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Research on Switch Signals of Electrical Equipment in Power Distribution Systems

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Abstract. At present, monitoring the working state and energy consumption of an on-line equipment are extremely difficult and costly due to the complex working environment in a power distributed system. This paper provides a new way to determine the switching state of the on-line equipment and its position in the distribution network by means of the calculation of the electrical signals with a current and voltage sensor installed in the power supply entrance of the distribution system. Four mathematical models are developed to describe the voltage and current responses detected by sensor for electrical equipment's switching, and a formula is got to calculate the position distance for the equipment. An experiment is provided to prove the validity of the mathematical models and the practicality of the formula. The results can help construct a monitoring system for the working states of the electrical equipments and their energy consumption with low costs.

Keywords: current response model, distance from sensor to electrical equipment, monitoring system for electrical equipment, voltage response model

1 Introduction

Power distribution systems have to face the power users with all different types of electrical equipment, It is obviously a extremely complicated engineering project to create a monitoring system to determine the states of the equipment and calculate their Electricity consumption in real time.

Currently, the electrical monitoring system is usually confined to a total electricity energy calculation for a local area, or a family house, or a building. It is also very difficult to monitor every single online equipment's state in real time. The main reason is that every single equipment monitoring has to use a specified measurement meter due to current technology level.

This paper aims at developing a new technology to realize the monitoring system simply through the power signal analyses from a sensor, it will bring a completely new situation on the equipment monitoring and their energy consumption calculation in the power grid. It means people can get all the online electrical equipment's operating states and their energy consumption information, only by extracting the power signals from one point of the power distribution system, without any more hardware investment and any construction. It will bring a revolution indeed for the power monitoring system, and it will promote the early realization of the concept of power equipment internet.

It is basically in a blank state to monitor all the online equipment operating states through the power signal analysis from one point of the power distribution system. Fortunately, the new technology can learn from fault location technologies, as long as we consider the switch's on or off as a fault action for

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the equipment in power distribution systems. In this way, the judgment of the switching state of the equipment and the location of the equipment is converted to the judgment of the fault state and the judgment of the fault location.

Several fault location approaches can be found in the later literature, which can be grouped into the following categories: impedance-based approaches [4-8], travelling waves and wavelet transform approaches [2-3], knowledge-based approaches [9-11], statistical analysis [12] and distributed device-based approaches [13-16] such as meters or sensor. In addition, there are some mixed approaches with a combination of these methods [1, 17-21].

In comparison, among all these methods, travelling waves and wavelet transform methods is more suitable for switching signal judgment. Traveling-wave fault-locating techniques are recognized as the most accurate methods used in power distribution systems currently, and further more, travelling waves and wavelet transform methods can provide high accuracy in fault location. However, travelling waves and wavelet transform methods may still have two major problems in practice, one is how to distinguish the waves between the one reflected from the fault point and the others from the remote end of the line [20], the other is how to strictly capture the start time of the travelling wave [2].

In this paper, the signal responses caused by the switching off or switching on of the electrical equipment are modeled, and four mathematical models are developed, two for the voltage and current responses detected by sensor for electrical equipment switched from on to off and the other two for switched from off to on. Based on the models, the signal responses caused by the switching off or switching on of the electrical equipment can be easily distinguished from other reflected waves, and the start time of the travelling wave of the responses can be perfectly recognized. And then, the travelling waves and wavelet transform methods are used to analyze the signal responses to get the time and frequency information, from which, the states of the electrical equipment's switches can be judged, and the locations of the equipments can be located. An experiment is provided to prove the validity of the responses models and the practicality of travelling waves and wavelet transform methods.

2 The Mathematical Model for the Responses Detected by Sensor for the Electrical Equipment

2.1 The General Power Distribution System Architecture for Electrical Equipment

Some equipment use three-phase AC power supply, and some use single-phase AC power supply in the power distribution system. For simplicity of discussion, in this paper, only single-phase equipments are considered, but the results and conclusions from the discussion can be naturally applied to three-phase cases.

Without loss of generality and for simplicity of the calculations, we assume that the power lines of the power distribution system are lossless and uniform. Then the structure of the power system for the equipments in the distribution system can be shown in Fig. 1. In the Fig. 1, U_s is the single-phase AC bus voltage, U_1 is the first equipment workload in the single-phase AC power system, U_k, is the k-th workload, and U_n is the n-th workload, etc. Zc is the power line characteristic impedance. Z_1, Z_k, Z_n are Respectively, for the corresponding equipment workload input impedance, etc., and S_1, S_k, S_n are the corresponding switches as shown in Fig. 1.

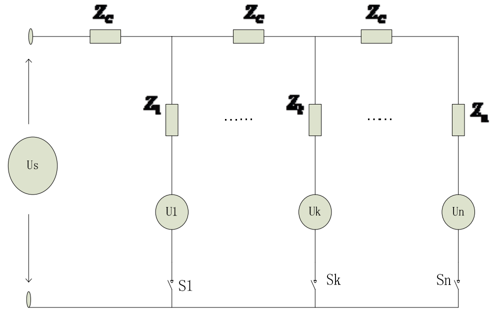


Fig. 1. Power distribution system diagrammatic sketch of electrical equipment

In order to monitor the states of the electrical equipment on the switches, the current and voltage sensor are installed at the incoming power line, so that the switching signals of the electrical equipment from all the respective branches can be detected

Without loss of generality, the switching of the k-th branch can be chosen to be analyzed. According to the Thevenin theorem, the Fig. 1 can be simplified as following Fig. 2. In the Fig. 2, Z_s is the equivalent input impedance of the input power, Z_N is for the equivalent impedance of all the other branches, U_N is the equivalent workload voltage for all the other branches. And the marked sensor is used to detect the current and voltage at the point shown in Fig. 2 which is installed in the input node of the input power.

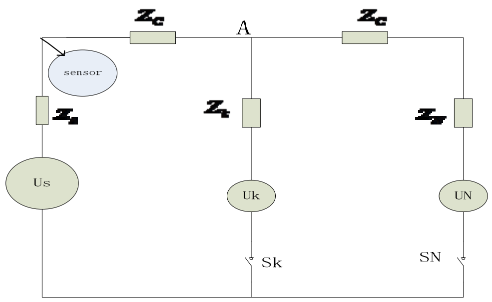


Fig. 2. The simplified Power distribution system diagrammatic sketch for k-sth branch

2.2 The Equivalent Architecture of the System with Equipment Switching between On and Off

According to the principle of signal transmission, when the switch S_k changes from the closed state to the open state or from the open state to the closed state, it will definitely cause impulse signals to the other two branches connected in A (see Fig. 2).

Considering that the impulse signal transferred to U_N will only affect the impulse signal magnitude but not the characteristic transferred to the sensor, the U_N branch can be ignored, and as a compensation, the impulse signal should be multiply a constant attenuation factor β. Thus, the responses to the sensor can be analyzed for the impulse signals caused by switch operation of S_k, the other branches will not be considered. Then, the Fig. 2 can be simplified as Fig. 3.

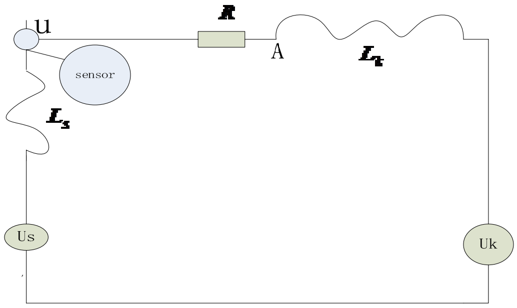


Fig. 3. The Further simplified diagram sketch for a branch

2.3 The Response Model for the equipment Switch Operation

The response model for the equipment switched from on to off. Firstly, the case can be considered that the equipment in k-th branch switches from on to off. In this case, it is equivalent that a reverse step impulse voltage $-U_k$ is superposed to the k-th branch. If only considering the response to the sensor for the S_k switch operation, the power distribution system diagram sketch can be shown as Fig. 4.

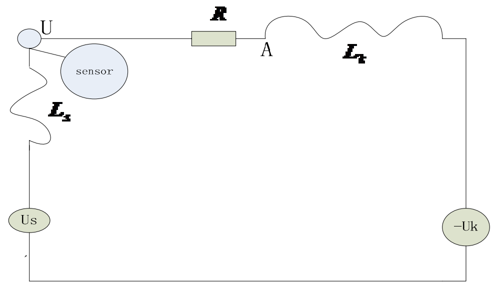


Fig. 4. The equivalent diagram sketch for S_k switch from on to off

In the Fig. 3 and Fig. 4, R is the Characteristic resistance, L_k is k-th branch inductance, L_s is the single-phase input power inductance, and U_s is the single-phase input power voltage, U is the voltage of the sensor, which is used to detect the response for the k-branch to switch from on to off. Assume i_k is K-th branch current caused by the switch operation. Then according to the Fig. 4, the equations (1)-(3) can be got as the following:

$$Ri_k = (-U_k) - U_s - L_s \frac{di_k}{dt} - L_k \frac{di_k}{dt} \quad \textbf{(1)}$$

$$U = (-U_k) - i_k R - L_k \frac{di_k}{dt} \quad \textbf{(2)}$$

$$U_s = (-U_k) - i_k R - L_k \frac{di_k}{dt} - L_S \frac{di_k}{dt} \quad \textbf{(3)}$$

LAPLACE transforms are performed on (1) and (2) (3), respectively, then (4), (5), (6)can be got as the following:

$$Ri_k(S) = -U_k(S) - U_s - SL_s i_k(S) - SL_k i_k(S) \quad \textbf{(4)}$$

$$U(S) = -U_k(S) - i_k(S)R - SL_k i_k(S) \quad \textbf{(5)}$$

$$U_s = -U_k(S) - i_k(S)R - SL_k i_k(S) - SL_s i_k(S) \quad \textbf{(6)}$$

Equation (7) can be got from (4) and (5) as the following:

$$U(S) = \frac{-SL_s}{R + S(L_k + L_s)} U_k(S) + \frac{R + SL_k}{R + S(L_k + L_s)} U_s \quad \textbf{(7)}$$

Equation (8) can be got from (6) as the following:

$$i_k(S) = \frac{-U_k(S)}{R + S(L_k + L_s)} + \frac{-U_s}{R + S(L_k + L_s)} \quad \textbf{(8)}$$

Assume the step impulse signal $U_k = \frac{\lambda}{S}$, (λ is constant), then the voltage and current response detected by the sensor for the step impulse signal $-U_k$ are respectively:

$$\Delta U(S) = \frac{-\lambda L_s}{R + S(L_k + L_s)}, \quad \Delta i_k(S) = \frac{-\lambda}{S(R + S(L_k + L_s))}$$

Take constant δ as the compensation attenuation factor due to neglect the other branches, then we can get: $\Delta U(S) = \frac{-\delta\lambda L_s}{R + S(L_k + L_s)}$, $\Delta i_k(S) = \frac{-\delta\lambda}{S(R + S(L_k + L_s))}$, let $\eta = \delta\lambda$, finally the voltage and current response detected by the sensor can be got for the step impulse signal $-U_k$, they are equation (9) and (10) respectively as the following:

$$\Delta U(S)=\frac{-\eta L_s}{R+S(L_k+L_s)},\ (\eta \text{ is constant}) \quad \textbf{(9)}$$

$$\Delta i_k(S)=\frac{-\eta}{S(R+S(L_k+L_s))}\ (\eta \text{ is constant}) \quad \textbf{(10)}$$

The LAPLACE inverse transformation is performed on (9) and (10), respectively, then we can get the voltage and current response in the time domain as the following equation (11) and (12) respectively:

$$\Delta U(t)=-\eta L_s e^{-\frac{R}{L_s+L_k}t} \quad \textbf{(11)}$$

$$\Delta i_k(t)=\frac{-\eta}{R}-\frac{(L_k+L_s)}{R}\eta L_s e^{-\frac{R}{L_s+L_k}t} \quad \textbf{(12)}$$

Obviously, the voltage response detected by the sensor is a downward decay exponential function, and the current response is a sum of a downward constant and a downward decay exponential function.

The response model for the equipment switch from off to on. Following the same procedure as in section 2.3.1, considering the case that the equipment in the k-th branch switches from off to on. In this case, it is equivalent that a reverse instantaneous impulse voltage $-U_k$. Similarly, according to the Fig. 4 with the switch changed from off to on, the following two equations can be got:

$$U(s)=\frac{-SL_s}{R+S(L_k+L_s)}U_k(S)+\frac{R+SL_k}{R+S(L_k+L_s)}U_s$$

$$i_k(S)=\frac{-U_k(S)}{R+S(L_k+L_s)}+\frac{-U_s}{R+S(L_k+L_s)}$$

Assume the instantaneous impulse signal $U_k=P(t)=\begin{cases}\rho, when: t=0\\ 0, when: t\neq 0\end{cases}$ here, ρ is constant. Then the voltage and current response detected by the sensor for the instantaneous impulse signal $-U_k$ are respectively:

$$\Delta U(S)=\frac{-S\rho L_s}{R+S(L_k+L_s)},\ \Delta i_k(S)=\frac{-\rho}{R+S(L_k+L_s)}$$

Take constant δ as the compensation attenuation factor due to neglect the other branches, then the responses can be expressed as: $\Delta U(S)=\frac{-S\delta\rho L_s}{R+S(L_k+L_s)}$, $\Delta i_k(S)=\frac{-\delta\rho}{R+S(L_k+L_s)}$

let $\theta=\delta\rho$, finally the voltage and current response detected by the sensor for the instantaneous impulse signal $-U_k$ can be got, they are equation (13) and (14) respectively as the following:

$$\Delta U(S)=\frac{-S\theta L_s}{R+S(L_k+L_s)},\ (\theta \text{ is constant}) \quad \textbf{(13)}$$

$$\Delta i_k(S)=\frac{-\theta}{R+S(L_k+L_s)},\ (\theta \text{ is constant}) \quad \textbf{(14)}$$

The LAPLACE inverse transformation is performed on (13) and (14), respectively, and let $\mu(t)=\begin{cases}1, when: t=0\\ 0, when: t\neq 0\end{cases}$, then the voltage and current response in the time domain can be got as the following equation (15) and (16) respectively:

$$\Delta U(t) = -\frac{\theta L_s}{L_k + L_s}\mu(t) + \frac{R\theta L_s}{L_k + L_s} e^{-\frac{R}{L_s + L_k}t} \quad \textbf{(15)}$$

$$\Delta i_k(t) = -\theta e^{-\frac{R}{L_s + L_k}t} \quad \textbf{(16)}$$

Obviously, the voltage response detected by the sensor is a sum of a downward instantaneous pulse and a upward decay exponential function, and the current response is a downward decay exponential function.

3 The Location Judgment for the Equipment with the Switch's Operation

The above equations (11), (12) and (15), (16) have been derived to express the voltage and current response models detected by the sensor as the equipment switched from on to off and from off to on. According to the models, It is easily to determined whether the electrical equipment in a branch is switched on or off.

However, in order to determine which electrical equipment is switched, more information is needed. If distance from sensor to electrical equipment can be calculated, the related equipment will be located.

A technique to locate the fault distance accurately is provided in [2], but it needs to sample several traveling waves and a BP neutral network algorithm has to be used to calculate the accurate fault distance. as a fault initiate in a power distribution system, the different mode of traveling waves have different transmission velocities, the traveling wave velocities of propagation mode 1 and 2 are roughly constant, while wave velocity of propagation mode 0 is frequency-dependent [22-24], and the transmission velocity gets slower as fault distance increases along the faulted line [3, 25-26].

In this paper, a new technique is provided, only one travelling wave is needed, and the BP neutral network algorithm is not necessary, because the voltage and current response models detected by the sensor can help to recognize the right traveling wave caused by the switch's operation and get the start time of the traveling wave. And actually, the civil power supply circuit always consists of a live line and a neutral line, the transmission velocity for the travelling wave along the neutral line is faster than the live line, because the neutral line is directly or indirectly grounded and the neutral line seems to be close and the live line seems to be open for the travelling wave at the terminal of transformer [27].

Assume the wave velocity of neutral line is V_n, the wave velocity of live line is V_l, The moment of the neutral line wave arrives at the sensor is t_n, and the moment of the live line wave arrives at the sensor is t_l, and the distance from the electrical equipment with switch operation to the sensor is D, then the following equations can be deduced:

Since $V_n t_n = V_l t_l = D$, then $\Delta t_{\ln} = t_l - t_n = D\frac{V_n - V_l}{V_n V_l}$;

And finally formula (17) can be got:

$$D = \Delta t_{\ln} \frac{V_n V_l}{V_n - V_l} \quad \textbf{(17)}$$

Where $\Delta t_{\ln}$ is the time difference between t_l and t_n.

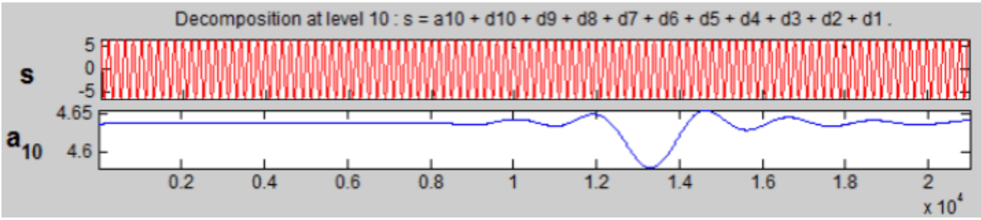
4 System Test Experiment and Analysis

4.1 Models Verification

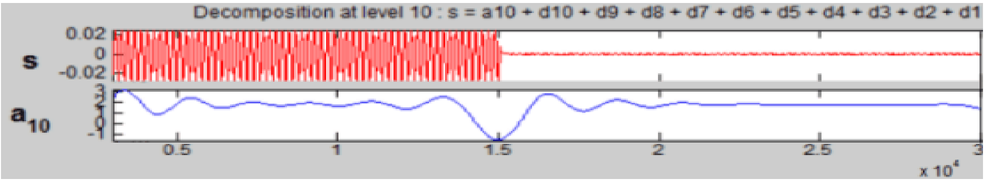
In this experiment, the switch-on or switch-off operation of each electrical equipment in the related live line branch can be judged according to the four signal models of (11) (12) and (15) (16), and according to (17), and the distance from the electrical equipment to sensor can be calculated.

The verification program is: a electric iron is installed in a power branch line in laboratory, which is 1475 meters from the sensor. A data acquisition card from NI (National Instrument company) is used for sampling. The wavelet transform is applied to all the sampled data.

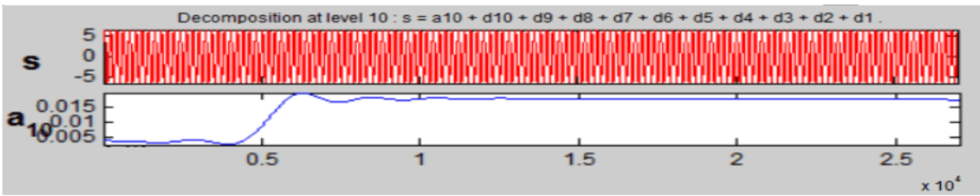
For the wavelet transform, the discrete wavelet transform (DWT) is used with 10 level decomposition, dmey is the mother wavelet from the matlab. Assume s is the original sampled signal (voltage or current), after wavelet processing with 10 level decomposition, the signal can be decomposed as: *s=a10+d10 +d9+d8+d7+d6+d5+d4+d3+d2+d1*. All the related decomposed results for a10 can be seen in Fig. 5(a) to Fig. 5(d).



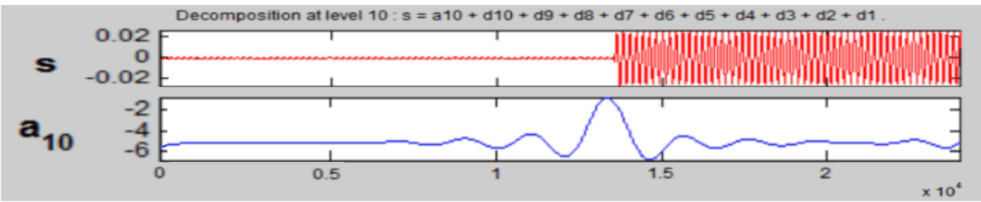
(a) Voltage response (a10) shows a switch changed from on to off { $\Delta U(t) = -\eta L_s e^{-\frac{R}{L_s+L_k}t}$ }



(b) Current response (a10) shows a switch changed from on to off { $\Delta i_k(t) = \frac{-\eta}{R} - \frac{(L_k+L_s)}{R}\eta L_s e^{-\frac{R}{L_s+L_k}t}$ }



(c) Voltage response (a10) shows a switch changed from off to on { $\Delta U(t) = -\frac{\theta L_s}{L_k+L_s}\mu(t) + \frac{R\theta L_s}{L_k+L_s}e^{-\frac{R}{L_s+L_k}t}$ }



(d) Current response (a10) shows a switch changed from off to on { $\Delta i_k(t) = -\theta e^{-\frac{R}{L_s+L_k}t}$ }

Fig. 5. The responses detected by sensor which are conformed to the models

Fig. 5 demonstrates that voltage and the current responses detected by sensor is conformed to the obtained four models respectively. In these figures, the unit of x axis is sample points, and y axis is coefficients of wavelets at 10 level.

4.2 The Calculation for Distance from Sensor to Electrical Equipment

In order to calculate the distance from sensor to electrical equipment, the sensor is used to sample the currents of live line and neutral line simultaneously, and the wavelet transform is applied to the sampled data. The Fig. 6 to Fig. 7 are the results:

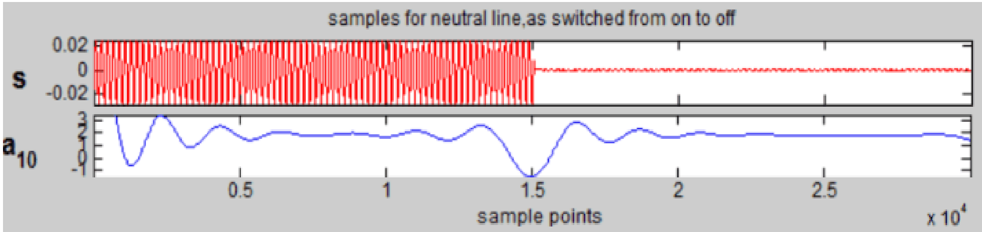


Fig. 6. Current signal and coefficients for a10 for neutral line as switched from on to off

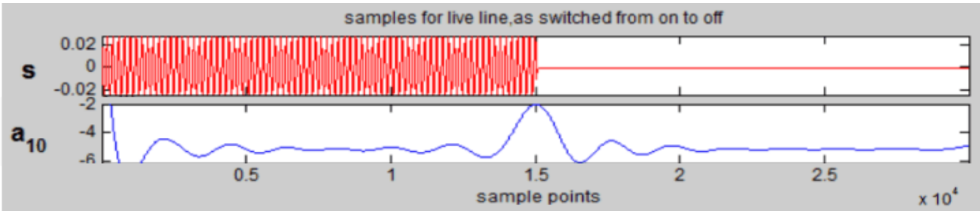


Fig. 7. Current signal and coefficients for a10 for live line as switched from on to off

The Fig. 6 to Fig. 7 show the analysis result of the sensor's current responses as switched from on to off. The response variation of a10 decomposed from current signal samples of neutral line and live line by wavelet transform can show that there is operation of switching from on to off occurred (see Fig. 6 and Fig. 7). And then the approximation algorithm in matlab is put to calculate the coefficients of a10's approximation, the calculation result can show the operation of switching from on to off occurred at 14948 sample point for neutral line and at 14950 point for live line.

According to the same process, the operation of switching from off to on occurred at 13416 sample point for neutral line and at 13418 point for live line.

As the sampling frequency is 1MHZ, the time interval between two sampling points is 1us, the time difference between the moments of the travelling wave arriving at the sensor for neutral line and live line is about 2us.

So in the above test experiment, the travelling wave along the neutral line arrives at the sensor is similarly 2us faster than along the live line, as the electrical equipment (electric iron) switched from on to off or from off to on.

There are some algorithms to calculate the transmission velocities for travelling wave along the live line and neutral line [2], and it will be definitely the follow-up topic for this research. In this paper, both the traveling wave transmission velocities for neutral line and live line are measured by instrument, the velocity for live line is 2.01×10^8 meters per second and is 2.76×10^8 meters per second for neutral line. Then the distance can be got with the formula (17):

$$D = \Delta t_{\ln}\frac{V_n V_l}{V_n - V_l} = 2\times10^{-6}\times\frac{2.76\times10^8\times2.01\times10^8}{2.76\times10^8-2.01\times10^8} = 1479.36\text{m (meters)}$$

Compared with the actual distance (1475meters), the deviation is less than 4meters. So it can be concluded that the right electric iron is switched off (on) which is 1475 meters away from the sensor.

5 Conclusions

The mathematical models in this paper are verified by the experiment, it means that equipments' switches operation in the power distribution system can be determined based on the responses of the sensor, And the accurate time difference between the time arriving at the sensor for aerial wave and zero mode wave can be accurately calculated by travelling waves and wavelet transform method due to contributions of the response models.

Further more, the distance calculation formula (17) is deduced and the location for switched equipment can be accurately calculated based on the formula with the time difference obtained by the travelling waves and wavelet transform method.

The results in this paper are very helpful for building a monitoring system for the working states of the electrical equipment and their energy consumption with low costs which can be simply constructed with only one sensor and a calculation unit.

In order to achieve that goal to build a monitoring system with one sensor and a calculation unit, more research work should be done for the following topics in the future:

(1) How to get the accurate transmitting velocities for zero mode and aerial mode online in real time.

(2) How to use other feature information in the responses detected to make the specific equipment more easy to determine, thus, we can locate the equipment not only by the distance.

(3) Fast and effective algorithm for travelling waves and wavelet transform method waits to be developed.

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