Arc Fault Detection in DC Distribution System by Wavelet Transformation

Prof. Dipti D Patil
Assistant Professor, Electrical Engineering Department,
A. C Patil College of Engineering
Kharghar, Navi Mumbai ,Maharashtra, India
dipti_patil@rediffmail.com

Prof. Priyanka R. Tarmale
Lecturer, Electrical Engineering Department,
A. C Patil College of Engineering
Kharghar, Navi Mumbai ,Maharashtra, India
ptpriyankatarmale@gmail.com

Abstract –Arc faults are significant with respect to reliability and safety concern for electrical systems which can cause stoppage in intermittent operation and electrical shock hazards which can even result in fire. Arc fault in such vast systems are random and challenging which makes the study of arc fault detection using arc signature difficult. The high-frequency content of the arc requires fast sampling, which are having long memory, which requires proper data storage for fast processing and analysing the arc. As signal to noise ratio is low and arc signal are not periodic in nature, commercialized existing techniques like Fourier Transform do not work well since they depend on recognising pattern with time domain or frequency domain. In contrast, wavelet Transform (WT), recently developed method for analyzing, provides a time and frequency approach to analyze target signals with several resolutions. In this we study the performance of the Fourier Transform arc detection method compared to the wavelet decomposition method by using synthetic waveforms. These waveforms are created by combining measured waveforms of normal background noise from inverters in DC source along with waveforms of arcing events. This paper proposal proposes a method based on Wavelet Packet analysis which has the localization characteristics to detect low-voltage DC arc fault. The mother wavelet selection is studied as well by using various orders of Daubechies wavelet. The simulated results using the synthesized test signals coincide with theoretical analysis derived from wavelet filter banks. And the effectiveness of this method has been proved by the simulation analysis with the MATLAB software and the arc simulation experiments.

Index Terms* – *Fourier Transform (FT), Short Time Fourier Transform(STFT), Wavelet Transform (WT),Cassie Arc.

I] INTRODUCTION

The growing need for highly reliable power supply for critical applications like in hospitals, date centers, telecommunication systems, and semiconductors industry, there is increase in use of power electronic converter (PEC). PECs have been extensively incorporated in the power system i.e. in renewable energy sources like wind and solar and energy storage systems.[1]For this power distribution system should be designed by considering factors like system architecture, energy flow control, and protection and power quality. In the dc distribution systems, recent developments are done in renewable energy technology system which should be flexible and able to utilize all the energy sources and also flexible for future expansion. In residential applications, a dc micro-grid structure is used for dc buildings which are having higher voltage in dc systems.

The reasons like combination of high dc voltage lines, deterioration of wire insulation due to rodent bites and abrasion due to chaffing with trees, building walls, or conduit during installation can cause electric arcs to occur. Arc faults can occur in small-scale load in residential systems as well as large-scale distribution systems and can also cause harmful threats to the human safety. Arc fault has a major problem in electrical installation.[2] This dc arc may result in shock hazard, fires, and system failure or fault in the micro-grid. If dc arc faults are not detected and extinguished on time, the arc fault could spread to adjacent circuits and endangered the power sources, control systems, or even cause explosions in a confined space due to the growing arc pressure. With arc fault, it is also important to detect arc flash, which is the prefault event of sparking and dielectric breakdown. As long as this problem exists, dc distribution systems face significant disabilities which threaten their extensive use. Thus, arc fault detection is extremely important for reliable and safe system operation and is a prerequisite for widespread adoption of dc microgrid systems.

II] PROBLEM OVERVIEW

The detection of ac arc faults has been well developed with commercial products designed for safety. In the time domain, the current of DC arc fault will decrease or increase sharply, and in the frequency domain, it contains much high frequency harmonic. A much smaller work has done related to arcs in dc electrical systems and commercialization of sensing and protection devices [5]. A significant complication to their detection is that arcs in dc systems are not periodic, and thus may not have easily recognizable amplitude or frequency signatures for pattern recognition-based detection techniques. However, the low-voltage DC arc has characteristics of instantaneity and high-resistivity, so it’s hard to detect the fault by methods in time or frequency domain.[6] At present, low-voltage DC breaker in use prevents the wire from heat injury only when short-circuit or over-current happens. In order to improve the system’s security, it is necessary to add the arc fault protection into the low-voltage DC breaker. There is no natural mechanism for periodic extinction and reignition of the arc in dc systems, which makes detection difficult especially for series arc faults. Although many methods for dc arc detection have been studied, a simple, accurate, reliable and cost-effective solution is still needed.

Statistical methods are adopted to identify arc by studying the variance of arc (voltage or current) signal. Spectral analysis using Fourier techniques is done to decompose the frequencies of a sustained arc fault. The characteristics of dc arc have been studied in both frequency and time domain. In the frequency domain, DC arc detection is done by (FFT) method. However Fourier analysis requires a linear system and stationary signal. Wavelet Transform has a particular feature of time-frequency localization. As a result it can overcome the shortage of Fourier analysis. In, with wavelet packet based analysis, dc arc energy in different sub-bands is quantified into one variable by using the reconstruction coefficients in each band, these methods give insight into the frequency characteristics of a dc arc and also present the challenges in arc detection, such as noise recognition, calculation time reduction, and differentiation from load changes.

A] Objectives

The main objective of this proposed system is to study DC arc fault and the effects of the DC arc fault on electrical distribution system and to study different available methods for arc detection and note there limitations. To study and implement the new method, i.e Wavelet Transformation in MATLAB simulation and try to compare results with conventional method (FFT-Fast Fourier Transform), with the help of MATLAB simulation.

B] Arc Model

Detecting arc flash is a difficult problem, since high current flows through a metal- to- metal connection, and arc flash involves short-term current flowing through ionized air which does not draw sufficient high root-mean-square current, or has a high energy (I^2t) which can trip a thermal circuit breaker.[2]This is in DC micro-grid and system which is energized by renewable energy sources. For this if arc is taken, which sustains for hours or even days, since overcurrent protection systems remain inactivated due to left undetected which causes fire or any safety hazards.

i) Arc Model Blockset in MATLAB:

The MATLAB program is suitable tool for the computation of power system transients Arc models were originally developed for better understanding of the current interruption process in high voltage circuit breakers and for designing interrupting chambers. Because of non-linear behavior of arc and very small time constants are involved, correct numerical treatment of the arc-circuit problem is important. MATLAB program is suitable tool for the computation of power system transients [8].

The Cassie arc model is written as a differential equation:

$$\frac{1}{g}\frac{dg}{dt}=\frac{d\ln g}{dt}=\frac{1}{\tau}\left(\frac{u^2}{U_C^2}-1\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where,

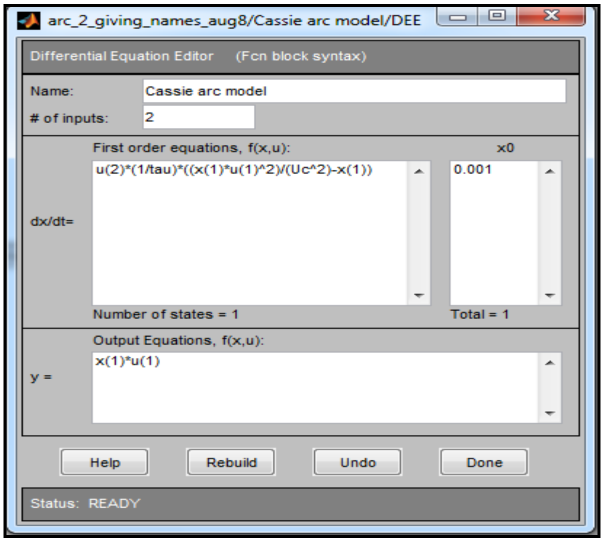
g= conductance of the arc;

u=voltage across the arc;

i=current through the arc;

U_C= constant arc voltage;

τ= arc time constant.


arc_2_giving_names_aug8/Cassie arc model/DEE

Differential Equation Editor (Fcn block syntax)

Name: Cassie arc model

# of inputs: 2

First order equations, f(x,u):

dx/dt=

```
u(2)*(1/tau)*((x(1)*u(1)^2)/(Uc^2)-x(1))
```

x0: 0.001

Number of states = 1

Total = 1

Output Equations, f(x,u):

y =

```
x(1)*u(1)
```

Status: READY

Fig 2.1 Cassie arc model in MATLAB

III] CONVENTIONAL METHODS FOR ARC DETERMINING

A] Arc Fault Circuit Interrupter (ARFCs)

AFCI is a new product in a resindential application to protect against series and parallel arc fault that may cause a fire. AFCI must be capable of distinguishing between normal circuit condition and unwanted, unsafe condition**.** Some research however had concluded that, neither branch/feeder AFCI nor combination AFCI would accurately detect all series arc faults. Other non-arcing related signals, such as switching harmonics from inverters and dc/dc optimizers may also generate signals in this frequency band which can lead to false detection, by covering the main arc signal. This limitation of false detection can cause loss of revenue and grid instability when the generation trips offline both unwanted and unexpectedly.

B] Fast Fourier Transformation (FFT)

Fourier Transform is a reversible transform, that is, it allows going back and forwarding between the raw and processes (transformed) signals. FT decomposes a signal to a complex exponential function of different frequencies.[10] The way it does is defined by the following two equations:

$$X(f) = \int_{-\infty}^{\infty} x(t) * e^{-2j\Pi ft} dt. \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

t= time

f=frequency

x=denotes the signal in frequency domain

X=denotes the signal in frequency domain

i) If the result of this integration is a large value, then we say that: the signal x(t), has a dominant spectral component at frequency "f". This means, a major portion of this signal is composed of frequency f.

ii) If the integration results in a small value, then this means that the signal does not have a major frequency component of "f" in it.

iii) If the integration results in zero, then this means that the signal does not contain frequency component of "f" at all.

Equation (2) follows that, no matter where in time the component with frequency "f" appears, it will affect the result of the integration equally as well i.e it does not depend on time. This is why Fourier Transformation is not suitable if the signal has time-varying frequency i.e the signal is non-stationary. FT works best for periodic signals, this can be said its limitation, because the ARC fault in power system is unpredictable, hence non-periodic in nature. Only frequency information is given by traditional Fourier Transform approaches, and the time-domain information is not provided to find out exactly when the event occurs.

C] Short Time Fourier Transform (STFT)

There is a minor difference between STFT and FT. In STFT, the signal is divided into small segments, where these segments of the signals can be assumed to be stationary. For this purpose, a window function "w" is chosen. The width of this signal where it's stationary is valid.[10] The following definition of the STFT summarizes all the above explanations in one line:

$$STFT_x^{(w)}(t, f) = \int_t [x(t) * w^*(t - t')].e^{-j2\Pi ft} dt$$

x(t) is a signal, w(t) is the window function, and * is the complex conjugate. STFT of the signal is nothing but the FT of the signal multiplied by a window function.

The problem with the STFT is with the width of the window function that is used.

We can only know the time intervals in which certain band of frequencies exists which are a resolution problem.

A narrow window ⟹ will good time resolution, poor frequency resolution.

Wide window ⟹ good frequency resolution, poor time resolution.

In order to see these effects, two different windows lengths are taken for consideration, and we will see, how these can be used for computing with STFT.

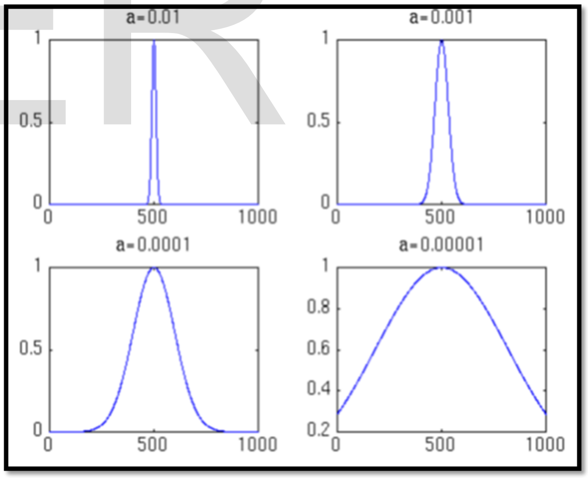


Fig.3.1 Different scales for deciding window.

IV] THE ULTIMATE SOLUTION: THE WAVELET TRANSFORM

A] Wavelet Transform (WT)

In an analysis of the inrush and the fault currents it is observed that the inrushes current as well as the fault current signals are non-periodic in nature and also observed that these signals are oscillating in nature which contains localized superimposed power frequency and its harmonics. [2] The wavelet transform is capable of providing the time and frequency information simultaneously, hence giving a time-frequency representation of the signal. The WT was developed as an alternative to the STFT. We pass the time-domain signal from the various high pass and low pass filters, which filter out either high frequency or low-frequency portions of the signal. This procedure is repeated, every time some portion of the signal corresponding to some frequencies being removed from the signal. All of them together and plot them on a 3-D graph, we will have time in one axis, frequency in the second and amplitude in the third axis. This will show us which frequencies exist at which time.

B] Discrete Wavelet Transform (DWT)

The discrete wavelet transform (DWT) is defined as:

$$C(j,k)=\sum_{n\in Z} s(n)g_{j,k}(n)$$

Where, $j \in N, k \in Z$

where *C(j, k)* is the corresponding wavelet coefficient, *n* is the sample number, *s(n)* is the signal to be analysed, and $g_{j,k}(n)$ is the discrete scaling function (also called as the father wavelet), which for dyadic-orthonormal WT is defined :

$$g_{j,k}(n)=2^{\frac{-j}{2}}g(2^{-j}n-k)$$

The auxiliary function to this is the mother wavelet. With this initial setting, the DWT can be easily implemented by multiresolution analysis.[11] As shown in Fig.4.1 at each level j, the approximation signal Aj can be created and detail sign al Dj can be created signifies that *s* is the sum of its approximation Aj improved by the fine details.

$$s=A_J+\sum_{j\le J}D_j$$

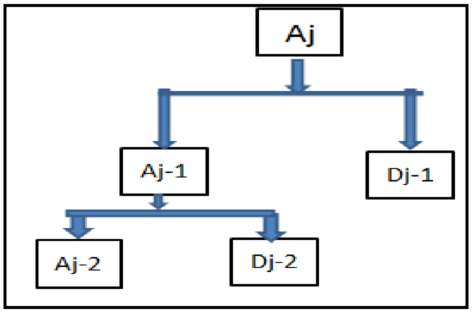


Fig 4.1 Dyadic wavelet decompostion tree

V] COMPARISON OF DWT WITH CONVENTIONAL METHODS

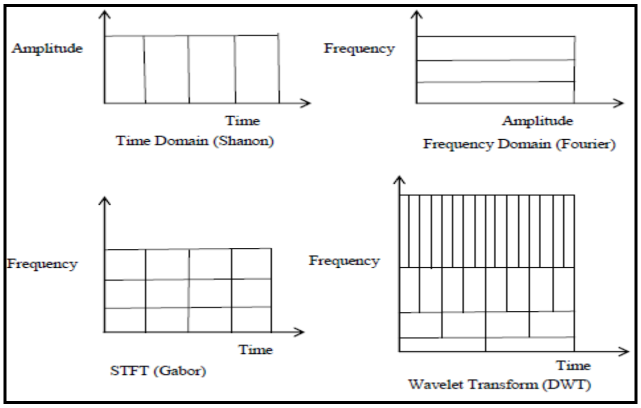


Fig. 5.1 Different Transformation methods

VI] IMPLEMENTATION OF FFT & WAVELET TRANSFORMATION IN MODEL

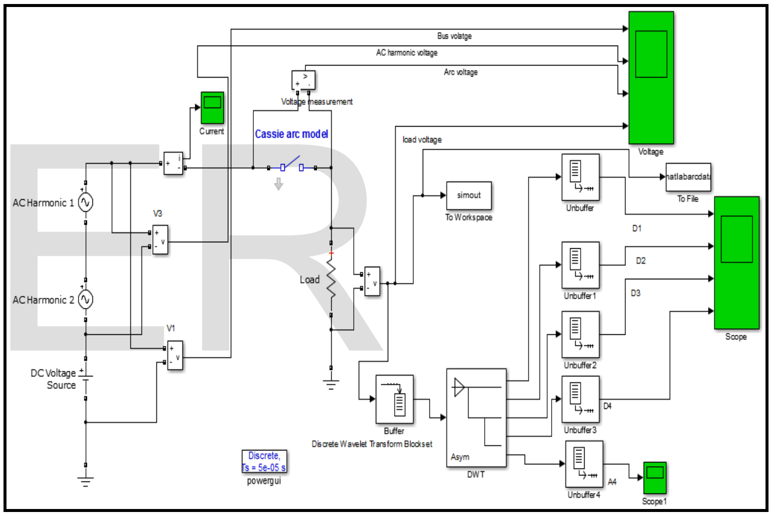


Fig.6.1 Simulink model of the PV array dc system [2]

Components for Model:

- DC voltage source-100 V
- 120Hz Double-frequency power line ripple (ac voltage2)-10V amplitude
- 2000 Hz Double –frequency power line ripple (ac voltage 1)-10V amplitude.
- Dyadic Analysis Filter Bank-Decomposed signals into sub bands with smaller bandwidths
- CASSIE ARC as series arcing

VII] SIMULATION RESULTS

A] Voltage waveforms with Double-frequency power line ripple and switching ripple in DC voltage source.

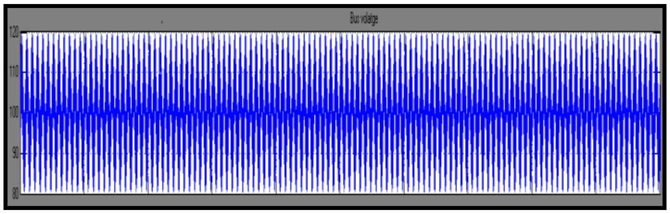


Fig.7.1 Voltage waveform of dc system with 120 Hz double-frequency power line ripple (ac voltage 2), 2 kHz Switching ripple (ac voltage 1)

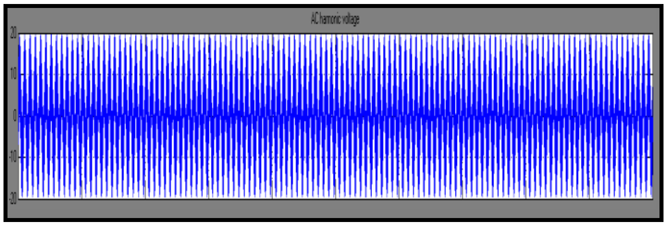


Fig.7.2 Voltage waveform of 120 Hz double-frequency power line ripple (ac voltage 2),2 kHz switching ripple (ac voltage 1)

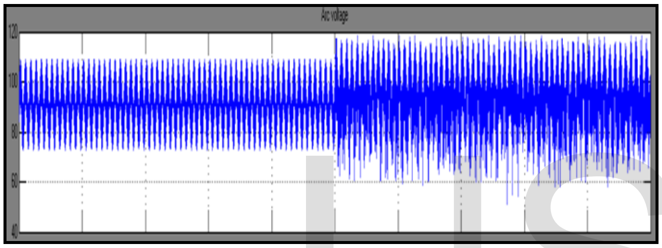


Fig.7.3. Voltage waveform of dc system with 120 Hz double-frequency power line ripple (ac voltage 2) , 2 kHz switching ripple (ac voltage 1) with arc starting at 0.5 sec.

B] FFT Analysis of Arc Voltage Waveform:

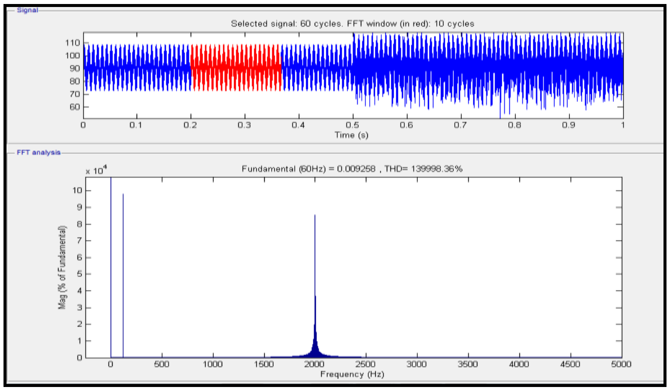


Fig.7.4 FFT analysis of synthetic dc voltage before onset of arcing.

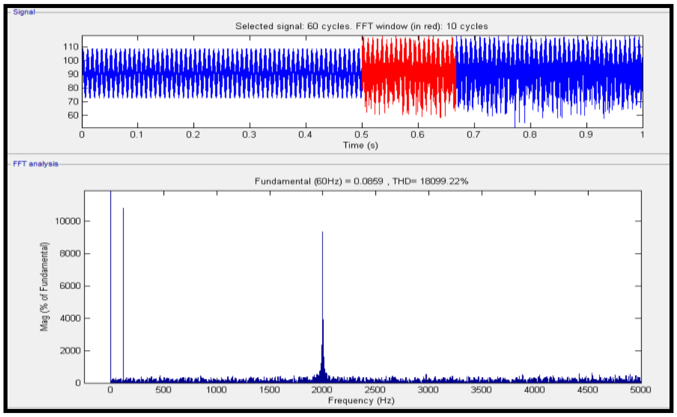


Fig. 7.5 FFT analysis of synthetic dc voltage after the onset of arcing

C] Result Analysis by Fast Fourier Transform:

The FFT results as shown in fig.6.8 , the DC voltage without arc fault, while dc voltage with arc fault, as shown in fig.7.5 There is no easily distinguishable change in the FFT spectrum from before and after the onset of the arc. The Fourier Transformation tells whether a certain frequency component exists or not. This information is independent of where in time this component appears. This is why Fourier Transformation is not suitable if the signal has time-varying frequency i.e the signal is non-stationary.

D] Result Analysis by Wavelet Transformation:

According to research studies and arc fault signal analysis on dc systems, the bandwidth for the FFT analysis is adjusted as 5000Hz.For wavelet decomposition considered in this model the frequency band for four level of wavelet decomposition selected approximately by,

$$\frac{Bandwidth}{2^{K}}$$

For above model, frequency bands for wavelet decomposition can be given as:

.

D1= 1.25~2.5kHz

D2= 625~1.25kHz

D3=312~625Hz

D4=156~312Hz

The result of the Wavelet Transformation (Daubechies 9) of the synthetic arcing waveform shown in Fig.7.6, clearly demonstrates an obvious difference in the WT from before and after the onset of the arc. This WT provides an easily observable signal.

D] Wavelet Decomposition of Arc Signal:

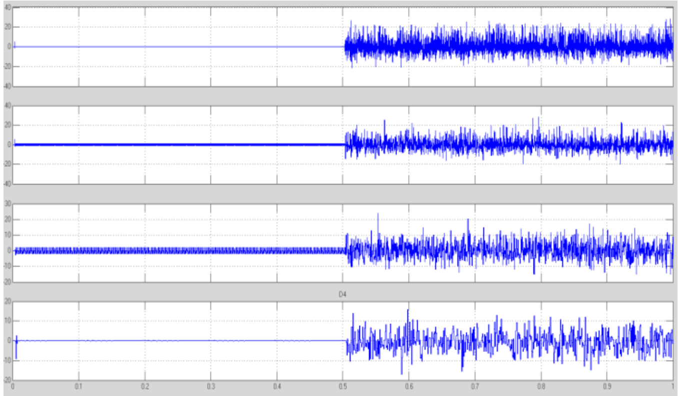


Fig.7.6 Wavelet decomposition result of synthetic arcing waveform (at 0.5 s, the switch across the arc generator opens and current begins to flow in the arc. Load voltage signal is processed by WT by Daubechies 9 as above)

CONCLUSION

This project has proposed a new approach for arc analysis in dc microgrid systems based on WT. The fundamental feasibility of applying WT has been presented. A comparison between the Fourier transform method and the proposed WT method has been studied with simulation analysis results. The presence of switching harmonics and ambient electrical noise can mask the arc signal, making detection of an arc difficult. Fourier analysis is usually not able to discover transient signals and abrupt changes like sudden arc faults and arc flashes. If the duration of the arc flash lasts for a very short period of time in comparison with the sampling window of FFT, it is likely that the arc flashes will not be observable. However, WT is extra ordinarily effective with detecting the exact instant the signal changes. The results suggest that the approach is not just capable of analysing arc fault in dc systems but that it also provides a more readily detectable signal and better performance than the FFT method. In subsequent work, we have studied arc fault signals in the presence of inverter noise by adding ac harmonics as power ripple and switching harmonics using waveforms synthesized from real-world PV system voltages and currents. These waveforms are comprised of superimposed arcing and inverter electrical noise at a user-specified arc-signal-to-noise ratio. The test results using the synthesized test signals coincide with foregoing theoretical analysis .Although the example system used in this project was a PV dc collection grid, the results of the arc fault analysis algorithm can be applied generally to any dc system.

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