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Online Partial Discharge Detection and Location System Using Wireless Sensor Network

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Abstract

Partial discharge (PD) is an important indicator of insulation condition in a power transformer. In this paper, an online monitoring system for detecting and locating the PDs using Wireless Sensor Network (WSN) was proposed and realized. The system could detect the PDs and locate them with good accuracy. This system had the advantages of easy deployment and low cost. The chip CC2430 was used as a control unit and also used for RF communication in the sensing node. SimpliciTI protocol was adopted for WSN to get good accuracy for time synchronization. Experiments were conducted in a simulated environment and result showed the system was able to measure the location coordinate within a certain error range. The causes of the error and methods of improvement were discussed in this paper.

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Keywords: Wireless Sensor Network; partial discharge; online monitoring; location; SimpliciTI

1. Introduction

The insulation of a power transformer is an important part and its integrity plays a decisive role for the safe operation of the unit. The diagnostic examination of partial discharges (PD), which is powerful, non-destructive and sensitive, is one of the well-known and approved diagnostic tools for the condition assessment of insulating systems. Gas, ultrasonic, heat and electromagnetic wave are generated by the partial discharges. Hence several methods were developed to detect the PDs by collecting electric signals, ultrasonic signals or electro-magnetic signals. Ultrasonic PD measuring is one of the widely used methods for on-site/on-line applications because of its high immunity against certain external disturbing signals and the capability of location the PD sources [1-2].

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The use of WSN in PD detection eliminates the need for sensor communication cables and reduces the overall cost of installation with commercially available RF chips now being more inexpensive. Further, wireless monitoring will provide the necessary galvanic isolation between a monitored item and the user situated at a remote location. There were a few researches on the use of WSNs for monitoring PD activities. Though some publications discuss in general the use of WSNs for condition monitoring applications in a high voltage environment [3-5], it appears that little work has been undertaken on the implementation of WSNs for PD detection. To test the effect of using WSN for PD detection, a system consisting of low power smart wireless nodes and ultrasonic sensors for online PD detection and location was build and the experiment results are showed in this paper.

2. System Architecture and Experiment

2.1. System overview

The designed system consists of five wireless sensor nodes and a computer as a base station as shown in Fig. 1. Four of nodes are sensing nodes and the fifth is the access point (AP). The function of the sensing nodes is collection of the ultrasonic arrival time data and transmitting it to the AP. And the AP node gathers the data from four sensing nodes and sends it to the base station via RS232 connection. In the base station, there is a database storing all the data and a program with a certain algorithm to calculate the 3D coordinate of the PD source.

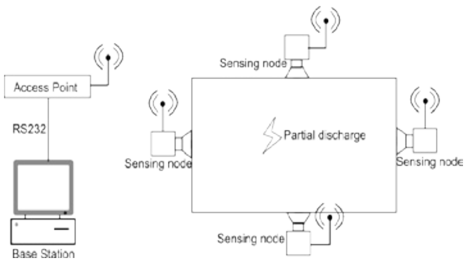

Fig. 1. Structure of the PD location system designed

2.2. Principle of PD source location

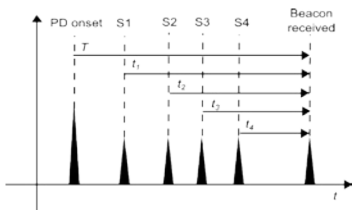

Fig. 2. Schematic visualization of ultrasonic arrival time in reference to the beacon received

After PD occurred in the transformer, the ultrasonic wave traveled from PD source to each sensing node assuming the propagation routes were straight and no obstacle along the routes. The exact moment the PD occurred could not be measured, but the moment of ultrasonic wave hit each sensing node could be recorded. The AP node sent beacons for time synchronization periodically. The beacons were carried by electro-magnet wave which travels at light speed, so the time difference of beacons reaching different nodes could be ignored. The time between ultrasonic wave arrival and beacon received was the key data for calculating the coordinate of the PD source. The relation between ultrasonic arrival times and beacon received point is illustrated in Fig. 2.

The associated sphere functions with the three unknown PD coordinates in space (x, y, z), unknown PD occurred time T in reference to beacon received point, the measured arrival times t_i, the assumed sound velocity V, and the Cartesian sensor coordinates (x_i, y_i, z_i) have relationships and can be given by Eq.(1):

$$(x-x_i)^2+(y-y_i)^2+(z-z_i)^2=[V\cdot(T-t_i)]^2 \quad i=1,2,3,4 \tag{1}$$

In order to solve this system of non-linear equation, a non-linear least squares problem could be created and the Lederberg-Marquardt algorithm was used to solve this problem. The Lederberg-Marquardt algorithm is an iterative technique that locates the minimum of a multivariate function that is expressed as the sum of squares of non-linear real-valued functions [6-8]. It can be thought of as a combination of steepest descent and the Gauss-Newton method. Levenberg-Marquardt algorithm is widely adopted in many math softwares.

PD coordinate and ultrasonic arrival time could be acquired by solve this system of non-linear equations.

2.3. Sensing nodes design

Sensing nodes were responsible for detecting ultrasonic signal and recording the arrival time. It consisted of an ultrasonic sensor, an amplifier unit, a comparison unit, a plus detection unit, a control/RF unit and a power supply unit, as illustrated in Fig. 3.

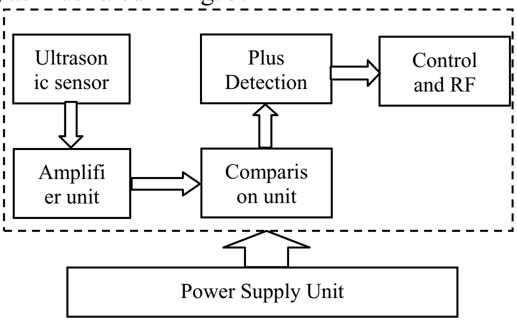

Fig. 3. Function unit and Architecture of the sensing node

The harmonic frequency of the ultrasonic sensor was 40 kHz. So the signal output from the amplify unit was alternate voltage with the frequency of 40 kHz in mill volt level. Amplify unit was used to get a voltage level signal which was easier for detection and analysis. The operation amplifier AD8034 was adopted in this unit. The circuit diagram of the amplifier unit is shown in Fig. 4. The signal came out from amplify unit was measured by oscilloscope and one example of measurement result is shown in Fig. 5. There was a cut-off distortion found in the wave of the signal due to the high gain of the amplify unit. Since the ultrasonic signal decays as the propagation distance increasing, the amplify unit had a 22.6 dB gain so that it could detect a small signal from far distance.

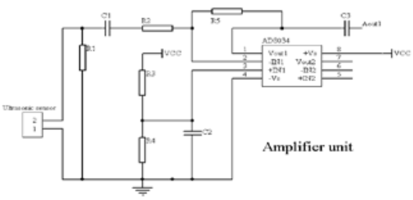

Fig. 4. Circuit diagram of the amplifier unit of sensing node

The comparison unit was used to compare the amplified signal to a preset threshold voltage limit. If the signal exceeded the threshold voltage limitation, it indicated an ultrasonic signal was received. The general voltage comparator LM393 was adopted in this unit for its low cost and easy to use.

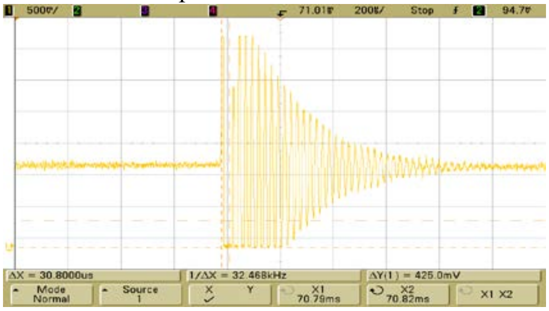

Fig. 5. Amplified ultrasonic signal displayed by oscilloscope

After the signal passed to the comparison unit, it was turned into voltage pluses with very small plus width. In order to make it easier to be detected by the control unit, a plus detection unit was added between comparison unit and control unit. The plus detection unit expended the plus width from several microseconds to 20 microseconds or so. The circuit of the plus detection unit consisted of a capacitor, a resistor and a diode. The circuit diagram of the comparison unit and plus detection unit is shown in Fig. 6.

The control unit was the core part of the sensing nodes. It was responsible for collecting the time data of ultrasonic wave arrival and sending it thought WSN. The CC2430 from Texas Instruments was chosen to build the control unit. It is a system-on-chip (SoC) solution for 2.4GHz 802.15.4/Zigbee applications. The enhanced 8051 MCU in CC2430 was used to manage the operation of sensing nodes, collect time data and manage the RF transceiver to communicate with AP. The actual fabricated sensing node contains two modules. Module 1 consists of an amplifier unit, a comparison unit, a plus detection unit and a power unit. Fig 7 shows the circuit board of module 1. Module 2 contains the control/RF unit that made by Yang *et al.* [9].

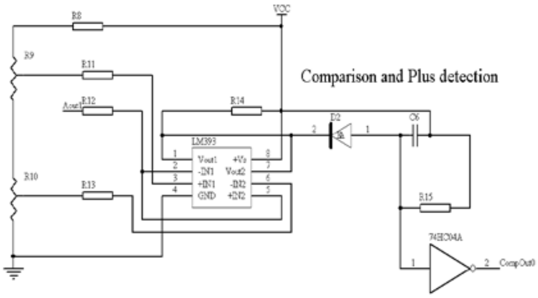

Fig. 6. Circuit diagram of the comparison unit and plus detection unit in sensing node

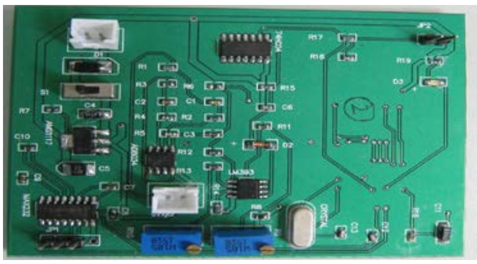

Fig. 7. circuit board of amplifier unit, comparison unit, plus detection unit and power unit.

2.4. The access point and base station

A star topology was used in the designed WSN. The Access Point acted as the hub of the network and was used primarily for network management duties. It supported such features and functions as sending beacons for time synchronization purpose, management of network devices in terms of linking permissions, conflict avoiding and communicate with base station etc. The core of an Access Point was also CC2430 chip so that the same protocol could be implemented and it would communicate with sensing nodes smoothly.

A base station was a computer with software that could communicate with the WSN designed here and was able to calculate the coordinate of PD origin based on the time arrival data. The software was written in C++ language with function of managing RS232 serial communication and calculation. The objective of calculation part was to solve the equations list above. The Levenberg-Marquardt algorithm was realized in the software.

2.5. WSN software design

A lot of applications used the ZigBee protocol stack Z-Stack on CC2430 ([10-11]) and it was also been tested on the system designed in this paper. The experiment result showed that Z-Stack could not meet the accuracy requirement of time synchronization. It could only achieve milliseconds level accuracy where microsecond level was required. The ultrasonic wave travels in the oil inside a transformer with a speed of 1400 m/s. With the millisecond mistake, the location error could be more than one meter which is not acceptable.

In order to reduce the time error to microseconds, a relatively simple protocol SimpliciTI from Texas Instruments was adopted in the designed system. It is a connection-based peer-to-peer protocol. It supports 2 basic topologies: strictly peer-to-peer and a star topology in which the star hub is a peer to every other device. SimpliciTI is a 3 layers network protocol instead of 5 as most ZigBee protocol is. So it was easier to modify it for a beacon-based time synchronization application. Experiment result showed that 80 microseconds time synchronization error could be achieved using a modified SimpliciTI protocol.

The software of WSN operated in following sequences. After AP was powered on, the microcontroller performed hardware and system initialization, including initializing RF module, UART etc. Then the system entered a cycle with no boundary. Tasks executed in each cycle were following: (1) Granting permission for new nodes to join the network. (2) Broadcasting beacon for time synchronization. (3) Processing the message received from other nodes in memory buffer. (4) Responding to the events of hardware input like key stroke.

The software in sensing nodes was designed to collect data and cooperate with AP. After sensing nodes was powered on, the RF module and external interrupt was initialized in the control unit of sensing nodes. Then the sensing nodes attempted to establish a connection with AP. After the connection was setup successfully, sensing nodes turned off the radio to save the consumption of power. When an ultrasonic wave was detected, an external interrupt would be triggered. In response to the interrupt, the sensing nodes started a timer immediately and turned on the radio to receive beacon. After a beacon was received, the timer would be stopped and the time would be recorded. An indication of data collection was sent to AP and sensing nodes started to wait for AP's response. The time data was sent to AP when a permission to send was received by sensing nodes. Then the sensing nodes went to sleep mode again.

3. Results and Discussion

3.1. Pd location measurement experiment

After the time data was transferred to base station, the software designed would solve the equations above and calculate the coordinate of the PD origin. Since it is difficult to solve the non-liner quadratic equations directly, an iteration algorithm was used in the software. A mathematic simulation was conducted to validate the algorithm.

Several points were selected to be the assumed PD sources. Given the sensor coordinates of (84.4, 30.5, 34), (-1, 38, 19), (49.5, 65.5, 30), (28.5, 65.5, 47.5), the distances from an assumed PD source to each sensor coordinate was calculated. Then the time of ultrasonic traveled in each distance can be found using the sound speed of 340 m/s. Assume the beacon received time is the same as the moment the last sensor detect a signal, the time difference between each sensor could be calculated. Feeding the time difference into the software and comparing the calculation result with the assume coordinates, the error of the calculation result was got as shown in Table 1.

Table 1. Validation result of the calculation algorithm

Assumed Position(cm)	Calculation result(cm)	Max Error(cm)
(10, 10, 10)	(9.985574, 9.964726, 9.910478)	0.09
(10, 20, 10)	(9.999964, 20.000146, 9.999991)	0.0001
(30, 20, 30)	(30.000022, 19.999975, 29.999728)	0.0003
(30, 20, 40)	(29.999823, 19.999695, 40.000608)	0.0006
(40, 20, 40)	(39.999858, 19.999777, 40.000364)	0.0003

From the validation result, it can be found that the calculation algorithm only brings very minimum error to the location result. And the implementation of Levenberg-Marquardt method can be trusted.

Experiments were conducted in order to test the functionality of WSN and accuracy of location in a simulated environment. An electrode point discharge was used as PD source to simulate PD in the air which generated the ultrasound wave. The position of the sensors and the PD source were pre-established. Since the experiments were done in the air, the sound speed 340 m/s was used in the system. When PD occurred, the system could detect it and calculate the coordinates. Five different points of PD was tested with the sensor coordinates of (84.4, 30.5, 34), (-1, 38, 19), (49.5, 65.5, 30), (28.5, 65.5, 47.5). The actual coordinates vs. calculated ones are showed in Table 2.

Table 2. Measured PD location vs. actual coordinate

Actual Position(cm)	Measured result(cm)	Max Error(cm)
(48.5, 19.5, 40)	(47, 17, 37.4)	2.6
(48.5, 19.5, 40)	(44.4, 12.3, 43.7)	7.2
(33.5, 24, 11)	(31.6, 18.2, 9.8)	5.8
(52, 53.5, 34)	(50.2, 51.7, 32.7)	1.8
(47.5, 33.5, 33)	(45.6, 36.7, 31.8)	3.2
(36, 34, 21)	(35, 35.8, 20.9)	1.8

The experiment result shows that the majority location error of the system is around 2-3 cm. However, there are 2 experiments show that the error of the system can reach more than 5 cm. It indicates that the system introduced in this paper is not solid enough to get a stable PD location measuring result. Especially for same PD actual location (48.5, 19.5, 40), the measuring result turned out to be much different. Since the calculation algorithm have been validated and result shows that it brings little error, the cause of this large error can be traced back to the arrival time of ultrasonic wave. The possible reason in the arrival time error can be as following:

1) The error of time synchronization. Because each sensing node have individual clock, the recorded time data could be different even if the signal had reached different sensing nodes at the same time. Experiments were conducted to evaluate the error of time synchronization and results are showed below.

2) The structure-borne problem [12]. In the designed system, it is assumed that all ultrasonic waves are travels directly from the PD origin to the ultrasonic sensors. However, the ultrasonic wave can travel faster in solid than in air or oil. So there might be shortcut existed that ultrasonic spent less time on it.

3) Threshold level setting. The arrival time was determined by comparing the output from sensor with a preset threshold voltage level limit. The accuracy of the arrival time may be improved by finding a better voltage level that can balance between the false alarm and sensitivity of the system.

3.2. Time synchronization experiment

The accuracy of time synchronization is essential factor for the accuracy of the PD location measurement result. The sensing nodes were grouped in pairs to test the accuracy of time synchronization. In the sensing nodes of each pair, the external interrupt pins of control units, which are responsible for detecting the ultrasonic signal, were connected by wire. A voltage signal was provided to the connected interrupt pins to simulate that a signal arrived both sensing nodes at the same time. Based on the function designed in sensing nodes, the time duration between signal arrival and beacon received in each node was sent to the base station through the AP. And the difference between the time data sent from each sensing node is time synchronization error. More than 10 experiments were done for each pair repeatedly. The statistic characteristics of the synchronization errors in each pair can be found in Table 3.

Table 3. Statistic Characteristics of The Synchronization Errors In Each Sensing Nodes Pair (All Units In Ms)

	Average	Std Dev	Max
Error between node 1 and node 2	10.27	5.75	23.00
Error between node 1 and node 3	40.90	23.03	78.00
Error between node 1 and node 4	2.22	4.12	9.00

From the experiment result, it can be found that the arrival time in different nodes subjected to at most 78 microseconds error. It contributed a large part of the calculation error. The cause of this error came from the different speed of timer in each sensing nodes. The time data was gotten from a timer in CC2430 in each sensing nodes. And the timer speed was defined by the resonant frequency of crystal oscillators connect to CC2430. So time synchronization accuracy can be further improved by reducing the difference of crystal's resonant frequency.

3.3. Sensitivity analysis

In order to understand the relation between the location error and time synchronization error, a sensitivity analysis was conducted using the software in base station. Given the sensor coordinates of (84.4, 30.5, 34), (-1, 38, 19), (49.5, 65.5, 30), (28.5, 65.5, 47.5) and assumed PD source coordinate of (40, 20, 40), a set of arrival times (t_1, t_2, t_3, t_4) relative to the beacon received time could be calculated. An error of Δt was added to each arrival time separately and the results were feed into the calculation software to get coordinates. Fig. 8 shows the maximum error of calculated coordinates using ($t_1+\Delta t$, t_2, t_3,

t_4), (t_1, $t_2+\Delta t$, t_3, t_4), (t_1, t_2, $t_3+\Delta t$, t_4) and (t_1, t_2, t_3, $t_4+\Delta t$) compared with reference point (40, 20, 40).

Fig. 8. Maximum error of calculated coordinates using ($t_1+\Delta t$, t_2, t_3, t_4), (t_1, $t_2+\Delta t$, t_3, t_4), (t_1, t_2, $t_3+\Delta t$, t_4) and (t_1, t_2, t_3, $t_4+\Delta t$) compared with reference point (40, 20, 40).

It is found that sensing node 3 and sensing node 4 were more sensitive to the error of time synchronization. And the location error increased rapidly along with the increase of arrival time error. Since different sensing nodes have different sensitivities to the time synchronization error, the optimization of sensor location is also a solution to reduce the impact of time synchronization error. And increasing the sensing nodes number may also gain the similar effect but need further validations.

4. Conclusions

In this paper, an online monitoring system for detection and location the PDs was proposed and realized. It used a WSN into traditional ultrasonic PD detection system. The simulation experiment shows that majority location results have errors around 2-3 cm but occasionally it could reach up to 7 cm. Through experiments and analysis, it was found that the accuracy of the system can be further improved by following methods: 1) Increasing the time synchronization accuracy between different sensing nodes; 2) Optimization of the location of the sensing nodes. Future researches can be focused on these areas.

Compared with cable networks, the WSN is much easier to deploy, provides good isolation between target transformer and people, and reduces the noise during transmit. PD detection and location system using wireless sensor network have a good application prospect.

Acknowledgements

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