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Mechanisms of electric arc detection based on current waveform spectrum and incremental decomposition analysis

Abstract. *This paper presents two methods that enable arc detection, these are frequency analysis FFT and incremental decomposition of current increase in time. Both methods enable arc detection and provide additional information as compared to currently existing commercial solutions.*

Streszczenie. *W artykule zaprezentowano dwie metody umożliwiające wykrywanie występowania łuku elektrycznego: analizę częstotliwościową FFT oraz metodę badania rozkładu przyrostów prądu w czasie. Obydwie metody umożliwiają detekcję łuku oraz dostarczają dodatkowych informacji w stosunku do istniejących obecnie rozwiązań komercyjnych. (**Metody detekcji łuku elektrycznego w oparciu o analizę widmową oraz przyrostową przebiegu prądowego**).*

Keywords: electric arc, signal processing, spectrum analysis, incremental decomposition.
Słowa kluczowe: łuk elektryczny, przetwarzanie sygnałów, analiza widmowa, analiza przyrostowa.

Introduction

Formation of electric arc is a highly disadvantageous phenomenon that appears increasingly in electric installations. This phenomenon can occur in both the renewable energy installations [1÷5] and in the railway electric traction [6÷9]. The negative effects of electric arc can be experienced in households, where micro-power photovoltaic or wind energy systems have been used, as well as in industrial power systems [10÷16]. On the basis of the above, it can be concluded that the scale of this phenomenon is very extensive.

In order to protect electrical installations from occurrence of electric arc, methods based on detection of sudden voltage drop and light-emission of electric arc are currently applied. Further, research is being carried out into current waveforms spectral analysis [17], which provides additional information on the load nature and the distortion degree of nonlinear receivers' network. Some kind of analyses might be taken from power quality measuring methodology [18].

In addition, studies are conducted into alternative methods, which are less computationally complex, to obtain information on the dynamics of changes that appear in the investigated waveform, an example of such an analysis is incremental decomposition of current increases over time.

Electrical arcing problem

Arcing occurs when voltage is high enough to breakdown the dielectric between two conductors, as had been observed in the photovoltaic power systems, where panels are connected in series so the voltage between them is quite high. It can easily happen even for low voltages in the mains power systems, when the distance is relatively small, for example inside the cable with insulation damaged by a nail or between contacts of the fastener, when the screw is not tightened well. Cables can be also crushed by the moving objects, e.g. windows or doors. Besides the human error, arcing may be also caused by aging of electrical installation due to environmental influences such as temperature or moisture.

Standard electrical installation protective devices, such as circuit breakers are not suitable for detecting arcs because of limited current that comes with them. Current flow, while arcing, is not acting as during short circuit and has too low value to trigger the breaker before the fire starts. Fortunately, arcing fills in the specific noise to the power system, which can be detected by sampling current waveform, performing specific signal processing algorithm on acquired samples and then analyzing the results.

Arc fault detection devices

Siemens 5SM6 arc fault detection device is intended to detect arcing in the mains power system. It is a module designed to fit the DIN rail in order to provide easy installation in the distribution board. Figure 1 shows the block diagram of it.

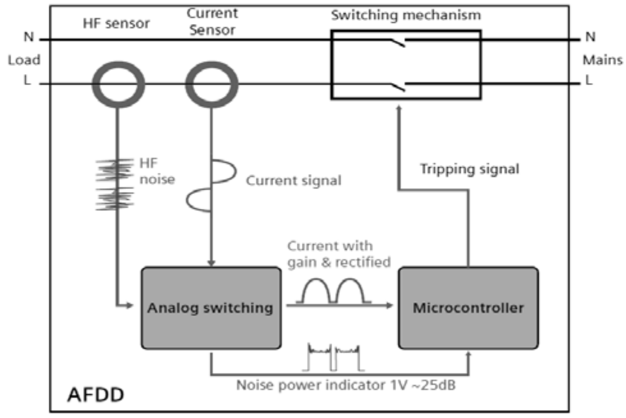

Fig. 1. Block diagram of the Siemens 5SM6 detector [19]

Live wire is crossed through two sensors. The first one measures the low frequency signal, which is proportional to the current flowing in the mains. The second one provides the high frequency signal, which is proportional to the noise caused by load and possible arcing. Both signals go to the analogue part of the circuit, which is amplifying them to provide the proper gain and then rectifying and filtering. Next, signals are digitized and analyzed by the microcontroller, which is calculating several values indicating specified states that occur in the mains while arcing. When the calculated values are greater than specified limits, the microcontroller detects arcing and disconnects the load by the switching mechanism. To prevent unwanted shutdowns, high frequency signal is analyzed in the spectrum, where signals during arcing and normal operation are easiest to discriminate, that is from 22 to 24 MHz.

Texas Instruments RD-195 arc detection evaluation board is designed to detect arcing in the photovoltaic power system. It is intended to be connected in series with solar panels, on the negative side of the string. It has two data busses: RS-232 to exchange data with computer (mainly to alert while arcing is detected) and JTAG for implementation of author's-specific signal processing algorithms. Figure 2 shows the block diagram of the RD-195 arcing detector.

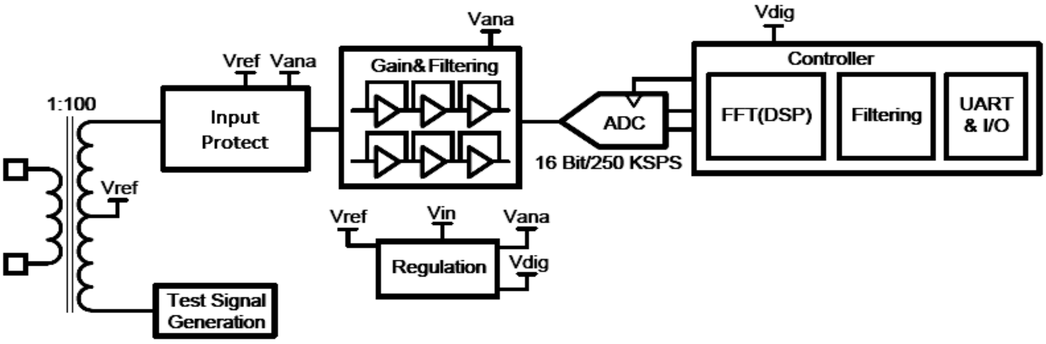

Fig.2. Block diagram of the Texas Instruments RD-195 detector [20]

Primary winding of the measuring transformer is connected as described above, so the voltage proportional to the current flowing in the system is inducted on the secondary winding. The signal from the transformer is then applied to the input protection circuit, which limits its value to protect the rest of the circuit. The signal is then filtered by the band-pass Butterworth filter with low limit cut-off frequency of 40 kHz and 100 kHz for the high limit. It also features the proper gain. Filtered and amplified signal is then digitized by the bipolar analog-to-digital converter controlled by the microcontroller, which performs a real-time fast Fourier transform on the gathered samples and then compares the shape of its frequency spectrum with the one measured while arcing. If the shape is similar to the reference, arcing is detected and specified alert sent through the RS-232 bus. As in the previous circuit, such a band of the filter is selected, where arcing is easy to discriminate with non-arcing.

Arcing detection based on a fast Fourier transform

At present, arc detection methods are also being developed, as based on the analysis of the current spectrum. Frequency analysis of the current flowing in the installation enables to determine whether there was an electric arc, and also what type of loads collect energy from it. It is possible to specify the type of load that consumes the energy on the basis of local maxima analysis in the current spectrum in the situation, when there is no electric arc. However, arc detection is based on an analysis of the spectrum shape. This shape is due to the continuous and random current spikes, which are caused by the presence of an electrical arc. Arc detection criterion consists in selecting such a band, in which it introduces the highest harmonics in relation to disturbances, which are present there all the time.

Arcing detection based on incremental decomposition

Incremental decomposition is the author's algorithm invented to speed up the process of arcing detection through decreasing the amount of calculations needed to obtain the signal's spectrum. While the fast Fourier transform calculates the frequency spectrum of the measured signal, incremental decomposition calculates how much values of the next samples changed and then increases the output vector by one, where the index is equal to the calculated value. This gives the incremental spectrum of the signal. Figure 3 shows the algorithm of the calculations.

All calculations are performed in a single loop. A variable named i is the index of the sample, d is the temporary value of the difference calculated between the samples, s is the vector of input signal and o is the vector of incremental spectrum. The calculations start from zeroing the value of i, which is then checked if it is lower than the number of samples minus one, it is 2047 in this example. If it is, the value of d is calculated. It is the absolute value of the difference between the next samples. Next, the output vector is increased by one, where its index is equal to d. The last step is increasing the value of i by one and the algorithm goes back to the conditional block. If the value of i is equal to the number of samples decreased by one, calculations are finished.

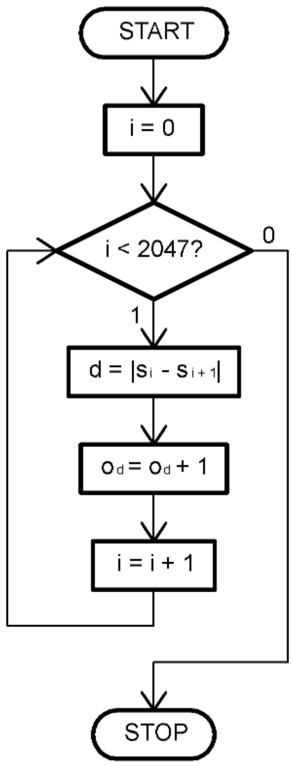

Fig. 3. Algorithm of the incremental decomposition calculation

The first advantage of implementing the incremental decomposition algorithm is that it operates on the whole numbers, which are easier to process than floating-point complex numbers, on which Fast Fourier Transform operates. The second advantage in the incremental decomposition is that there are no multiplication or division operations, only subtraction and addition are needed to perform the whole algorithm. These simple calculations take less time than multiplying complex values used in the Fast Fourier Transform.

The two advantages mentioned above, enable incremental decomposition algorithm to be implemented using the simplest microcontroller, while the Fast Fourier transform needs relatively better hardware to perform in a real-time.

Results of using a Fast Fourier transform

As mentioned in the introduction, arcing fills in the specific noise to the power system. This noise appears on the frequency spectrum calculated using the fast Fourier transform. While non-arcing calculated spectrum has another shape than arcing. Figure 4 and figure 5 show the frequency responses of signal while non-arcing and while arcing, respectively.

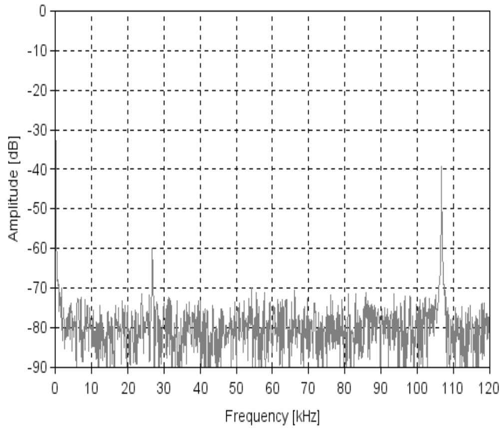

Fig. 4. Frequency spectrum of signal measured while non-arcing

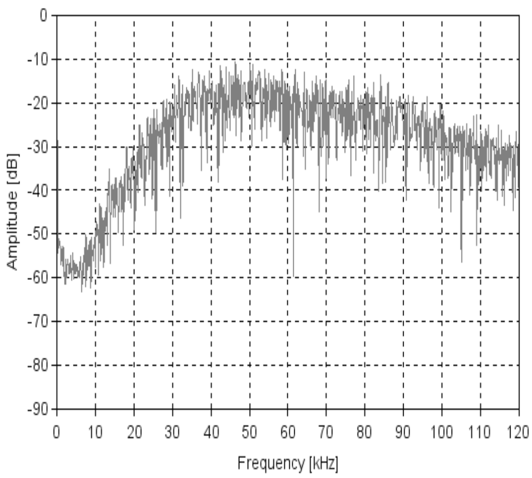

Fig. 5. Frequency spectrum of signal measured while arcing

Signals shown above were measured using the Texas Instruments RD-195 arc detection evaluation board. In the spectrum of signal while non-arcing, the direct current component dominates. There is also a higher harmonic on about 107 kHz. While arcing, the frequency spectrum is approximately equal to the input filter frequency response, so arcing fills in the white noise on that frequencies. Both spectrums are easy to discriminate.

Results of using incremental decomposition

Incremental decomposition is appropriate for arcing detection, because noise while non-arcing is relatively low compared to the situation when arcing appears. Figure 6 and figure 7 show the incremental spectrums of signal while non-arcing and while arcing, respectively.

As shown in figure 6, signal while non-arcing is relatively low and has higher numbers of repetitions of lower increments. The peak is on 0.0015 mV/μs with 300 repetitions of that increment. Figure 7 shows that noise while arcing is strong and there are lower numbers of increment's repetitions, but the spectrum reaches much higher values of increments than while non-arcing. That allows to use very simple algorithm to discriminate these two signals. It is needed only to check the peak value of increment and the peak value of repetitions. If there are a lot of repetitions, there is no arcing and if there are high increment's values, arcing is present.

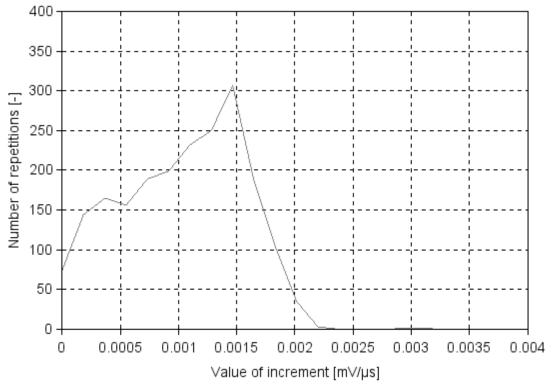

Fig. 6. Incremental decomposition of signal while non-arcing

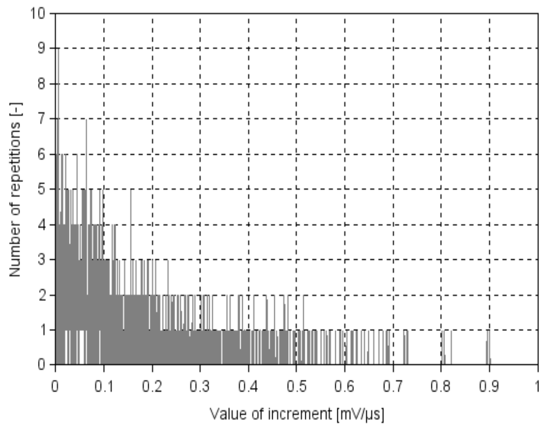

Fig. 7. Incremental decomposition of signal while arcing

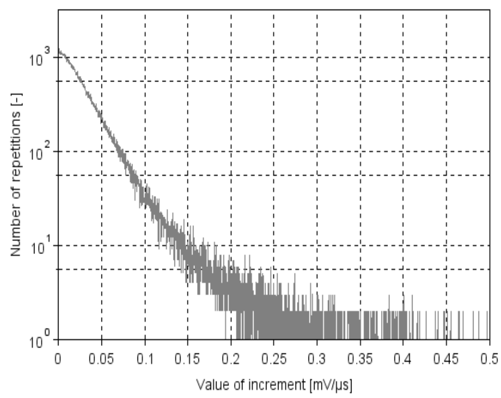

Fig. 8. Incremental decomposition of signal while 0.5 A arcing

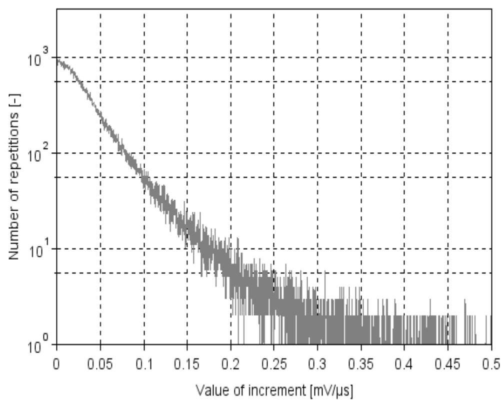

Fig. 9. Incremental decomposition of signal while 2 A arcing

As tests have shown, incremental decomposition also enables to discriminate signals while paying special attention to the arc current. Spectrums in the figures 4 ÷ 7 were made using short series of 2048 samples, but if we consider the bigger amount of data, it is possible to discriminate when the arc current had the greater value. Figure 8 and 9 show the incremental spectrums of signal when the arc had a current of 0.5 A and 2 A, respectively. Both spectrums above were calculated using 99 series of 2048 samples. While arcing with 2 A current, more repetitions of increments with greater values have been noted. In this case, the algorithm for recognising the arc current is also simple, while only the peak value of increment must be calculated, but this value must be designated by testing and taking an average, in view of random nature of sample's values while arcing.

Conclusion

The paper presents the use of FFT frequency analysis of current waveform and author's method: incremental decomposition of current increases over time. The first one allows to detect electric arc presence and implement any additional analysis of the spectrum shape, in order to determine the type of load powered from the network. However, it requires the use of microcontrollers with a relatively large computational power. The second analysis, due to its low computational complexity, can be applied in the protection systems with microcontrollers that are clocked by relatively low frequencies.

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