Journal of Computer and Communications, 2018, 6, 92-103
http://www.scirp.org/journal/jcc
ISSN Online: 2327-5227
ISSN Print: 2327-5219

Real Time Power Monitoring Detection Based on Sequence Time Domain Reflectometry Approach

Sam Moayedi, Subhaditya Shom, Andrew Harms, Mahmoud Alahmad

University of Nebraska-Lincoln, Omaha, Nebraska, USA
Email: smoayedi2@unl.edu, sshom@unomaha.edu, harms@unl.edu, malahmad2@unl.edu

How to cite this paper: Moayedi, S., Shom, S., Harms, A. and Alahmad, M. (2018) Real Time Power Monitoring Detection Based on Sequence Time Domain Reflectometry Approach. *Journal of Computer and Communications*, **6**, 92-103.
https://doi.org/10.4236/jcc.2018.61010

Received: October 22, 2017
Accepted: December 26, 2017
Published: December 29, 2017

Abstract

Sequence Time Domain Reflectometry (STDR) have been demonstrated to be a powerful technique for detecting the length of cable or length of open circuit or short circuit cables. Using this method along with using smart meter on the main electrical panel board to monitor consumption if load at each circuit, enable user to monitor power consumption at each node (power outlet) only by operating a smart digital meter and an STDR circuitry on each circuit at the main electrical panel board. This paper introduces this method and examines it on dead-wire and energized wire with a load connected across it. Experimental results are demonstrated for both types. Test result show the potential application of this approach to provide consumption information and potential cost saving via feedback for users.

Keywords

Wire Length Detection, Sequence Time Domain Reflectometry (STDR), Time Domain Reflectometry (TDR), Maximum Length Sequence, Coupling, Power Consumption Monitoring

1. Introduction

People in their daily life interact with electricity via their electrical devices ranging from, laptops to phone chargers. New electrical devices with different application are connecting to power grid every year and this increases the total power consumption. These devices can be connected and operated at different times. Some loads can be disconnected or turned off after user finished working with them but sometimes these devices can be left "on" for hours per day. Users sometimes get surprised by their electricity bill's amount that need to be paid.

Therefore, users want to know their power consumption details so they can manage to reduce some of their unnecessary usage. Currently regular meters can provide total power usage like kWh. Based on this fact, offering consumers with enough feedback of their electricity usage rates is an essential step to reducing the energy waste [1]. By energy management and using technologies advancements, oil consumption can be dropped by 15% lower by 2040 [2]. According to Energy information administration (EIA), in 2016 residential sector consumed 20,413 trillion British thermal unit (Btu) that is one fifth of total U.S total power consumption and 3.85 Trillion kWh (64%) of it in form of electricity [3]. Research suggests that residential customers account for a significant amount of energy wastage [4]. It should be mentioned that some electrical devices consume energy while they are turned off or in standby mode. This type of consumption being called "Phantom Load". A research on energy with Wisconsin utilities accounted phantom loads for costing more than *$3* billion dollars annually [5]. American Council for an Energy Efficient Economy (ACEEE) conducted a study and found that feedback devices cannot increase the energy saving by itself [5]. Therefore, there should be new methods to encourage energy savings through users. For instance, any method that can be used for identification of type and location of load would benefit smart buildings to save energy. Hence, focus of the research should be on monitoring the electrical nodes where loads are connected to the building power lines to observe the consumption and conservation.

Integration of new technologies and methods can lead to developing better smart buildings. Using smart sensor for each load in order to measure and record load characteristics and send captured data to main server at system entrance for further analyze can be an example of this new technologies. Wireless monitoring network using a Wi-Fi and ZigBee technologies and a PIC-based software is being investigated in [6] to control home's electrical facilities remotely in order to reducing household energy.

An existing method that is used to locate open and short conditions of electrical cables is Time Domain Reflectometry (TDR). TDR is a Non-Intrusive Load Monitoring Methods (NILM). This method has been used for locating faults on wire like short circuits or damage to wire structure [7]. TDR method relies on measuring the time-delay of injected signal with its reflection into the cable. TDR needs a load recognition algorithm based on a database of load signatures to distinguish different loads. Furthermore, TDR cannot be used on live wires.

Due to above mentioned technique's limitations, a new technique for locating power consumption nodes as Sequence Time Domain Reflectometry (STDR) along with measuring the power at the desired circuit by smart power meter has been proposed in this paper that overcome those constraints. In this method, a high frequency pseudo-noise sequence (PN Sequence) sends through the wire and it reflects back at any impedance mismatches or discontinuities [8].

Section 2 discuss about TDR method. Section 3 represent the STDR method. Section 4 discuss the experiment procedure. Section 5 describes the results. Conclusion given in Section 6 and Section 7 talks about future works.

2. Time Domain Reflectometry

Time Domain Reflectometry (TDR) method has been used for locating discontinues on wire like short circuits, faults or damage to wire. A pulse signal shape injects to the wire and it reflects back at any impedance mismatch. By analyzing the signal's time for traveling to the end and back and using the velocity propagation (VOP) of wire, delay can be calculated. Using delay which is a time constant, length or distance can be computed. Signal transmission for single flow is pictured in **Figure 1**.

In **Figure 1**, signal generates at TDR and injects to wire. The initial reflection occurs at the beginning of cable where attaches to TDR due to impedance mismatch and its reflection coefficient is Γ_0 and can be calculated by Equation (1) [9].

$$\Gamma_0 = \left(Z_1 - Z_0/Z_1 + Z_0\right) \quad (1)$$

where Γ_0 is reflection coefficient, Z_1 is cable impedance and Z_0 is signal generator impedance. T_{01} is the transmission coefficient from TDR to wire and described in Equation (2). Also, T_{10} is the transmission coefficient from wire to TDR and given by Equation (3) [9].

$$T_{01} = 1 + \Gamma_0 \quad (2)$$

$$T_{10} = 1 + \Gamma_{10}. \quad (3)$$

In Equation (3), Γ_{10} is the reflection coefficient that describes signal reflection back to the line at the junction of TDR and shown in Equation (4) [9].

$$\Gamma_{10} = \left(Z_0 - Z_1/Z_0 + Z_1\right) \quad (4)$$

When signal reaches at the end of cable, depends if there is a load or no load, reflection coefficient Γ_{12} at the load can be written as Equation (5) [9].

$$\Gamma_{12} = \left(Z_2 - Z_1/Z_2 + Z_1\right) \quad (5)$$

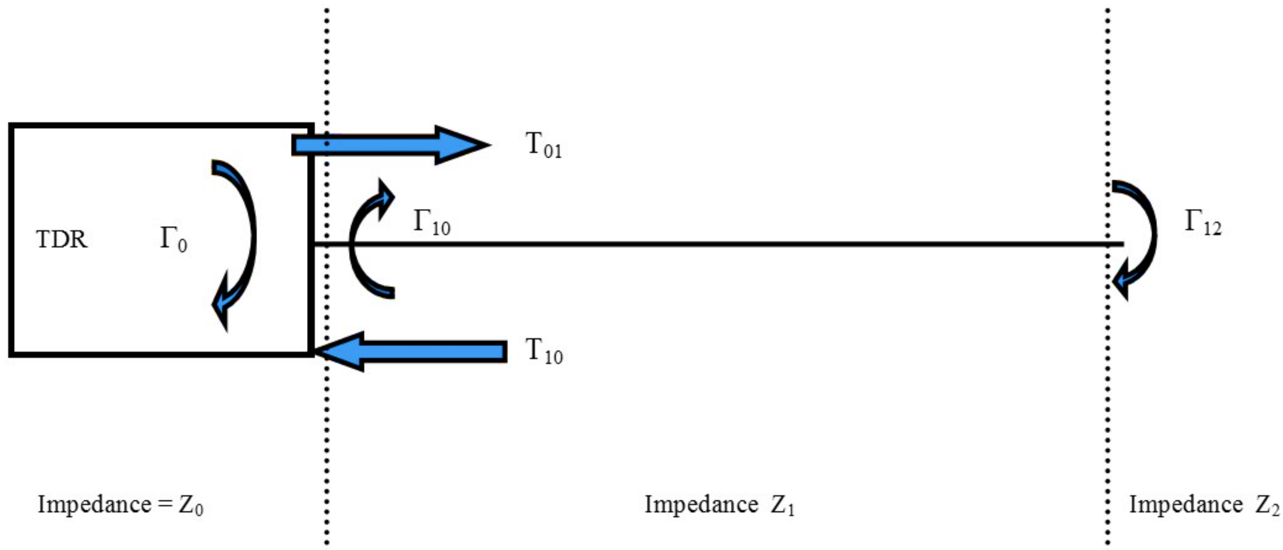


Figure 1. A single section TDR on a transmission line [6] [7] [8] [9].

Different branches can be added to the shown single section to make a complex system and similarly using the above mentioned equation, system can be analyzed.

TDR method calculates the time difference of the injected and reflected signal. Any impedance mismatches can be visible as a step in output. In TDR, using the achieved time difference and being aware of the velocity of propagation (VOP) in that specific wire or cable, length of wire can be computed. Equation (6) describes the VOP [7].

$$VOP = v/c \tag{6}$$

In Equation (6), v is velocity of signal in cable (inches per nanosecond) and c is Speed of light (299792.4 kilometer per second). Velocity of signal can be calculated through Equation (7). In Equation (7), d is the distance or length of cable and t is the time delay of signal that travels from point of incident and reaches the first impedance mismatch and reflects back [7]

$$v = (2 \times d)/t \tag{7}$$

Length or distance can be calculated using Equation (8)

$$L = (VOP \times c \times \Delta t)/2 \tag{8}$$

In Equation (8), Δt is the measured time delay in nanoseconds and length L is in meter.

By using Equation (7) and injecting a pulse into the 1.066-meter coaxial cable with 50-ohm resistance (RG-58A/U), measured time delay is 10.8 nanoseconds displaying in oscilloscope. Accordingly, v calculated to be 0.197 meter per nanosecond (7.777 in/ns). By using this number and applying it to Equation (6) and converting units into inch, VOP for this type of coaxial cable is 0.659 or 65.9 percent of speed of light.

By knowing the VOP of each cable and measuring the time delay, length can be calculated. But TDR is not best way to be used on live wire due to this fact that reflection can be hidden under noise signal of the signals in the tested wire. In addition, sometimes reflected signal overlap the incident signal because of very high speed of signal and the width of incident signal [10].

3. Sequence Time Domain Reflectometry

A procedure that can test energized cables or wires repeatedly and can offer location of fault, discontinuities, impedance mismatch or junction can be advantageous over the conventional test methods. Therefore, sequence time domain reflectometry (STDR) has been studied. STDR is more effective in fault detection, cost, accuracy [7]. STDR technique uses a continues pseudo-noise sequence along with processing gain to mitigate background noise [11].

This method is similar to time domain reflectometry although instead of using a single pulse, a maximum length sequence (m-sequence) will be used. In this technique, a high frequency m-sequence generated in arbitrary signal generator injects to the wire and upon any impedance mismatch it reflects back. Procedure in this method described as following:

3.1. Maximum Length Sequence (m-Sequence)

In order to transfer data between sender and receiver, it should be more than one message transmitting from sender and receiving by receiver. Simple method is by sending a pure impulse signal and measuring the time delay of signal in the medium. But amount of total energy's short pulse is limited and even by increasing the time duration to transmit more total energy, getting a sharp peak of time delay in correlation would be difficult. Therefore, by generating and applying a proper coded signal, the duration can be increased while the total transmitted energy increasing as much as maintaining the sharp peak in correlation. Hence m-sequence is being used in STDR method [12].

M-sequence (binary maximal length shift-register sequence) is part of pseudo noise codes that is the longest in PN-sequence code and had been studied well and are perfect fit for STDR technique. M-sequence is combination of ones and zeros that are periodic [6]. In addition, linear feedback shift-register (LFSR) and exclusive-OR (XOR) gate's circuits can produce this sequence. M-sequence code is an optimal choice due to lowest side-lobes in autocorrelation [13]. **Figure 2** layouts the block diagram of a LFSR generator with degree r [14].

M-sequence has a period of n that has shown in Equation (9). In Equation (9) r is degree of the generator polynomial.

$$n = 2^r - 1 \tag{9}$$

$g(x)$ is the primitive binary polynomial of degree m and it can be seen in Equation (10).

$$g(x) = g_r x^r + g_{(r-1)} x^{(r-1)} + \cdots + g_1 x + 1 \tag{10}$$

g_r corresponds to switch position. If switch is open, then g_r is equal to *zero* and if it is closed it represents *one*.

It should be mentioned that degree of generator polynomial is one unit less than the length of $g(x)$. For example, if r is equal to *4* then length of $g(x)$ is *5*.

3.2. Autocorrelation and Cross-Correlation

In order to interpret the signal in STDR which being carried on live wire, correlation method is being used. Correlation compares reference signal with the reflected signal. In other word, correlation measures the similarity between two phenomena [12]. In case of similarity between those signals, correlation value

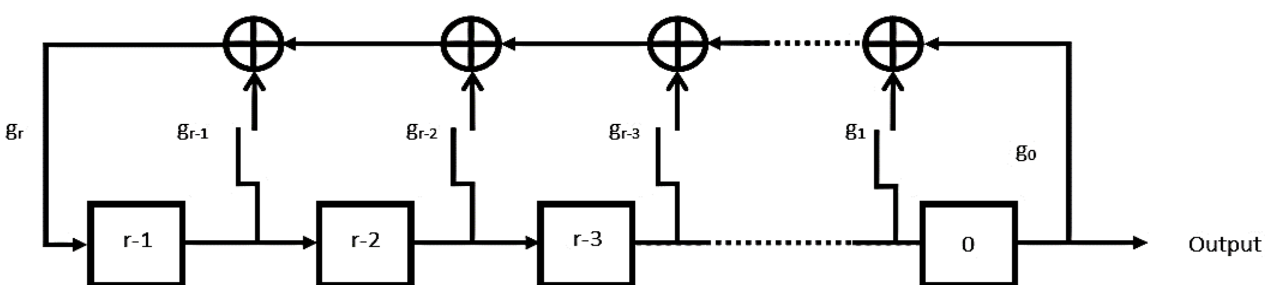


Figure 2. Linear feedback shift register for m-sequence [14].

would be high and it would be less if no match being detected between them. Autocorrelation is the correlation between a signal with the same shifted signal in time as a function of delay that can detects the period of signal. Cross-correlation is the comparison of two different signals to detect their similarities [12].

3.3. Coupling

Connecting sensitive or expensive measurement devices directly to the live or energized wire can cause damages to the devices. Therefore, coupler or coupling circuit designed to provide an indispensable galvanic isolation of the low voltage measurements device from high voltage power lines [15]. For instance, in power line communications (PLC), modem can be connected to the power line through couplers at both sender and receiver sides. Couplers classified into two main groups of inductive coupler and capacitive coupler. Inductive couplers are electrically separated or insulated from energized wire hence no direct electrical linkage is made. In this type of coupler, a magnetic core clamped around the cable and the whole circuit works as a transformer and signals can be induced to the power cable. Capacitive couplers are low cost and can be as simple as a single series capacitors or L-C filter. In most of PLC capacitive couplers, a transformer also added to increase the protection, impedance matching and also passing high frequency communication signal [16]. Capacitors in capacitive couplers should be able to pass high frequency signal and block or filter high voltage signals of power line thus they need to be high voltage capacitors [15]. Capacitors designed such a way that have a low impedance to allow high frequency signal to pass and have high impedance to block power line high voltage signal. Impedance of capacitor Z_c described in Equation (11).

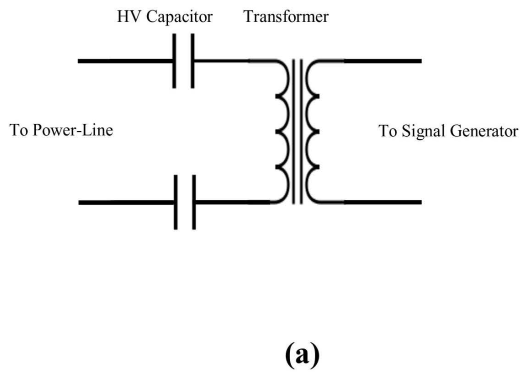
$$Z_c = 1/(2\pi fC). \tag{11}$$

Frequency has shown by f and C is capacitance in Equation (11). For instance, if it is desired to inject a 1.5-MHz signal into the wire using a 100 Nano-Farad capacitor, impedance for high frequency signal would be about 0.8-ohm while it is about 26.5 kilo-ohms for 60-Hz power line voltage.

Figure 3(a) represents the circuit for simple capacitive coupler. Also capacitive coupler that physically built can be seen in **Figure 3(b)**.

4. Experiment Procedure

Before proceeding to conduct experiment, length and frequency of signal should be calculated. The maximum length of a number 12 American wire gauge (AWG) in a building planned to be 45.72 meter (150 ft.) long. Moreover, one period of generated m-sequence signal should travel to the end of cable and reflect back before the next period generated. Therefore, velocity of propagation of *12* AWG cable calculated using Equation (6) to Equation (7) and it is 71.7% of speed of light. Applying this number to Equation (6), time period is 450.2 nanoseconds [7]. For this experiment KEITHLEY-3390 function generator is used. This signal generator can produce arbitrary wave-form up to 10 MHz with minimum of 30



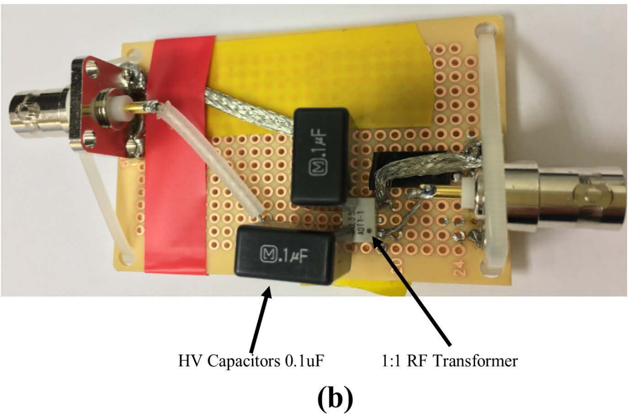


Figure 3. Coupler circuit and physical capacitive coupler.

nanoseconds rise and fall time. Length of the m-sequence (L_m) was computed to be 14.24 bit by Equation (12). The possible sequence is 15 bit.

$$L_m = Period/30ns \tag{12}$$

Therefore, time period based on the 15-bit sequence with minimum rise and fall time of 30 nanoseconds is 450 nanoseconds. Equation (13) yields to associate frequency to this time period that is 2.22-MHz.

$$Frequency = 1/T \tag{12}$$

Therefore, a 15-bit m-sequence signal with frequency of 2.22-MHz and voltage of 10 volt needs to be generated in signal generator. Later this signal injected to the three different number 12 AWG circuits with length of 15.24 meter (50 ft.), 16.76meter (55 ft.) and 27.43 meter (90 ft.). Incident and reflected signals data captured from scope and stored in computer for further analysis. Using MATLAB software cross-correlation of both incident and reflected signals calculated and graphed. Location of the peaks in the correlator corresponds the distance to the impedance mismatch or discontinuities.

5. Experiment Results

In this work, two different experiments conducted. In the first experiment, location of discontinuities in an open circuit 15.24 m (50 ft.) dead-wire detected. Experiment two was carried out on the energized wire of a building and after few minutes one load connected to that circuit to perform power consumption measurements. In this experiment a TED digital meter was installed on the target circuit at the main electrical panel board and location of power outlet along with changes in corresponding load was indicated.

5.1. Test on 15.24 m (50 ft.) Dead Wire in Open Circuit State

In this test, signal was injected from signal generator and reflected back. Cross-correlation of signals were calculated using MATLAB software and result shown in **Figure 4**.

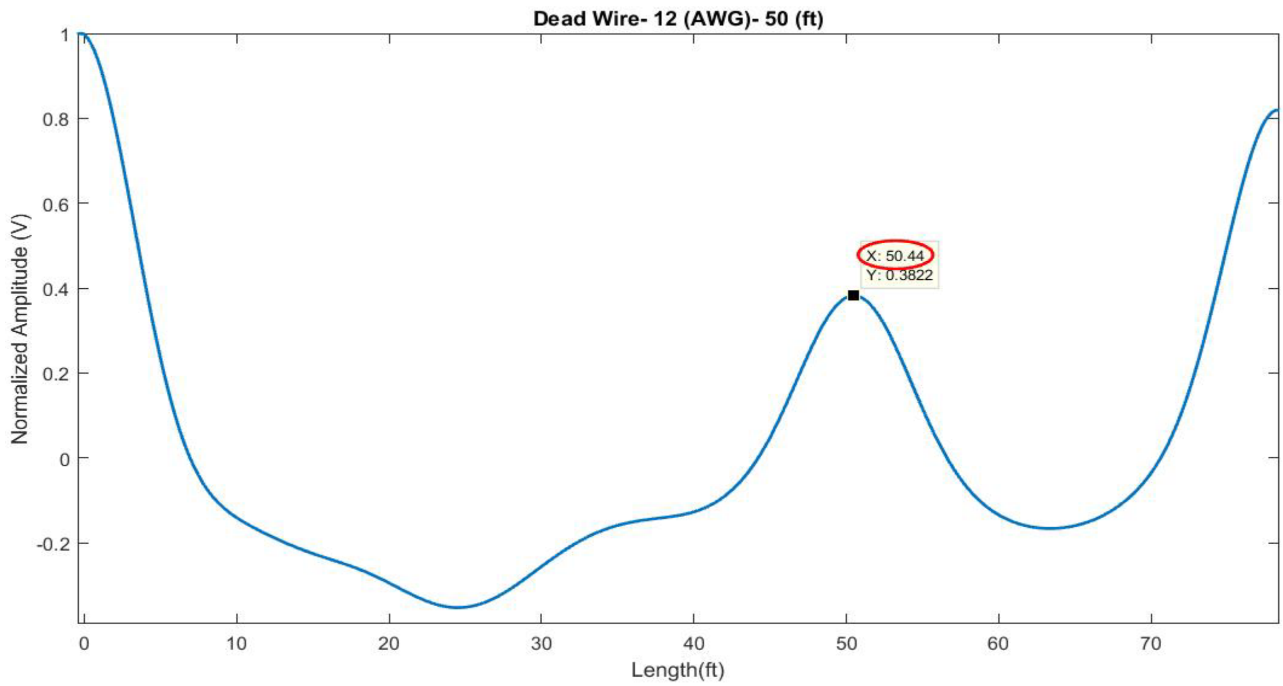


Figure 4. Result for cross-correlation for dead wire open circuit 15.24 m (50 ft.) long cable.

As can be seen in **Figure 4**, the highest peak occurred at 0 feet which corresponds to the highest similarity between two signals that is signal's period and repeats at every 450 nanoseconds. The other significant peak represents the length of 12 AWG cable at 15.37 m (50.44 ft.) with 0.8% error compare to the real physical length (15.24 m).

Another case in this test is applying the same signal into the same wire while it has been short circuited at the end of cable. From Equation (5) Γ_{12} is −1. **Figure 5** illustrates the cross-correlation result of cable while it was short circuited at the end.

According to **Figure 5**, lowest point in cross-correlation graph is at 15.16 m (49.74 ft.) that indicates short circuit at that end of cable. Error for this value is 0.5% compare to real physical value (15.24 m).

5.2. Test on Two Different Live Wires with Active Load

Purpose of this method is to minimizing the number of power consumption's measuring sensors on each power outlet. Thus, for this experiment only a single digital power meter was installed on the desired circuit at the main electrical panel board. Prior energizing the circuit and while circuit is open, circuit analyzed through the STDR method. Later, power line energized and a load connected to the power outlet as a typical residential load. This test ran for three different time states to verify results. For purpose of measuring the consumed power at circuit, TED Pro 6000/3000 was used. TED Pro 6000/3000 can monitor and log power usage and display the live data through its commercial software. Data extracted from TED software and power line circuit analyzed through the

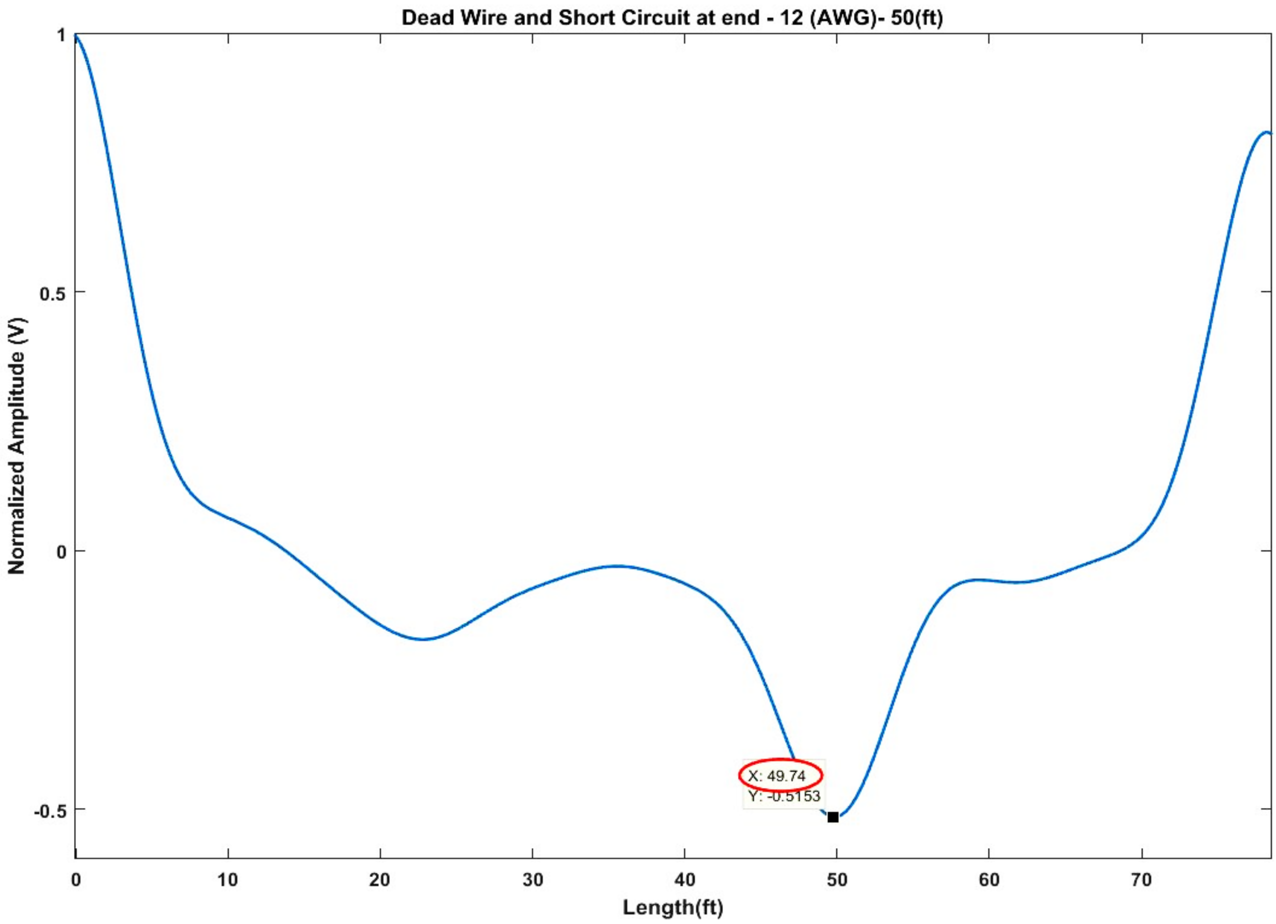


Figure 5. Result for cross correlation for dead wire short circuit 15.24 m (50 ft.) long cable.

STDR approach for locating the load by correlating the load location to consumed power in watts. Results is shown as a graph in **Figure 6**.

As shown in **Figure 6**, live wire test started at 11:21 morning and load connected at 11:23 to 11:26. Estimated power outlet location was 27.4 m (90 ft.) which can be seen in the marked area of open circuit data. After connecting a computer and monitor (inductive and resistive) load, location is constant compare to short circuit state and amplitude decreased which represents the active load. In order to verify the proposed method, location and power consumption of another circuit was examined too. In this case a 1500-watt heater load used. Location of load prior and after connecting to the desired node extracted, analyzed and presented in **Figure 7**.

According to **Figure 7**, location of node before and after feeding the load was detected and verified. In this test resistive load has a lower peak compare to the no-load condition that represents the presence of load in the cross-correlation analysis.

6. Conclusion

This paper presented a novel method for measuring the power consumption of

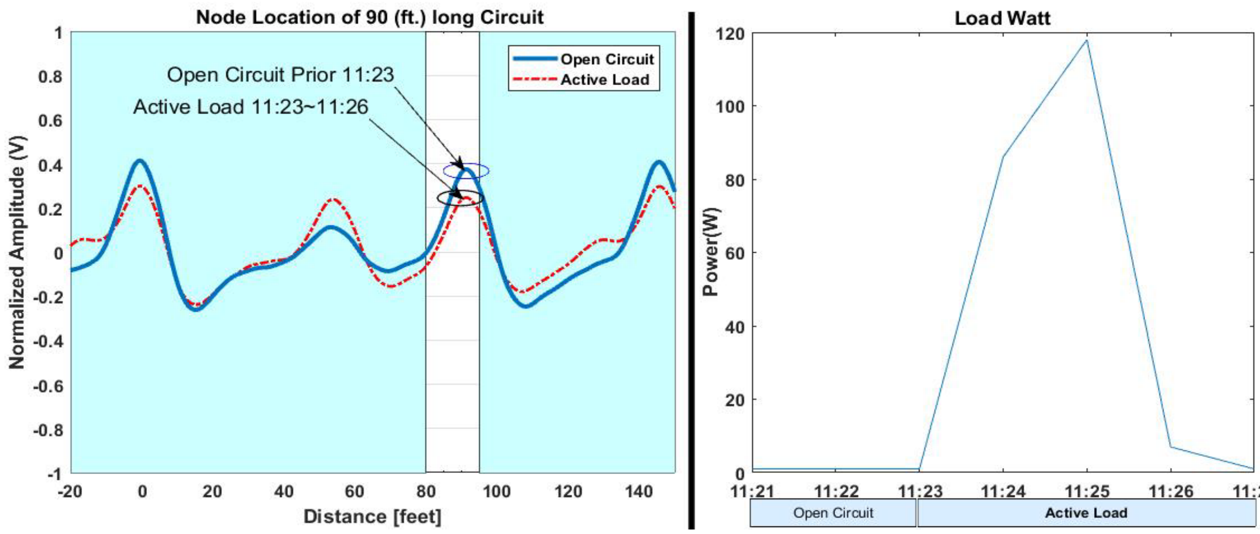


Figure 6. Power consumption and its corresponding node location.

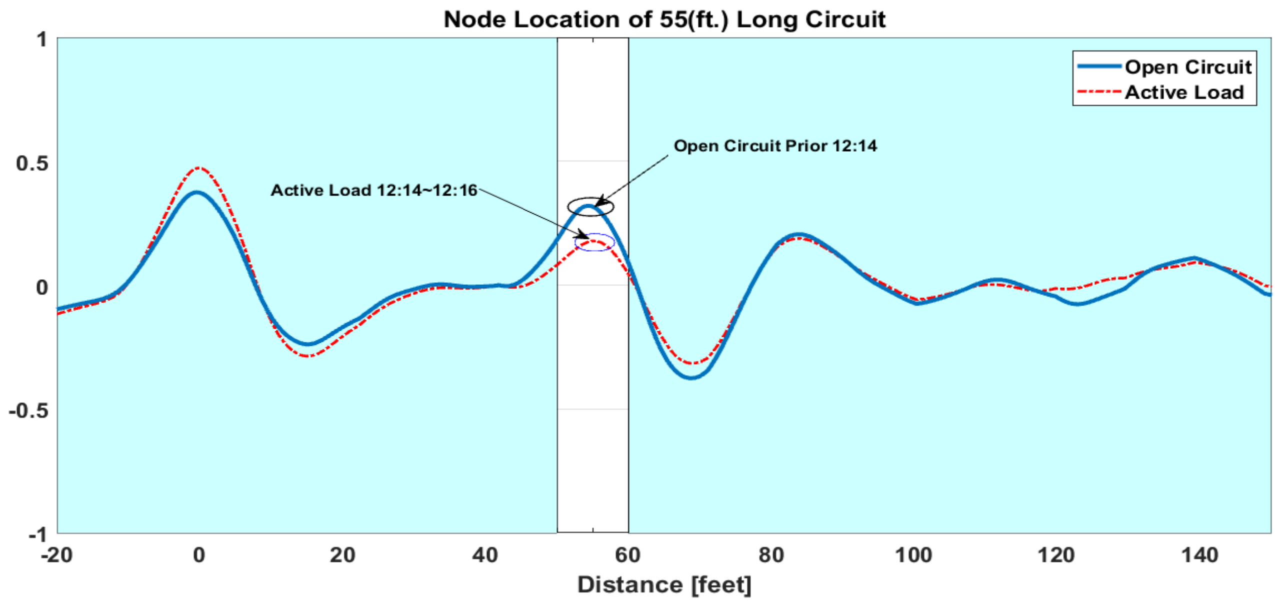


Figure 7. Power consumption and its corresponding node location.

connected load and its associated location in the energized power line using m-sequence and STDR technique. By using the provided equations and TDR method, VOP of cables along with time period of proper signal for signal generator computed. Coupling circuit designed in way to block high voltage signal from power line and protect the devices.

Different tests were performed for the dead wire and energized wire to detect the length of cable. These tests relied on the cross-correlation of incident and reflected signal. Power meter (TED) was monitoring the power consumption of desired node's circuit at the main panel board while simultaneously location of the connected load at residential electrical system discovered via STDR. Demonstrated results verified the accuracy of technique.

7. Future Studies

Based on the achieved results in this work, future focus will be on eliminating of any power meter sensor or device and instead analyzing the STDR data to identify loads based on their load signature.

References

[1] Alahmad, M., Nader, W., Neal, J., Shi, J., Berryman, C., Cho, Y., Lau, S.-K., Li, H., Schwer, A., Shen, Z., Stansbury, J. and Zhang, T. (2010) Real Time Power Monitoring & Integration with BIM. *Proceedings of the* 36*th Annual Conference of the IEEE on Industrial Electronics Society* (*IECON*), Glendale, 7-10 November 2010, 2454-2458. https://doi.org/10.1109/IECON.2010.5675385

[2] World Economic Forum (2016) Future of Oil & Gas. http://www3.weforum.org/docs/GACFutureofOilandGas_Executive_Summary.pdf

[3] US Energy Information Administration (EIA) (2016). http://www.eia.gov/energyexplained/index.cfm?page=electricity_use

[4] Marino, D.L., Amarasinghe, K. and Manic, M. (2016) Building Energy Load Forecasting Using Deep Neural Networks. *Proceedings of the* 42*nd Annual Conference of the IEEE on Industrial Electronics Society* (*IECON*), Florence, 23-26 October 2016, 7046-7051. https://doi.org/10.1109/IECON.2016.7793413

[5] Alahmad, M., Hasna, H. and Sordiashie, E. (2011) Non-Intrusive Electrical Load Monitoring and Profiling Methods for Applications in Energy Management Systems. *Proceedings of Systems*, *Applications and Technology Conference* (*LISAT*), Long Island, Farmingdale, 6 May 2011. https://doi.org/10.1109/LISAT.2011.5784233

[6] Visconti, P., Lay-Ekuakille, A., Primiceri, P. and Cavalera, G. (2016) Wireless Smart System for Monitoring and Driving of Household Electrical Facilities Remotely Controlled by Internet. *Proceedings of the* 16*th International Conference of the IEEE on Environment and Electrical Engineering* (*EEEIC*), Florence, 7-10 June 2016. https://doi.org/10.1109/EEEIC.2016.7555498

[7] Khan, N. (2015) Investigation of Sequence Time Domain Reflectometry (STDR) Application in Residential. M.AE Thesis, University of Nebraska, Lincoln.

[8] Reis, J., Castro, A., Costa, J.R.J.C.W.A. and Ericson, K. (2007) Sequence Time Domain Reflectometry for Transmission Line Analysis. *Proceedings of XXV Simposio Brasileiro de Telecomunicacoes* (*SBRT*), RECIFE, 3-6 September 2007.

[9] Wu, S.C. (2011) An Iterative Inversion Method for Transmission Line Fault Location. Ph.D. Thesis, The University of Utah, USA.

[10] García Fernández, P. (2014) Fault Detection in the DC Bus of a Vehicle. Master Thesis, University of Oviedo.

[11] Smith, P.S. (2003) Spread Spectrum Time Domain Reflectometry. Ph.D. Thesis, Utah State University, Logan.

[12] Golomb, S.W. and Gong, G. (2005) Signal Design for Good Correlation for Wireless Communication, Cryptography and Radar. Cambridge University Press, New York. https://doi.org/10.1017/CBO9780511546907

[13] Smith, P., Furse, C. and Gunther, J. (2005) Analysis of Spread Spectrum Time Domain Reflectometry for Wire Fault Location. *IEEE Sensors Journal*, **5**, 1469-1478. http://ieeexplore.ieee.org/document/1532290/ https://doi.org/10.1109/JSEN.2005.858964

[14] MathWorks (2017) PN Sequence Generator.

https://www.mathworks.com/help/comm/ref/pnsequencegenerator.html?s_tid=srchtitle

[15] Bilal, O., Liu, E., Gao, Y. and Korhonen, T.O. (2004) Designs of Broadband Coupling Circuits for PowerLine Communication. *Proceeding of 7th ISPLC*.

[16] Ferreira, H.C., Lampe, L. and Newbury, J. (2010) Power Line Communications: Theory and Applications for Narrowband and Broadband Communications over Power Lines. John Wiley & Sons Ltd., Chichester. https://doi.org/10.1002/9780470661291