Detection and classification of Array Faults in Photovoltaic System using Wavelet Packet Transform

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Abstract.

Due to nonlinear photovoltaic (PV) characteristics, working of maximum power point tracker, presence of the blocking diodes, and the low irradiance conditions prevents the operation of protection devices under fault conditions and leads to reduction of efficiency and even it may cause fire hazards. Additionally, the characteristics of photovoltaic (PV) array under certain partial shading conditions looks like fault characteristics and results in maloperation of the protection devices Thus, it is inevitable to design a fault detection algorithm for identifying and differentiating the faults and shading conditions to avoid false tripping of the protection system. To address the above problem, a fault detection method is developed by processing the available data of array voltage, current using wavelet packets. For analysing the array faults, a 4 x 4 PV system is considered and simulated by using MATLAB/Simulink. After observing the energy values for various faults with distinct %mismatch, shading and cloudy conditions, threshold values are determined for identifying the faults and partial shading condition.

Keywords. Photovoltaic (PV) Module, PV array Characteristics, Partial Shading, PV array Faults and wavelet packets.

1. INTRODUCTION

As per the REN21 report, globally the solar power generation is exponential increasing and has reached 720 GW [1] due to its easy installation, low maintenance and government subsidies. On the other side, PV systems are more vulnerable to various faults such as line to ground (LG) faults, line-line (LL), arc fault and mismatch faults. Among these, LL and LG faults induce massive fault currents and even it may create fire risks. One such fire hazard occurred in a 383kW PV array located at Bakersfield, California, in 2009 [2]. Furthermore, the Line-line faults and partial shading conditions exhibits similar operating characteristic [3]. Thus, it is necessary to detect and differentiate the LL faults and shading conditions. In the literature, to address this issue, various methods have been proposed using different techniques and some of them are reviewed as follows.

Line-line faults that occurs in Photovoltaic system and its impact are explained in and discussed the challenges in detecting the array faults such as active MPPT, non-linear output characteristics of photovoltaic arrays, fault impedance, location of fault, faults with low percentage mismatch [7]. More importantly, the fault occurred in night and progress from night to day period. Such faults are not detected by the existing protection system even when the irradiation changes to high values. Comparison based techniques, an online fault identification of PV system approach in [9] have measured outputs and model-forecasted outputs the difference between these 2 outputs are taken as a fault, these approach cannot provide information of type and location of fault. In [10]a new monitoring technique of PV system is introduced. It can identify static and dynamic shadowing, accumulation of dust, aging. similarly, those no. of sensors are required which leads to increasing in complexity and cost.

Signal-processing based methods, this method is used for analysing, extracting features of faulted PV array parameters and it works on time domain reflectometry, under normal conditions there is no reflections and uniform impedance throughout transmission line. When fault is occurred delay of signal, waveform distortions show type and location of fault. A TDR based technique [11] is used for detecting, locating open circuit faults, LG faults and it is implemented to 1MW plant but inverter switches are reducing operational performance.

Machine-learning based techniques [12], for detection and location of short-circuit faults a artificial neural network model is introduced it is implemented to 3x2 PV array and it takes irradiation, temperature, voltage, current at maximum power as input and provides terminal voltage to each PV module it have huge computational burden. For detection and diagnosis short circuit, open circuit, degradation faults, partial shading a extreme learning technique is implemented [13], this technique is very fast and accurate but the performance of this model is mainly depends on PV module and it cannot generalise across different PV module and also it needs large labelled data.

Thus, this paper proposes an effective algorithm based on wavelets for detecting faults and also able to differentiate from the normal environment condition. The rest of the paper is explicated as follows- section II-PV system configuration –protection devices, array faults and shading condition, Section III- illustrated the P-V characteristics under various LL faults and partial shading conditions, Section IV- discussed about wavelets, algorithm for the detection of faults, and validation of the proposed method followed by conclusion in Section V.

2. DESCRIPTION OF PV SYSTEM CONFIGURATION, ARRAY FAULTS

A 1.6 kW, 4 x 4 series-parallel connected PV array configuration with protection devices like OCPD, GFPD and with blocking and bypass diodes is shown in Fig. 1. Various possible LL faults that are occurred in the PV array are illustrated in Fig. 1: F1 – Single module LL fault or 25%mismatch (out of 4 module one module shorted), F2 – Two module LL fault or 50%mismatch (out of 4 module two module shorted), F3 – Three module LL fault or 75%mismatch (out of 4 module three modules shorted). Percentage mismatch is calculated based on no. of modules shorted by total no. of modules in a string of PV array. Another frequently occurring temporary fault known as shading, which occurs due to shadows of beside building, poles is shown in Fig. 1.

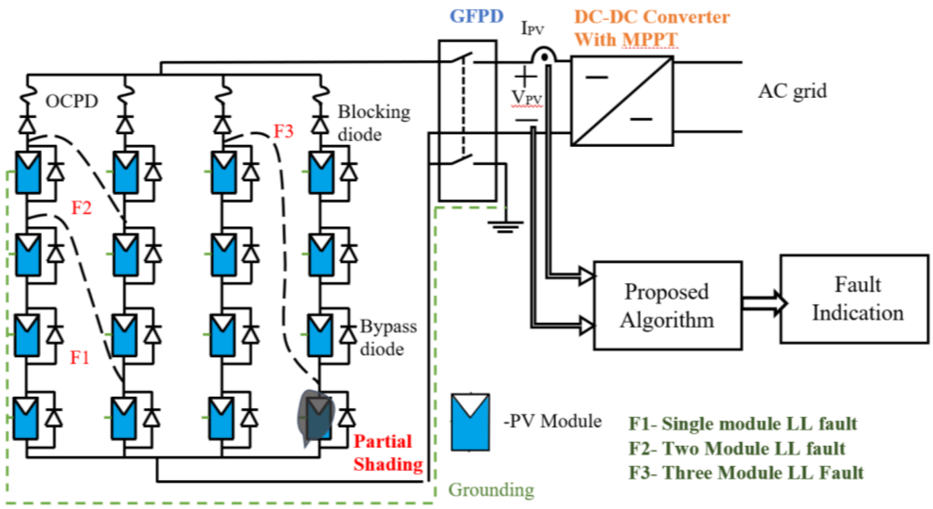


Fig. 2.1 4x4 PV System with protection device and proposed algorithm

3. SIMULATION RESULTS OF LL FAULTS AND SHADING CONDITIONS

3.1. Single Module LL Fault(F1)

Single module LL fault means one module is short circuited across 4 modules in the PV array it is also called as 25% mismatch. The single module LL fault(F1) as shown in Fig. 2.1 is simulated using MATLAB/Simulink and attained volage, current waveforms as shown in fig 3.1

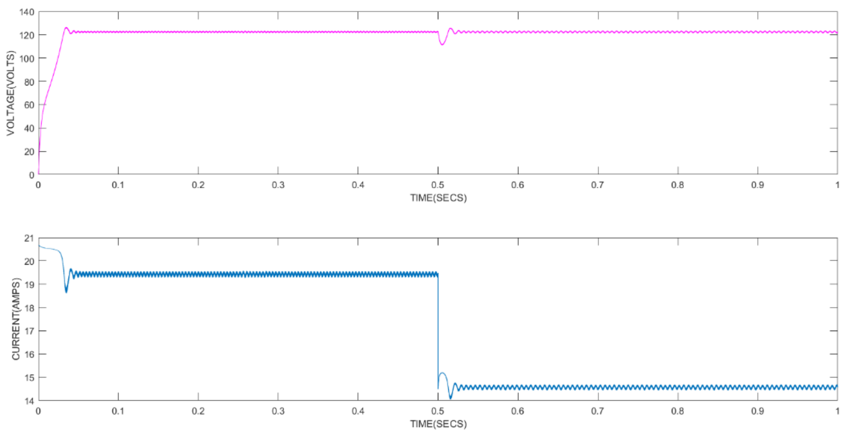


Fig 3.1 voltage, current waveforms of single module LL fault (F1)

3.2 Two Module LL Fault(F2):

Two module LL fault means two modules is short circuited across 4 modules in the PV array it is also called as 50% mismatch. The two module LL fault(F2) as shown in Fig 2.1 is simulated using MATLAB/Simulink and attained volage, current waveforms as shown in fig 3.2

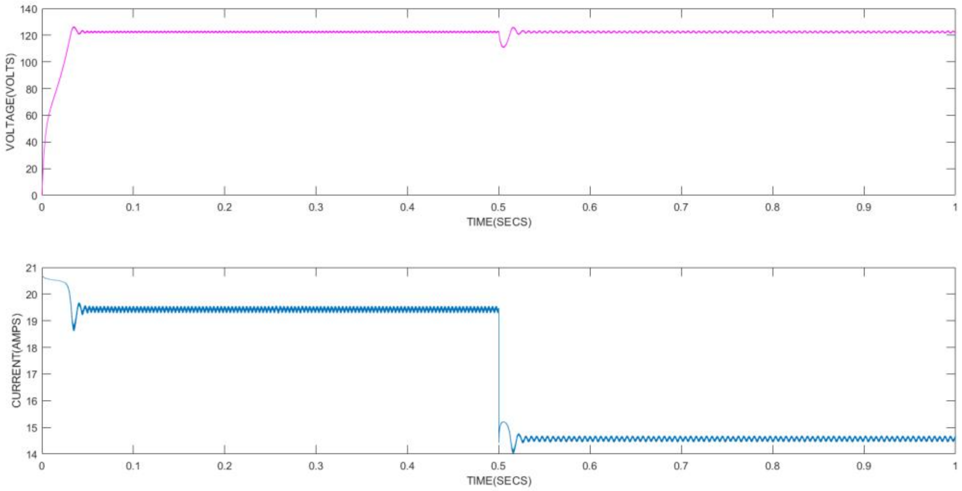


Fig 3.2 voltage, current waveforms of Two module LL fault (F2)

3.3 Three Module LL Fault(F3):

Three module LL fault means three modules is short circuited across 4 modules in the PV array it is also called as 75% mismatch. The three module LL fault(F3) as shown in fig 3.1 is simulated using MATLAB/Simulink and attained volage, current waveforms as shown in fig 3.3

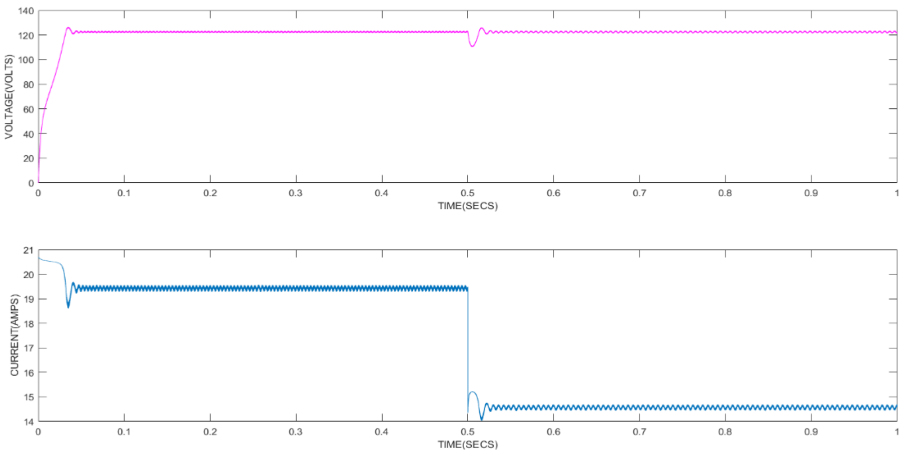


Fig 3.3 voltage, current waveforms of Three module LL fault (F3)

3.4 Partial Shading Condition:

It is classified into 2 types based on retain of shadow on PV panels

1. Static shading condition: It means area of shadow appeared on the PV panels is constant throughout a complete day.
2. Dynamic shading condition: It means area of shadow appeared on the PV panels is varied throughout a complete day.
3. The partial static shading condition is considered as shown in fig 3.1, it is simulated using MATLAB/Simulink and attained volage, current waveforms as shown in fig 3.4

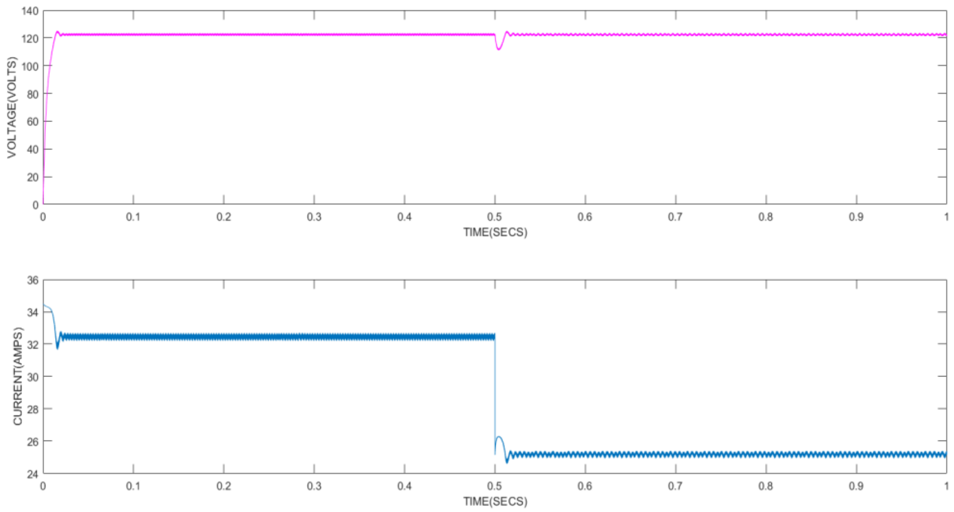


Fig 3.4 voltage, current waveforms of partial shading condition

By considering all the above graphs, it is concluded that both faults and partial shading condition have similar PV characteristics, for LL fault with > 25% age mismatch faults occurred within string the complete string is isolated and blocking diode opposes entering of reverse currents into the faulty string. The remaining strings supply power to load hence, from the above voltage and current waveforms it is concluded that at any of LL percentage mismatch faults the power delivered to the load is constant irrespective of type of faults.

4. Fault Detection Algorithm Based On Wavelets

During fault occurrences the PV parameters like fault voltages and fault currents are having abrupt changes in their waveforms, Fourier transform cannot represent abrupt changes in signal efficiently. The reason is Fourier transform shows data in sum of sine waves which cannot not localised in time or space. To accurately analyse signals that have abrupt changes a wavelet transform is used which is well localised in time and frequency.[14]

In CWT wavelet coefficients are calculated at each scale generates lot of data, requires more computation time and is overcome by sing DWT. However, DWT only approximations are decomposed into N-level. In wavelet packet analysis, for more accuracy the approximations as well as the details are decomposed into N-level

4.1 Extracted Features of PV system:

The extracted features are obtained from voltage across PV array and current though the PV array.

1) Difference in voltage across PV array between 2 successive samples.

$$\Delta V = V_{PV}(i+1) - V_{PV}$$

2)Energy of array voltages (E_{av}), the energy is calculated by doing summating the squares of its wavelet packets coefficients.

$$E_{av} = \sum V^2{}_{WPC}(i)$$

V_{WPC} = wavelet packet coefficient of voltage across array

3)energy of change in impedance (E_{IMP})

$$E_{IMP} = \sum Z^2{}_{WPC}(i)$$

Z_{WPC} = wavelet packet coefficient of change in impedance Z(i)

$$\text{Where } Z(i) = \frac{V_{PV}(i+1) - V_{PV}}{I_{PV}(i+1) - I_{PV}}$$

i=sample number.

By Examining the ΔV and energy values, the threshold values are assumed which are used to detect faults and separates faults from partial shading condition. An algorithm is to be implemented in such a manner that it should consider threshold values and its inputs are only from voltage across PV array and current though the PV array. When any fault or partial shading condition is occurred based on threshold values the algorithm should check whether it is belong to fault or partial shading region and concludes as fault or partial shading.

4.2 Fault Detection Algorithm (FDA)

The algorithm can be explained as follows:

Step 1: Get the features E_{AV}, and E_{IMP} for every t_0 seconds (1 s). Set i = 1.

Step 2: If $E_{AV} < \varepsilon 1$ (or) $E_{IMP} > \varepsilon 4$, then go to step 4; otherwise, go to next step.

Step 3: If E_{AV} lies within the limits (ε2, ε3) (or) $E_{IMP} > \varepsilon 5$, then go to step 4; otherwise, go to step 5.

Step 4: “Fault occurred.” Go to step 7.

Step 5: “Fault has not occurred.” Go to the next step.

Step 6: If i < 1000, increment i by 1 and go to step 2; otherwise, go to step 1.

Step 7: Disconnect the PV array from the ac grid

4.3 Determination of threshold values

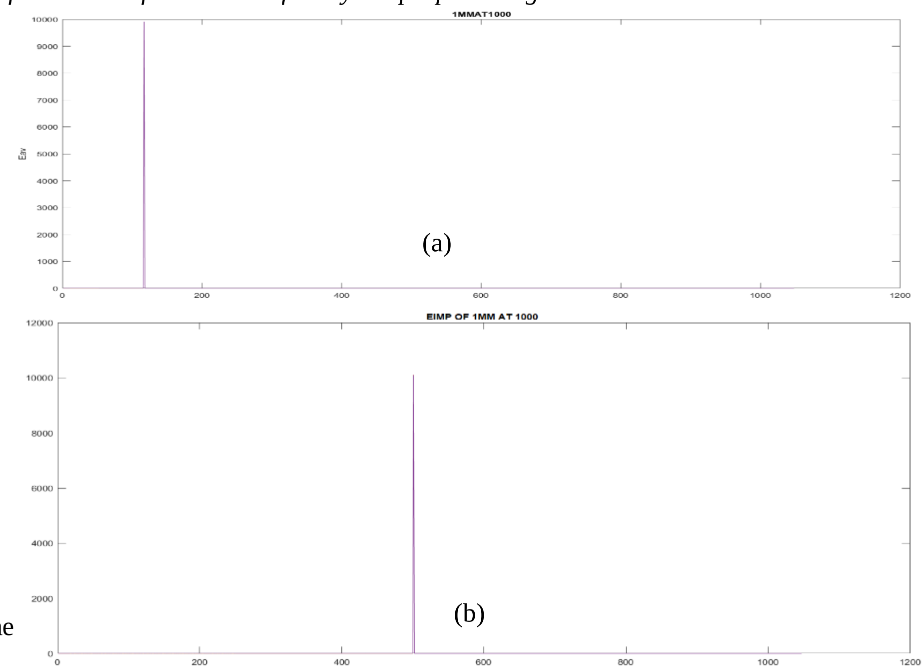
The threshold vales are determined by examining the energy values under various fault conditions at distinct irradiance values, partial shading conditions at one module, two module and cloudy conditions. The threshold values for identifying the LL faults are tabulated in Table 4.1

Table 4.1 Threshold values for E_{av} and E_{imp}

Variable	**Constant**	**Value**
E_{av}	ε_1	10,000
	ε_2	4000
	ε_3	5000
E_{imp}	γ_1	9000
	γ_2	$3x10^6$

4.4 Validation of the proposed method under 25% of mismatch fault

A one module fault LL fault is created and the corresponding energy values for the array voltage and impedance is computed by applying the wavelet packets and the corresponding energy values are plotted in Fig. 4.1(a) and Fig. 4.1(b) respectively. From the Fig. 4.1(a) and Fig. 4.2(b), it is clear that one of the energy condition (E_{imp} >9000) is satisfied and the fault is identified by the proposed algorithm.



5.

same

Fig. 4.1.(a) E_{AV} for 25% mismatch at 1000 irradiation and (b) E_{IMP} for 25% mismatch at 1000 irradiation.

tracker, bypass and blocking diodes in PV system. While in the presence of blocking diodes in PV array, the severity of fault current depends on percentage mismatch.

To detect and differentiate array faults and partial shading an algorithm is need to be implemented by using wavelet packets. By applying wavelets to the input data, energy values were calculated for different case studies such as faults with discrete %mismatch at distinct irradiance values, cloudy conditions and shading conditions. After observing the energy values, threshold values are determined. Based on these energy threshold values, faults and partial shading conditions can be identified and differentiated. Most of faults can be detected by using this method.

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