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Identification of Low Voltage AC Series Arc Faults by using Kalman Filtering Algorithm

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***Abstract*—Arc faults often occur in residential low voltage AC supply environment. It is dangerous because the sparks accompanying with arc faults may lead to electric fire even safety hazard. Effective methods of arc faults diagnosis in circuits are essential for safety interrupters in household. A novel method for low voltage AC series arc faults identification based on time-domain feature extraction by using Kalman filtering algorithm is proposed in this paper. This method monitors the instantaneous value of series current in circuits, calculates an elaborate pre-designed eigenvalue each power cycle by using Kalman filter with acquired current samples, and compares the eigenvalue with a reference value. Once the deviation between them exceeded a predefined threshold in continuous eight power cycles, the method reports an arc fault. Experimental research was studied in laboratory with typical electrical loads using the proposed arc faults identification method. Results show that it is applicable to detect arc faults within eight power cycles. The response time of the method could fit the minimum requirements of the standard UL1699.**

***Index Terms*—Circuits analysis, arc fault, fault diagnosis, Kalman filter.**

I. Introduction

Arc faults are dangerous in dwelling unit for the sparks accompanying with arc faults may lead to electric fire even safety hazard. Reference [1] presented three arcing failures occurred in low-voltage switchboards and discussed the behaviour of arcs with laboratory testing. Reference [2] explained the general behavior of arc in both AC and DC low-voltage circuits with Lorentz force law and the right-hand rule. Reference [3] discussed the method for the reduction and mitigation of arc-fault hazards to personnel and equipment.

At the past decade, many methods have been reported to diagnose the arc faults. Three types of approaches according to this issue in literature are briefly listed here:

1) Model based analysis [4]–[6]. Arc models usually come with complex differential equations and correspond with the electrical behaviour of arcs. Since arcs are usually complex physical phenomena with nonlinear and discontinuous characteristics, it is difficult to establish a precise model to describe the behaviour of arc with electrical measurements. The presented models are usually with their assumptions and suitable for some particular conditions.

2) Physical characteristics based methods. These methods observe the physical phenomena of arc, such as flash [7], sound or RF radiation [8]. The monitoring systems usually need some very expensive sensors, such as high speed video cameras, and need careful maintenance. Besides, these sensors could only inspect specific positions. These limits made such methods unsuitable for household use.

3) Electrical circuit analysis methods. These methods monitor continually current and voltage signals in circuits and search the characteristics of arc faults. Sampled data were processed in time domain, frequency domain, or their combination to extract some unique features of arc faults. Reference [9] presented an algorithm based on spectral analysis of current signal. Reference [10] used Daubechies Wavelets to detect arc faults. These kinds of methods are suitable for household use for the simplicity of implementation and maintenance.

In order to prevent electric fires caused by unintended arc faults in house, arc faults circuit interrupter (AFCI) was introduced [11], [12]. AFCI circuitry embedded with arc faults detection algorithm was considered to have the ability to break the power supply when arc faults happened. An effective arc faults recognition method is heart of AFCI. It is required the method can detect arc faults occurrence in circuits that contain most commonly used electrical loads in dwelling unit.

Typically, there are three types of arc faults: series, line-to-line (or parallel) and line to ground [11]. Line-to-line and line to ground arcs often come with large current and could be detected easily, but series arcs are usually high-impedance in circuits, which often occurs in the conductor series with the load. It means currents when arc faults occurred cannot be larger than the current when the loads working normally. In these cases the normal over-current protective device could hardly work effectively to detect the arc faults and break the circuit [11]. Although there are some commercial AFCI products in market, but most of them could not response accurately with series arc faults. Reference [13] reported that some AFCI products could not indicate series arcing condition in normal application case.

Thus, trying to find effective methods to recognize series arc faults should be an urgent priority for AFCI products and these methods should be able to be embedded easily in AFCI products. With this motivation, this paper investigates the

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serial arc characteristics in low voltage circuits of dwelling unit and presents a novel, easily implemented arc faults detecting method based on Kalman filter.

The paper is organized as follows: Kalman filter is introduced for sinusoid supply circuit in Section II, series arc faults data was acquired for typical loads in Section III, an arc faults identification method based on Kalman filter was proposed in Section IV, experimental test results of the method and discussion was in Section V, VI, and a brief conclusion was in Section VII.

II. Kalman Filter for Sinusoid Supply Circuit

Kalman filter, known as an optimal linear quadratic estimation, has the ability to deal with linear systems containing white noise and other inaccuracies in data measurement and processing. It can filter the noises and give a precise estimation of the system states. Kalman filter has been widely used in guidance, navigation and control of aircraft, etc. [14]. Kalman filter has also been successfully introduced in power systems for harmonic parameters, frequency and phase angle estimation [15], [16].

Kalman filter is applied to detect series arc faults here. Let's consider a voltage supply signal in residential power system with amplitude V_0, angular frequency ω, and phase angle φ, i.e.

$$v(t) = V_0 \sin(\omega t + \varphi). \quad (1)$$

By control theory, the static output of current of a stable system should be

$$i(t) = I \sin(\omega t + \psi), \quad (2)$$

where ψ and I are the phase angle and amplitude of the current, respectively.

Although ψ and I are determined by φ, V_0 and the transfer function of the loads, they can be measurable.

A discrete time current signal of $i(t)$ should be

$$i(kT_s) = I \sin(kT_s \omega + \psi), \quad (3)$$

where T_s is the signal sampling period, and k is the sample index. Let $\overline{i_k}$ be the observed current. Usually, $\overline{i_k}$ is not equal to $i(kT_s)$ due to disturbance. Assume that $\overline{i_k}$ has the following form

$$\overline{i_k} = I \sin(kT_s \omega + \psi) + \gamma_k, \quad (4)$$

where γ_k represents the disturbance of the measurement or operation condition. It is assumed γ_k to be a series of Gaussian white noise with zero-mean.

In order to design a Kalman filter to decouple the disturbance and recover the output i(t), we define two state variables as follows

$$x_{1_k} = I \sin(kT_s \omega + \psi), \quad (5)$$

and

$$x_{2_k} = I \cos(kT_s \omega + \psi). \quad (6)$$

Then we can obtain the state-space representation of the signal

$$\begin{bmatrix} x_{1_{k+1}} \\ x_{2_{k+1}} \end{bmatrix} = \begin{bmatrix} \cos(T_s \omega) & \sin(T_s \omega) \\ -\sin(T_s \omega) & \cos(T_s \omega) \end{bmatrix} \begin{bmatrix} x_{1_k} \\ x_{2_k} \end{bmatrix}, \quad (7)$$

where $i_k = I \sin(kT_s \omega + \psi) + \gamma_k$.

The state-space model indicates this is a linear time-invariant system. Let $X_k = \begin{bmatrix} x_{1_k} \\ x_{2_k} \end{bmatrix}$, $A = \begin{bmatrix} \cos(T_s \omega) & \sin(T_s \omega) \\ -\sin(T_s \omega) & \cos(T_s \omega) \end{bmatrix}$, and $C = \begin{bmatrix} 1 & 0 \end{bmatrix}$. Then (7) can be presented in a compact form as follows:

$$X_{k+1} = AX_k, \quad (8)$$

$$z_k = CX_k + \gamma_k. \quad (9)$$

Kalman filter is a wildly used algorithm that computes the conditional mean and covariance of the probability distribution of the state of a linear system with uncorrelated Gaussian process and measurement noise with the following equations [14]:

$$\widehat{X}_k^- = A\widehat{X}_{k-1}, \quad (10)$$

$$P_k^- = AP_{k-1}A^T + Q, \quad (11)$$

$$K_k = P_k^- C^T \left(CP_k^- C^T + R \right)^{-1}, \quad (12)$$

$$\widehat{X}_k = \widehat{X}_k^- + K_k \left(z_k - C\widehat{X}_k^- \right), \quad (13)$$

$$P_k = (I - K_k C) P_k^-, \quad (14)$$

where $\widehat{X}_k$ and $\widehat{X}_k^-$ are priori estimation and posteriori estimation of X_k. P_k^- is the error covariance of priori estimation and P_k is the error covariance of posteriori estimation. K_k is the gain of Kalman filter.

The Kalman algorithm works in a two-step process: prediction and updating. The filter first produces the estimations of the state variable and their uncertainty, called priori estimations. When the next measurement is finished, often with some random noise, these estimations are updated afterwards, which are called posteriori estimations. The two stages are repeated with predicting and correcting such that the filter output could track the input signal effectively.

By using Kalman filter, the white noise could be decoupled and then CX_k should converge to $i(kT_s)$. When the circuits are working normally, the Kalman filter should have the ability to track inputs current signals. Once series arc happened, the current signals would change rapidly and become chaos, there would be a large drift between the output of the Kalman filter and input currents. We could make use of this to report the arc faults occurrence.

III. Series Arc Faults Data Acquisition in Low-Voltage AC Circuit with Typical Loads

Experiment platform was set up to acquire current samples in AC circuits with and without arc faults using the same electrical load. The equipment is referred to the definitions and recommended parameters of UL1699 standard [17]. The serial arc faults generation and data acquisition platform is illustrated by diagram and photograph in Fig. 1, Fig. 2. Table I summarizes the technical data of the platform.

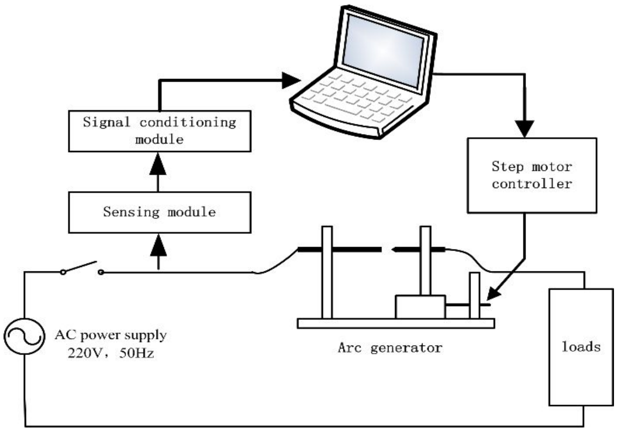

Fig. 1. Diagram of series arc faults generation and data acquisition platform.

TABLE I. TECHNICAL DATA FOR THE EXPERIMENT PLATFORM.

Index	Item	Parameters
1	Supply voltage/Rated Current	220V/30A
2	Main Control Module	NI/PCI6229
3	Step Motor Driver	Toshiba/TA8435
4	Oscilloscope	Tek/MSO2024
5	Current Sensor	Yaohuadechang/TA8349-250

Fig. 2. Experiment setup for series arc faults generation and data acquisition with computer and oscilloscope.

With the experiment platform, voltage and current records of different loads were collected. Typical waveforms of arc with 1000 W heater and 1000 W dimmer loads were shown in Fig. 3.

It can be seen in Fig. 3 that the voltage and current of arc faults are accompanied with typical arc faults characteristics, such as flat shoulder in the current around zero, and high-frequency chatters, etc. Different types of loads have different change in circuit waveforms when arc faults occurred. An effective arc faults detection method should be able to cover most of the commonly used electrical loads in household.

In fact, we cannot forecast where arc faults would happen in application cases. That means the voltage of arc could hardly be measured directly with prepositioned sensors. So we have to focus on the series current signal in circuit.

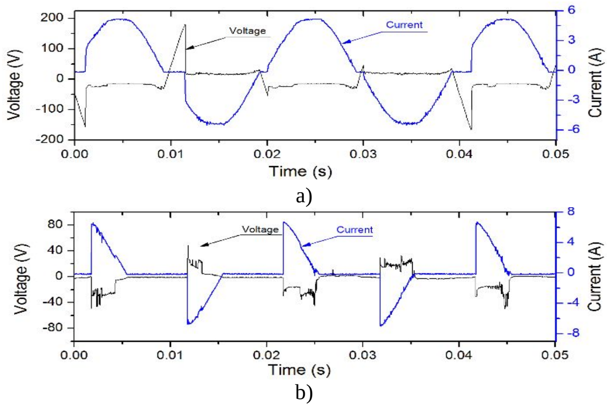

Fig. 3. Arc faults Waveforms of selected loads: (a) Voltage and current traces of arc with 1000W heater load; (b) Voltage and current traces of arc with 1000W dimmer load.

We have completed several experiments in lab. Current records of different loads from normal working to arcing are shown in Fig. 5(a)–Fig. 9(a). In Fig. 5(a) the load was a 1000 W heater, the arc faults happened at $t = 0.19$ s. The load in Fig. 6(a) was a 1000 W dimmer, it was a nonlinear load, the arc faults happened after $t = 0.19$ s, changes in amplitude and high frequency noises were shown in the current's records. In Fig. 7(a)–Fig. 9(a), the loads were one personal computer, two computers and an electrostatic copier, respectively.

IV. Arc Faults Identification Method Based On Kalman Filter With Current Samples

As mentioned before, an effective arc faults identification method for AFCI should be able to distinguish hazardous arcing from normal circuit conditions in residential electrical environment, i.e., the method uses the normal circuit information to find arc faults.

The basic design of the method we proposed is as follows. At the beginning, normal circuit data are recorded and then stored as a standard. If the values of circuit are out of the standard continuously, then arc fault happens. The Kalman filter is used to complete the data processing.

The criterion value is very important. Therefore, it is renewed at the every starting. It should be accurate and can fit the change of parameters of the equipment aging.

Because the periods of supply voltage $v(t)$ and loop current $i(t)$ are all $2\pi/\omega$, we sample the current for α times in each power cycle, where $\alpha=2\pi/(\omega T_s)$ should be near an integer value.

Define S_n ,as an eigenvalue, for each power cycle to be

$$S_n = T_s \sum_{k=(n-1)T_s}^{nT_s} \left| C\hat{X}_k \right|, \tag{15}$$

where n is the index of power cycle, starting from 1.

Without loss of generality, we can assume that at the first 5 power circles, the device is normal, we use the average current value $I_0 = (I_1 + \cdots + I_5)/5$ as a current reference to calculate normalized current later in order to reduce the effect of different loads, where I_k ($k = 1,\ldots,5$) is the amplitude of the current.

We select $S_0 = (S_1 + \cdots + S_5)/5$ as the standard, fix a threshold ε_0 and then monitor S_n by (18)

$$\pounds = |S_n - S_0|, \qquad (16)$$

where $(n > 5)$. If $\pounds \le \pounds_0$ then we consider the circuit is normal, if eight consecutive irregular records were monitored, the algorithm outputs an indication for arc faults.

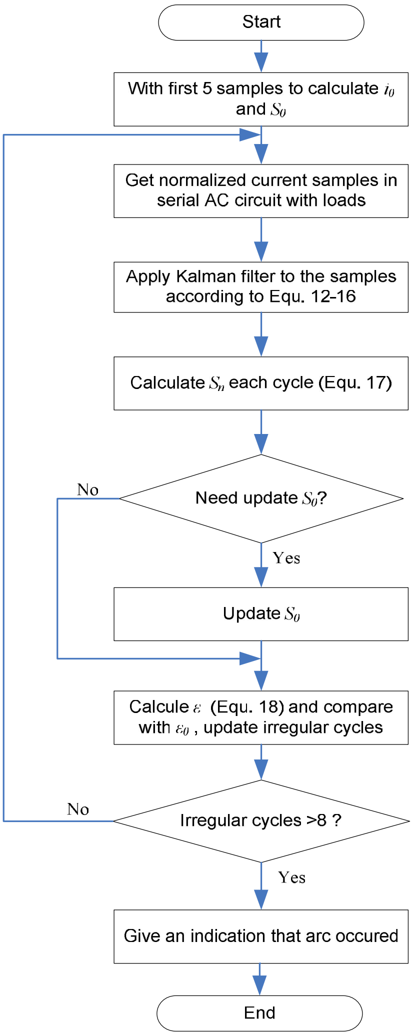

Fig. 4. Diagram of the proposed arc faults identification method with Kalman Filter.

Figure 4 presents the diagram of the arc faults identification method.

V. Identification Results for Typical Loads

Heater is a typical resistive load which means the current trace is sinusoidal during normal operation. A sample of current with 1000 W heater load and Kalman filter output were shown in Fig. 5(a). It's obvious that in normal condition, the Kalman filter could track the current input sample quite well.

The algorithm determines S_0 in first 5 cycles, and calculates the eigenvalue S_n each power cycle, as shown in Fig. 5(b). Figure 5(c) describes the decision procedure of the algorithm: from calculating monitoring the status of the circuit (7–16 cycles) to finally detect the occurrence of the serial arc in the circuit (17th cycle).

With online calculating S_n and the difference of S_n and S_0, the algorithm could recognize the arc faults happened in the series heater load circuit in eight power cycles, the response time of method is about 0.16 s, which is less than 0.5 s required by UL1699 [17].

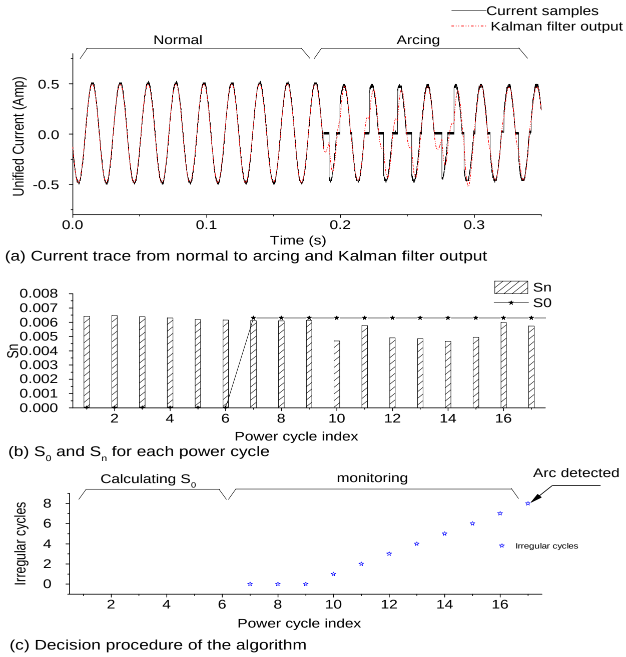

Fig. 5. Arc identification procedure for a 1000W heater load.

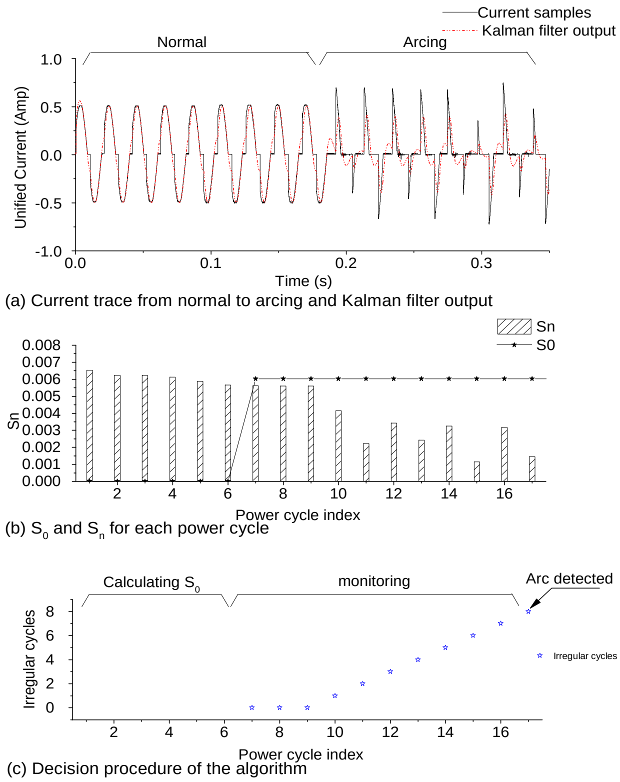

Fig. 6. Arc identification procedure for a 1000W dimmer load.

Figure 6(a) shows current trace and the Kalman filter output in a serial connection with a 1000 W dimmer load. Dimmer is a kind of highly nonlinear load which has a similar current trace with arc curves of resistive loads. It is important to identify the current trace which part is normal operation and which is nuisance arc happening.

Although the normal current trace of the dimmer load is nonlinear, but it's nearly periodic which made the S_n unchanged when the load working normally (shown in Fig. 6(b), 1-9 cycles). But when arc occurred, the eigenvalue S_n has a vibration because the nonlinear characteristic of arc. Figure 6(c) describes the procedure of algorithm by monitoring S_0 and S_n each cycle, and finally indicating the occurrence of serial arc in 8 power cycles.

Computers with switch-mode power supplies are wildly used in residential environment. Figure 7 shows the current samples and Kalman filter output for one computer load. It could be found that the variations of Sn from 1st cycle to 9th are extremely small when normal working and became large starting from 10th cycle during arc periods.

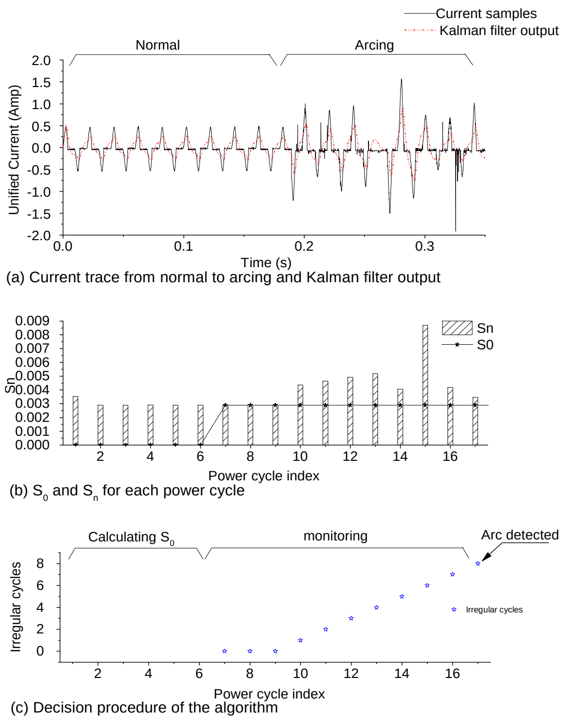

Fig. 7. Arc identification procedure for one personal computer load.

A two computer loads test was performed for there may be more than one computer working at the same time at home. Figure 8 shows the current trace and Kalman filter outputs. Again, the S_n has the ability to indicate the arc faults starting from the 11th cycle.

Moreover, in order to verify the generality of the arc de identification method proposed in this paper, current samples with a 1200 W electrostatic copier load were also collected, though it is not a normal residential load. Compared with the personal computer, the copier has fewer harmonics when working normally. It is similar with resistive load. This feature made it is easier to detect arc faults with the eigenvalue S_n. Figure 9 shows identification procedure for the electrostatic copier load.

From the experiments and analysis above, we can conclude that the proposed serial arc identification method was effective for typical loads in household environment if we select a suitable criterion ε_0.

Table II summarized the minimum and maximum values of the eigenvalue S_n for different loads, each with 100 random samples. It could be seen that if the ε_0 was set to 0.0004, the arc faults can be distinguished from normal operation for the typical loads described in this paper.

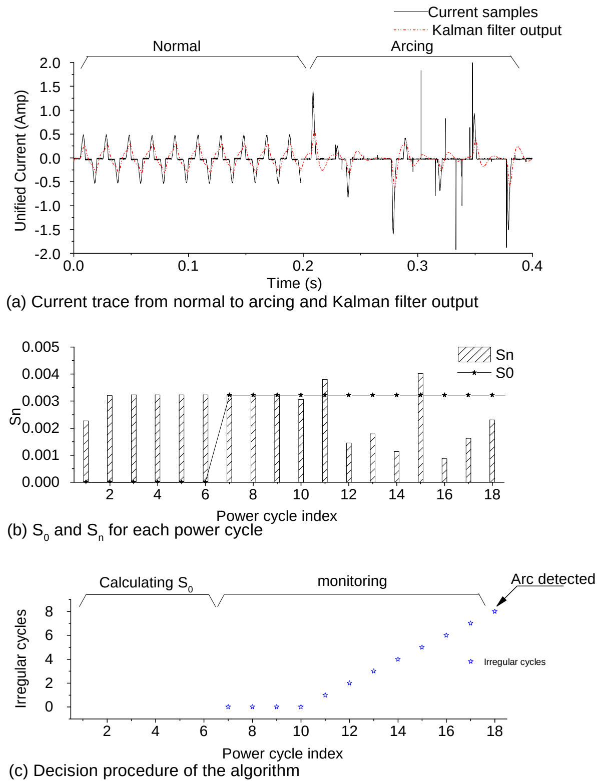

Fig. 8. Arc identification procedure for two personal computer loads.

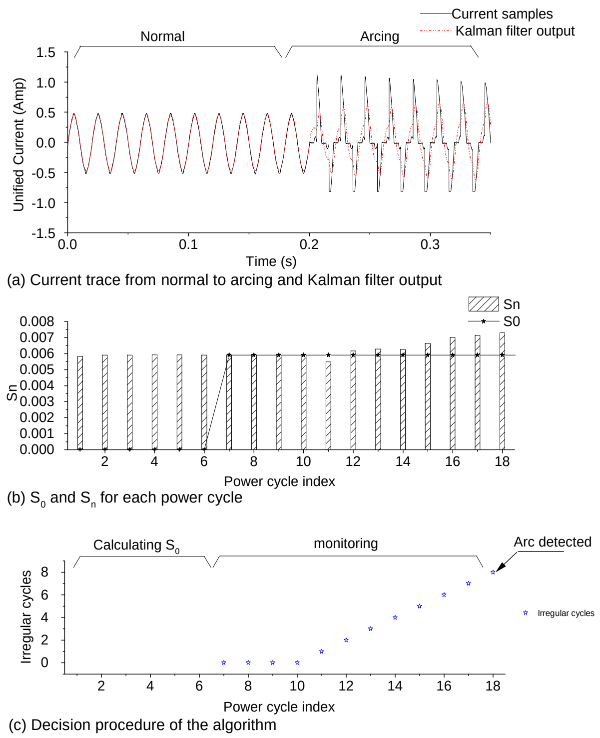

Fig. 9. Arc identification procedure for 1200 W electrostatic copier load.

TABLE II. THE EXTREME VALUE OF S_N FOR DIFFERENT LOADS.

Load type	**Power [W]**	**Normal**		**Arcing**	
		Min(S_n)	**Max(S_n)**	**Min(S_n)**	**Max(S_n)**
Heater	1000	0.0062	0.0068	0.0040	0.0058
Heater	2000	0.0061	0.0066	0.0045	0.0058
Dimmer	1000	0.0056	0.0063	0.0011	0.0042
1 PC	300	0.0025	0.0035	0.0035	0.0095
2 PCs	600	0.0025	0.0035	0.0005	0.0045
Copier	1200	0.0055	0.0058	0.0050	0.0075

VI. Discussion and Future Works

Normally, Kalman filter could work effectively in linear systems with white noise and inaccuracies. As arc faults are usually large disturbance in circuits, the Kalman filter could not track the input in time. That would produce a significant deviation. With this deviation, we designed a novel series arc faults identification method.

The method is valid for common electrical equipment, linear or nonlinear, in residential environment. In addition, Kalman filter can run in real time by using only the present input measurements and the previously calculated state; no additional past information is required.

A simple comparison with spectrum analysis (FFT or Wavelet analysis) used in literatures and Kalman filter we designed is shown in Table III. N is the number of samples per cycle and d, which equals to 2 in this paper, is the dimension of the state variable. If N is bigger than 256, the Kalman filter proposed would be more effective both in computational and space cost. That means the method could be embedded in hardware with a low cost microcontroller and current signal sampling, conditioning circuits.

TABLE III. COMPARISON AMONG FFT, WAVELET ANALYSIS AND KALMAN FILTER IN ARC FAULTS IDENTIFICATION.

Methods	Computation complexity	Space complexity
Fast Fourier Transform [18]	$O(N\log_2 N)$	$O(2N)$
Wavelet analysis [18]	$O(\frac{3}{2}N\log_2 N)$	$O(2N)$
Kalman filter [14]	$O(d^3N)$	$O(d^2)$

Meanwhile, there are still some works to do to improve the reliability of the method. If some loads has almost the same S_n when normal working and in arcing period, which we did not found at current stage, the method would cause a misjudgment. In addition, we assume in this paper that the loads would not change during the test. But in real world, the standard S_0 should be adaptive for multi-loads working parallel and could response the sudden loads change. Further work should be done concerning these issues.

VII. Conclusions

This paper focus on the effective identification method for series arc faults in residential low voltage circuits and presents a novel method based on Kalman filter according to this issue.

This method acquires instantaneous current samples in circuit and uses Kalman filter's output to calculate an elaborate pre-designed eigenvalue each power cycle and compare with a pre-acquired reference value. Once the error exceeded a pre-defined level, the method would report the arc faults occurrence.

With the series arc faults generation and data acquisition platform and the arc identification method, we did verification tests. Test samples of heater, dryer, dimmer, personal computers and electrostatic copier were acquired by the platform. We use the method to identify arc faults and achieve very satisfied results: all these data could be justified well, i.e. samples with normal working conditions were not reported by the method, and all the other samples with arc faults were reported. The research for the different number of same loads was also studied. All these results revealed the effective of the proposed method.

Compared with existing arc faults identification methods, the proposed identification method is simple with the computational complexity of $O(d^3N)$ and space complexity of $O(d^2)$, which could be embedded in circuit interrupters with low additional costs.

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