validated in the simulation environment. The results show that the effects of the conductor voltage and line geometry variation have been successfully decoupled. More details are available in the complete paper [9] at the end of this report. This method provides a promising solution to measure the conductor-to-ground clearance and assess the clearance between line conductors, thus to detect possible abnormal conductor movements, such as conductor gallop. At the same time, this method has the potential to measure overhead conductor voltage magnitude. It eliminates the need for high voltage isolation, which is normally required by conventional expensive and bulky high voltage

measurement solutions, and thus provides a low-cost solution for high-voltage measurement.

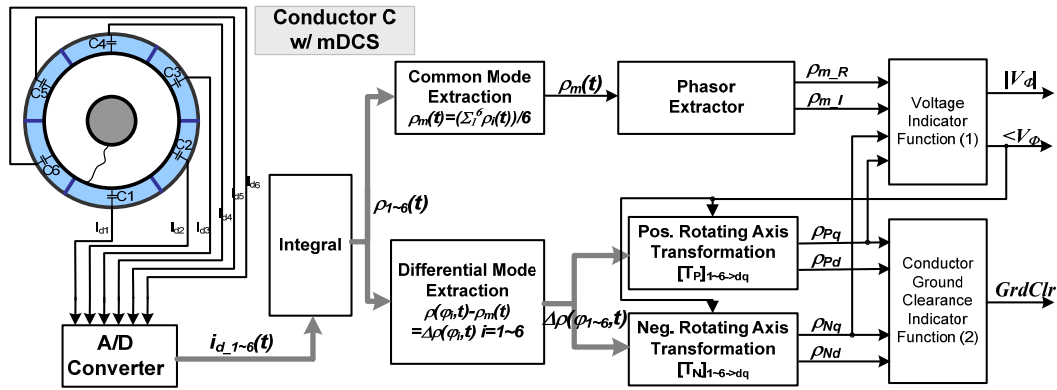


Fig. 7 Overhead line conductor voltage and conductor-to-ground clearance measurement based on mDCS scheme

3. Power Line Vicinity Monitoring via Electromagnetic Wave Propagation Detection

3.1 Electromagnetic Wave Propagation along Overhead Power Lines

Overhead power lines are essentially transmission systems wherein EM wave energy is guided or constrained by the line conductors. At high frequency of excitation, the EM wavelength (e.g. 150 m at 5 MHz) is much shorter than the length of the line itself (typically many miles). Therefore, an overhead power line can be viewed as a distributed-parameter structure along the line, and the EM wave propagation along the line is defined by its line parameters, i.e. series impedances and shunt admittances in a typical distributed-parameter line model [17].

As a non-uniformly distributed transmission line system, discontinuities along an overhead power line happen all the time because of many reasons, including the non-uniformly distributed terrain configuration, varying tower heights along the line, and other line disturbances, such as galloping and sagging conductors, gradual intrusion of tree limbs, skin and proximity effects of conductors and earth, insulation failure, etc. These phenomena are widely recognized by utilities as important factors to affect the reliability of the system. Since line discontinuities affect the EM wave propagation along a line, the accurate measurement and proper analysis of the wave propagation enables the detection of any variations in line parameters and thus to sense and locate the presence of incipient faults along the line.

3.2 Time-Domain Reflectometry based Line Vicinity Monitoring

To obtain the line discontinuity information with acceptable granularity, with the PLS module as the platform, a Time-Domain Reflectometer (TDR) based method has been developed by injecting a wide-bandwidth signal into an overhead power conductor from the PLS module. A novel information extraction procedure based on Time-Domain Reflectometry technology has been proposed to capture the impedance discontinuities along overhead power lines, and therefore to detect and locate line disturbances in the vicinity of the PLS module along the line, and to detect the presence of any line incipient faults.

Figure 8 shows an example of the TDR based PLS power line vicinity monitoring system, where the PLS modules are assumed to be clamped over the phase B conductor, with a 2 km separation from one module to another. Each PLS module is proposed to work as a TDR device, by injecting a short period of wide bandwidth frequency voltage signal of 10 volts into the phase B conductor once in a while, say every 5 minutes.

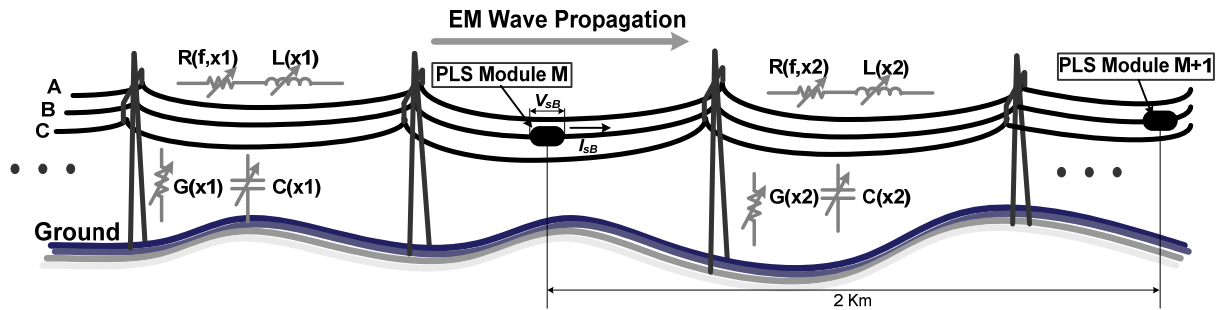


Fig. 8 TDR based PLS power line vicinity monitoring

The variation in equivalent impedance $\Delta Z_{eq}(l)$ seen by the PLS module is evaluated, which enables the capturing of any time-varying line discontinuity (line shunt impedance variation) in the close vicinity of each PLS module, thus to detect and locate the presence of line incipient faults. The “visible” range of each module is 4 km (both sides of the module), considering the EM wave attenuation along the line caused by line losses.

An “anti-chirp” process has been developed to extract information, where the measured signals in real time are firstly converted to quantities in the **Frequency Domain**. Then a modified Inverse Fourier Transformation (IFT) is applied to convert all values to the **Longitudinal Domain**, as shown in Fig. 9. The “anti-chirp” process provides the solution to the equivalent impedance variation in the longitudinal variable l , which directly describes a profile of line discontinuity variations at any point l along the power line with reference to the PLS module location.

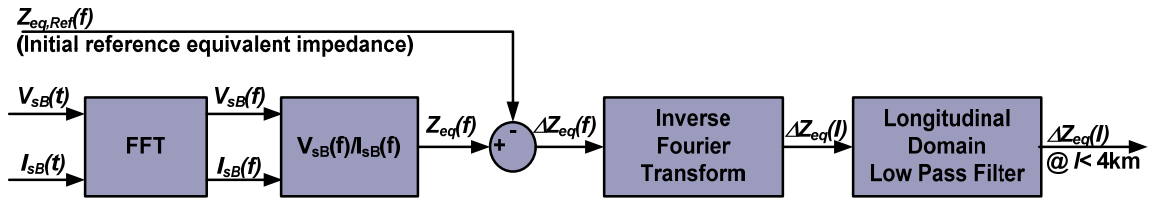


Fig. 9 “Anti-Chirp” process for information extraction

To validate the performance of $\Delta Z_{eq}(l)$ as an indicator to capture and locate the line disturbances, studies have been conducted in the PSCAD/EMTP simulation environment. The PSCAD/EMTP frequency-dependent line model based on a practical transmission line geometry configuration has been used for simulation validation.

A cascaded multiple-line-section setup has been used and provides the flexibility of changing line parameters at a certain location along the line, which is used to simulate the time-varying line disturbances along the line, such as line conductor galloping, conductor sagging, tree branches intrusion, etc.

Figure 10 shows an example of the detected equivalent impedance variation $\Delta Z_{eq}(l)$ in Longitudinal Domain subject to a certain line disturbance. To simulate line disturbances, the configurations of two elementary line section models are changed from the original line setup. About 1000 to 1500 meters to the right side of a PLS module under study, the conductor-to-ground clearance is decreased from 25 to 23 meters (by 2 meters) in order to represent a fault in the simulation. At the same time, to the left side of the PLS module, the conductor-to-ground clearance is decreased from 20 to 16 meters at a location between 2050 and 2080 meters away from the PLS module. Figure 6 indicates clear peaks on the magnitude of $\Delta Z_{eq}(l)$ at the locations where the line clearances have been changed. It also shows abrupt changes in the phase angle at the same locations. This result validates that, $\Delta Z_{eq}(l)$ is a promising indicator of the variations in shunt impedance of the line. It directly provides a profile of line disturbances at any point along the power line in the vicinity of the PLS module under study.

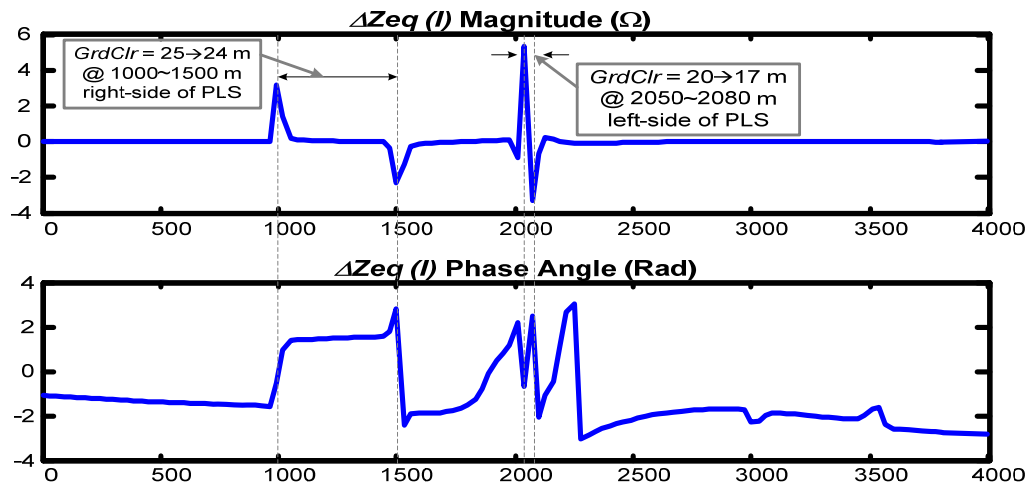


Fig. 10 “Anti-Chirp” process for information extraction

3.3 Issues

This TDR based method belongs to the category of intrusive sensing technologies, which potentially increases the cost, power requirement and complexity of the PLS module. Moreover, any interference from electromagnetic fields external to the overhead power lines must be considered. These incident fields may be generated by distant transmitting antennas or by nearby radiating structures. The induced current subject to such external incident-field coupling may generate current waveforms that can be falsely identified as the sensing signal, thus causing misjudging of incipient fault detection.

However, the TDR method has distinct advantages. Providing a profile of line disturbances at any location along the line, the TDR method, unlike the mDCS based method, is able to detect the line disturbances caused not only by line inherent movements (i.e. conductor sagging or galloping), but also discrete line disturbances (i.e. proximity of tree branches).

4. **Prototype PLS Module and Laboratory Power Line Sensor Network (PLSN)**

A laboratory PLSN has been set up in the Intelligent Power Infrastructure Consortium (IPIC) lab at the Georgia Institute of Technology as shown in Fig. 11. A prototype Power Line Sensor (PLS) module has been built with four functions integrated, and it has been tested on the Drake power line conductor as shown in Fig. 2. The experimental testing has shown that the module can be autonomously powered with the primary side power conductor current ranging from 100 A to 1200 A.

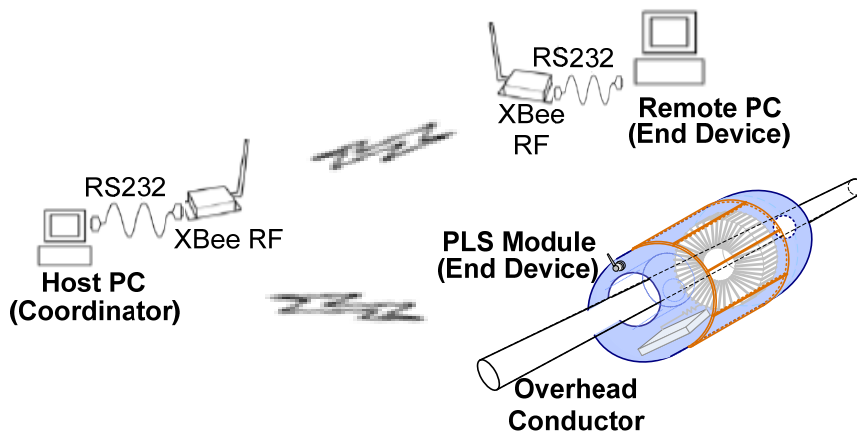


Fig. 11 IPIC lab Power Line Sensor Network

The concept of the proposed PLSN has been validated in a laboratory environment with the network performance given in Table I. Figure 12 presents four channels of signals received by the host PC every 0.2 ms continuously for two hours.

TABLE I
IPIC LABORATORY POWER LINE SENSOR NETWORK PERFORMANCE

PLSN Networking Performance	
Outdoor RF Range	1.6 km
RF data rate	250 kbps
Packet TX rate	20 msec (100-byte)
Sensing Channel	Up to 8

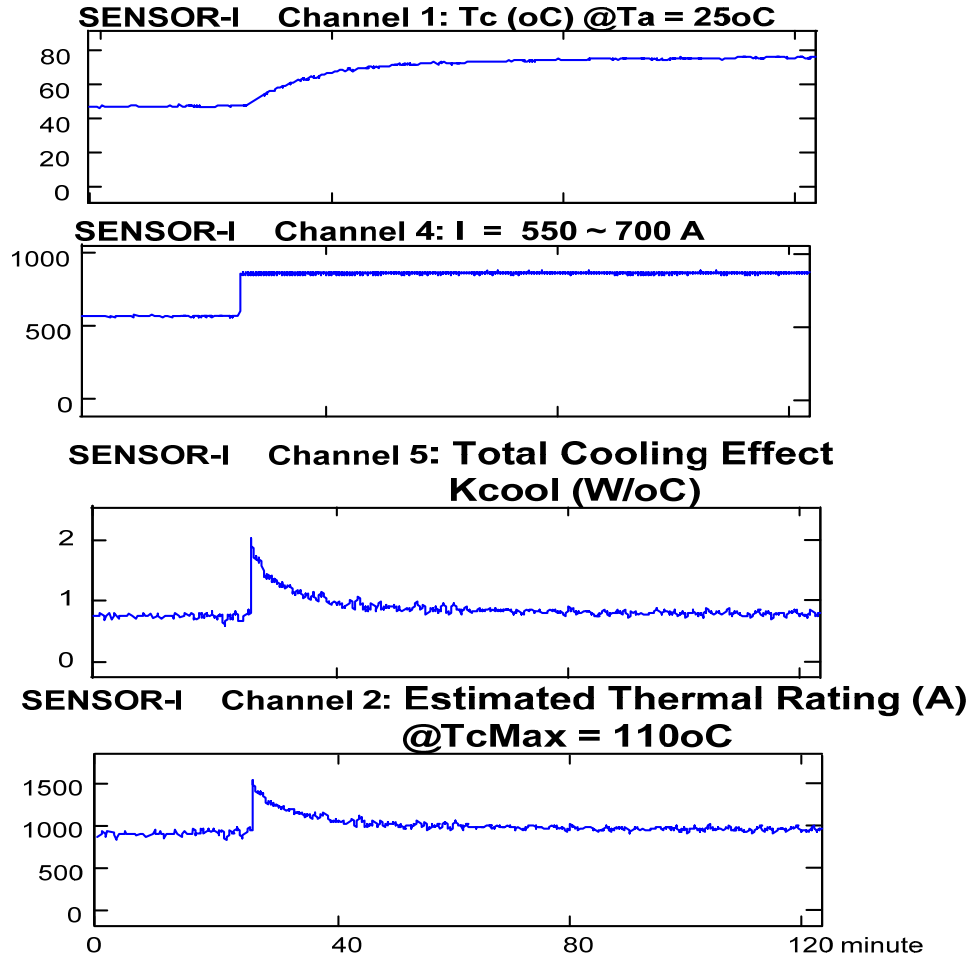


Fig. 12 IPIC Lab Prototype Power Line Sensor Network Experimental Results

To validate the Wireless Sensor Network (WSN) communication protocol performance and to evaluate the maximum transmission distance supported by this RF device, a loopback test between the PLS module and host PC has been performed in the lab environment. The test results show that outdoor transmission distance up to 400 meters with a transmission successful rate up to 80% is achievable. More details and results are available in the complete paper [7] at the end of this report.

5. Presentations at Conferences

- IEEE International Joint Conference on Neural Networks (IJCNN) 2009, June 14-19, 2009, Atlanta, USA.
- IEEE PES General Meeting 2009, 26 - 30 Jul. 2009, Calgary, Alberta, Canada.
- IEEE Energy Conversion Congress and Exposition (ECCE) 2009, Sept. 20-24, 2009, San Jose, USA.
- The IEEE Symposium on Diagnostics for Electric Machines, Power Electronics and Drives (SDEMPED'09), Cargèse (France), Aug. 31 – Sept., 2009.
- IEEE Intelligent System Applications to Power Systems (ISAP'09), Curitiba, Brazil, Nov. 2009.

D. Summary

A novel concept of a Power Line Sensor Network (PLSN) has been proposed to provide cost-effective, continuous and distributed large area monitoring of the power grid. By deploying low cost sensing technologies, and exploiting the cost effective communications technologies, i.e. Wireless Sensor Networks (WSNs), it allows a dramatic reduction in cost and enables a grid-wide, distributed deployment of the PLSN. A prototype Power Line Sensor (PLS) module with four functions integrated has been designed, fabricated and validated in the Intelligent Power Infrastructure Consortium (IPIC) lab. The lab PLSN has proven its capability as a platform to demonstrate more advanced functions in future work.

With the PLS module as the platform, an Echo State Network (ESN) based identifier has been developed to adaptively identify the overhead conductor thermal dynamics under different weather conditions on a continuous basis with good accuracy [1]. Through the use of the ESN model, the conductor temperature has been predicted for up to 30 minutes ahead to assist in determining the *Real-time Dynamic Thermal Rating* (RDTR) of the line in real time. This method removes the need for direct measurement of line ambient weather conditions by small weather stations, and gives an accurate assessment of the actual line thermal capacity to a “per-span” level of granularity.

A novel Multiple Displacement Current Sensor (mDCS), as a part of the PLS module, has been proposed to capture the spatial mapping of the E-field distribution around an overhead conductor, in order to sense the presence of incipient insulation failure between power conductors to ground, and/or to other nearby conducting objects. The analysis of the E-field distribution enables the independent measurements of both conductor-to-ground clearance and conductor voltage.

The electromagnetic (EM) energy wave propagation along overhead power lines has been investigated to detect the presence of incipient faults. The PLS module has been proposed to act as a Time-Domain Reflectometer by injecting a wide-bandwidth frequency signal into one conductor of a power line. The equivalent impedance seen by the PLS module has been evaluated to characterize and locate the line incipient failures, especially caused by shunt-impedance variations along the line.

The theoretical concepts on line EM signature measurement to indicate imminent insulator failure, or incipient contact with vegetation, show promise in realistic simulations. However,

laboratory experiments have been difficult because of the high sensitivity needed for signal extraction.

The design of the power supply for the PLS module has been validated through simulation and experimentation. However, the existing design requires a 'clamp-on' arrangement to harvest power from the line, which is less desirable for utilities, and can change the conductor temperature itself, leading to inaccurate estimates. Methods are being developed to improve the accuracy including an alternate 'energy harvesting' technique that would allow these sensors to operate as 'lick-n-stick' sensors that would not need to be clamped around the power line conductor. This part of the research has led to a follow-on project opportunity.

A comprehensive survey of the existing sensing technologies for power system application has been conducted and carefully analyzed. A complete survey of the state of the art in the fields of the existing communications technologies and the existing energy-scavenging technologies has also been conducted. These two sets of surveys lead to a good understanding of the full scope of potential applications, concerns, constraints and issues for the wide-scale deployment of distributed sensor networks for power grid monitoring.

D. Overall Project Deliverables after Four Years

1. Manpower

The following PhD candidates worked on different aspects of this project at Georgia Tech:

- Harjeet Johal, (now with General Electric Global Research)
- Yi Yang, PhD (now with Eaton Corp. Innovation Center, Milwaukee, USA).
- Rohit Moghe.

All students have learned how to

- conduct literature surveys
- develop computer code and run simulations
- prepare power point presentations and present their work to others
- write scientific papers
- collaborate with other members of the research group.

2. Follow-on Projects

The project has already generated significant knowledge, and has already resulted in several follow-on projects as we translate the underlying work to real sensor networks that can be deployed by utilities as they move towards a 'smart grid'. Sensors such as those proposed here will be the backbone of the smart grid.

- "Potential Applications for Sensor Networks in Power Delivery", funded by the National Electric Energy Testing Research and Applications Center (NEETRAC) at Georgia Tech.
- "Energy Scavenging for Wireless Sensor Device over Power Lines" funded by NEETRAC;
- "Stick-on" Current / Temperature Wireless Sensor" funded by NEETRAC

Utility interest in the demonstration of the functions targeted in this project is high. At the biannual meetings of the Intelligent Power Infrastructure Consortium (IPIC), 30-40 attendees from utilities and industries participate and are exposed to the developments from this project.

3. Publications

- Altogether 12 peer reviewed papers were published in international journals and conferences [1-12].

4. Courses Taught

- At Georgia Tech Dr. Harley taught a 3 credit hour one semester graduate level course on “Computational Intelligence in Electric Power” three times during the course of this project to a total of 28 students.
- At Georgia Tech Dr. Divan introduced and taught a 3 credit hour one semester graduate level course on “Advanced Power Electronics” four times during the course of this project to a total of 80 students.

5. Awards and Prizes

- SDEMPED Best Paper Award to, Y. Yang, R. G. Harley, D. M. Divan, and T. G. Habetler, "Thermal Modeling and Real Time Overload Capacity Prediction of Overhead Power Lines", Proceedings of the IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives (SDEMPED2009), Cargèse (France), August 31 - September 3, 2009

D. References

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 - [10] Y. Yang, R. G. Harley, D. M. Divan, and T. G. Habetler, "Real-Time Dynamic Thermal Rating Evaluation of Overhead Power Lines based on Online Adaptation of Echo State Networks", accepted by *IEEE 2010 Energy Conversion Congress and Exposition (ECCE)*, Sept 2010, Atlanta, GA.
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E. Publications arranged by Year

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F. Appendices