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Line-Line Fault Detection in Solar Photovoltaic Arrays

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ABSTRACT: The 21st century is witnessing a rapid growth in the electrical energy demand due to rise in a large number of electrical gadgets. The conventional sources of energy, which are reliably supplying the energy, are rapidly depleting and the crisis is not near. Therefore, the lookout of non-conventional sources of energy is still on, particularly, the one which can perfectly replace these conventional energy sources. Solar energy is a reliable option, but it also suffers from certain drawbacks such as low power-rating, high cost, low reliability, etc. The low reliability is due to the possibility of fault being hidden in the solar PV array, reducing its lifetime and efficiency as well. This paper discusses the scenarios in which fault may remain hidden, and, also tries to propose some methods to detect and remove such faults in a better and efficient manner.

There are quite a few methods available for detection of such hidden faults, which have been discussed in detail in the earlier papers, like Decision Tree-based Fault Detection, Outlier Detection, Use of PV circuit simulation, Output voltage and current detection method, Infrared imaging, etc.

INDEX TERMS – Blocking diodes; fault impedance; fault location; line-line fault; maximum power-point tracking; over-current protection device; PV array; PV fuse; partial shading; reverse connections.

NOMENCLATURE

V_{OC} Open Circuit Voltage
I_{SC} Short Circuit Current
R_s Series Resistance
R_{sh} Shunt Resistance
q Electronic Charge ($1.6*10^{-19}$ C)
A Ideality factor (1.5)
k Boltzmann Constant ($1.38*10^{-23}$ V/K)
T_{ref} Reference temperature (^oC)
T_{op} Operating temperature (^oC)
T_{rK} Reference temperature (298 K)
T_{aK} Actual temperature (in K) (303-343)
I_{scRef} Short-circuit current at reference temp.
N_s Number of cells in series (6)
N_p Number of cells in parallel (6)
I_{ph} Photon current
I_s Module saturation current
I_{rs} Reverse saturation current
E_{g0} Band gap (1.1 eV)
K_i Constant (0.0017)
V_o Output Voltage
I_{pv} Photovoltaic current

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V_{pv} Module voltage
I_L Light generated current
G Irradiation

I INTRODUCTION

Fault analysis in the solar PV arrays is a fundamental task to eliminate any kind of dangerous and undesirable situations arising in the operation of PV array due to the presence of faults. They must be detected and cleared off rapidly. The faults occurring in the PV arrays are – Ground faults, line-line faults, etc. In addition to these, there exists many undesirable operating conditions - Partial shading, reverse connections, changing illuminations, etc.

Ye Zhao et al[1][2][3] have discussed about the various challenges in line-line fault analysis and protection against these faults, particularly during two unique scenarios – Low irradiance conditions and Night-to-day transition. They also have discussed about the challenges to Over-Current Protection Devices (OCPDs) brought by the MPPT (Maximum Power-Point Tracker)[4]. They also have tried to propose two methods of fault detection – Decision-tree based fault detection[5] and Outlier Detection Rules[6].

Mohammed KhorshedAlam and Faisal H. Khan[7] have discussed about the different types of faults and fault detection techniques and also proposed about the transmission line model for PV panels, which can be useful for interpreting faults in PV using reflectometry methods.

A Chouder and S Silvestre[8] have discussed about the automatic supervision and fault detection of PV systems based on power losses analysis. It analyzes the faulty signal and the current/voltage ratios and identifies the type of fault.

T Shimakage et al[9] have discussed about the development of fault detection system in PV panel.
XiaoliXu et al[10] proposed the new current and voltage detection method to predict and locate the fault occurrence rapidly and accurately.

N Pandiarajan and RanganathMuthu[11] have explained step-by-step for Simulink modeling of Solar PV module.

This paper presents the analysis of solar PV module under faulty conditions and the recently proposed Outlier Detection Rule is planned to be utilized for fault detection.

II. FUNDAMENTALS OF PV SYSTEMS

The term ‘photovoltaic’ means the ‘production of electric current at the junction of two substances exposed to light’. Here, in solar PV system, the electron gains the energy from the photons (in the solar radiation) and starts moving, constituting electric current. Thus, the solar PV cell works. The output of the cell is in the order of few Watts. In order to achieve higher power rating, these PV cells are connected in series and parallel to form a solar module.

This PV module is operated in two modes – Stand-alone in remote areas where the power demand is lower and the extension of transmission lines is uneconomical, hybrid where the continuous supply of electricity is needed, combined with wind energy, diesel generator, battery back-up, etc. or combinations of these three and the output is connected to the grid.

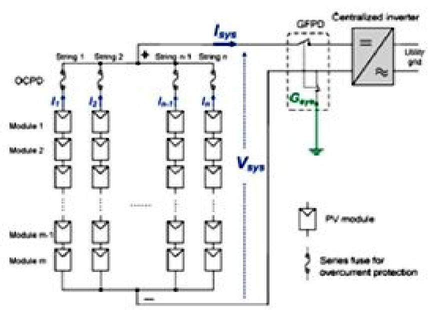

Fig. 1. Typical grid-connected PV array with a centralized inverter

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A typical grid-connected PV system consists of several major components – PV modules, power conditioning unit with MPPT algorithm, wirings and protection devices – Over-Current Protection Devices (OCPDs) and Ground Fault Protection Devices (GFPDs) as in fig. 1 [1][2][3].

A solar PV array is extremely susceptible to the faults – Line-line, Ground, Shading, Open-circuit, Mismatch, etc. as in fig. 2 [5].

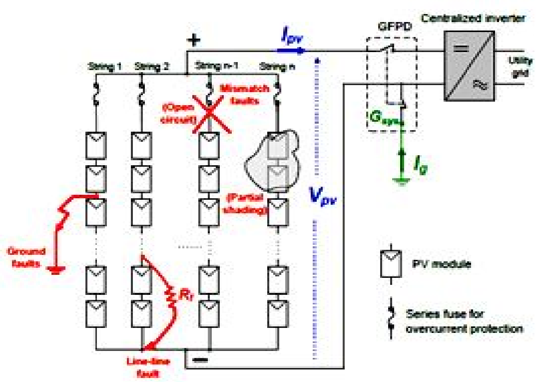

Fig. 2. Typical faults in Solar PV arrays

III. MODELING OF PV SYSTEM AND FAULT DETECTION

PV system is modeled in MATLAB/Simulink as in fig. 3. The block 'PV Module – Simulink Model' consists of six subsystems, each representing the equations below. The equations concerned with the modeling of the PV system are [11]:

$$T_{aK} = T_{op} + 273 \text{ - (1)}$$

$$T_{rK} = T_{ref} + 273 \text{ - (2)}$$

$$I_{pv} = N_p I_{ph} - N_p I_s \left[e^{\left(\frac{(V_{pv}+I_{pv}R_s)q}{AkTN_s}\right)} - 1 \right] - \left[(V_{pv} + I_{pv}R_s)/R_{sh} \right] \text{ - (3)}$$

$$I_{rs} = \frac{I_{scRef}}{[\{e^{(\frac{qV_{OC}}{N_s AkT})}\} - 1]} \text{ - (4)}$$

$$I_s = I_{rs}[\left(\frac{T_{op}}{T_{ref}}\right)^3] e^{\left(qE_{g0}\left(\frac{1}{T_{ref}} - \frac{1}{T_{op}}\right)/Ak\right)} \text{ - (5)}$$

$$I_{ph} = [I_{SC} + K_i(T_{op} - T_{ref}) * G] \text{ - (6)}$$

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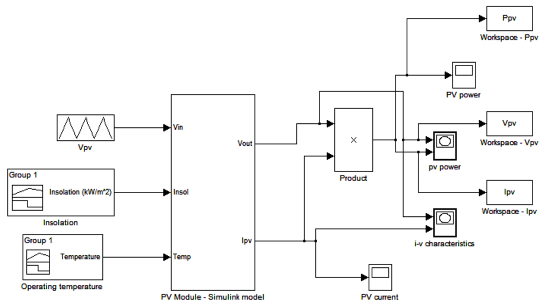

Fig. 3. Simulink model of PV Module

Alternatively, another model of PV module has been developed for facilitating the representation of faults as in fig. 4.

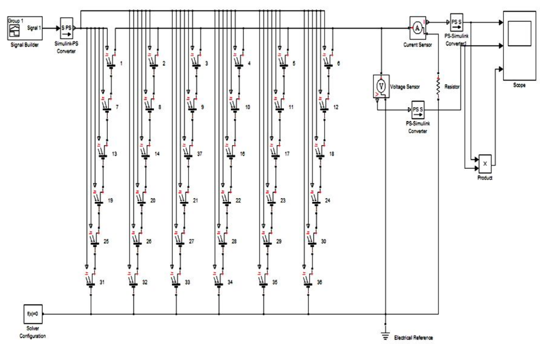

Fig. 4. Simulink model of PV Module

The different types of faults occurring in the solar PV systems are as shown in the fig. 5 [6]. The faults will damage solar PV system, cause fire and safety hazards, reduce reliability, lifetime and performance.
These may result in disadvantage for PV system.

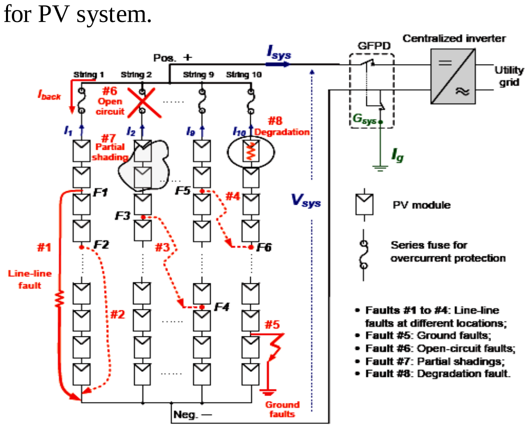

Fig. 5. Typical faults in a grid-connected PV system

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The different types of fault detection methods so far discussed are – current and voltage detection method [10], comparison of the output parameters under faulty and normal conditions [9] and power losses analysis [8], reflectometry methods [7], outlier detection rule [6] and decision tree-based fault detection [5]. All these different methods are discussed briefly below.

Current and voltage detection method utilizes the voltage and current sensors to detect the possibility of the damaged module. This method is very accurate and is used to conduct real-time fault detection of solar PV arrays [10].

The method discussed in [9] helps us to determine the performance ratio (before fault and after fault). They utilize irradiance, air temperature and AC output from the system. The comparisons of the actual output and the estimated output are performed and then it is determined whether fault is present or not.

The effect of fault on the output voltage and current is utilized in [8]. The PV panel under normal conditions, gives higher output than the PV array under fault conditions.

The method discussed in [7] proposes the transmission line model for PV panels that can be useful for interpreting faults in PV using different reflectometry methods.

The outlier detection rule [6] utilizes the measured values of the various parameters and checks for any anomalous data, if present, which is outlier. There are 3 rules – Hampel identifier, Boxplot rule and 3-Sigma rule.

The method in [5] uses a trainer kit for making any decisions. This method is disadvantageous in case of cost, but accurate. The trainer kit has to be programmed for the values of various parameters (irradiance, voltage, current, operating temperature).

IV. FAULTS AND MODELING OF PV SYSTEM UNDER FAULTS AND OUTPUTS

Line-line faults under two unique scenarios are discussed in this section. As in [1], the magnitude of the back-fed fault current depends on the irradiance levels. Hence, if the fault occurs during the periods when irradiance is low (during morning, evening or during cloudy days), the fault current is lower than the OCPD rating, hence, the relay will not be able to detect and clear the fault. Hence, the fault lays hidden. If the system is connected with MPPT, the fault current is lowered down by the MPPT, hence, the fault isn't cleared even during the high-irradiance period later in the day. But, if the fault occurs during high irradiance, it gets cleared by the OCPDs [1][2][4].

In the similar way, as in [3], during night, when there is no irradiation present, if the fault occurs, there will be no (or very low) fault current, hence the fault is not at all likely to be cleared. As the night-to-day transition occurs, the system with MPPT again responds faster than the irradiation, hence, the fault current is lowered, the OCPD doesn't work properly [1][3][4].

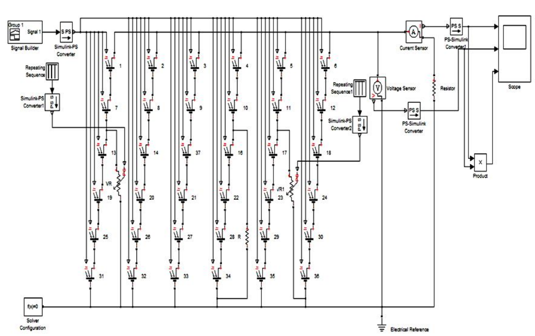

Fig. 6. Simulink model of PV panel under low-irradiance condition and mismatch faults

As in fig. 6, the fault in Ist string and the last string are low irradiance conditions. The fault in the IVth string is mismatch fault. The outputs obtained are shown in fig. 7. Similarly, the fault during night-to-day transition is shown in fig. 8 and the corresponding outputs in fig. 9. The PV array output under normal conditions is shown in fig. 10.

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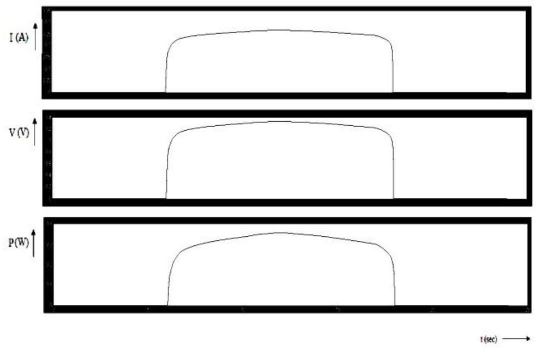

Fig. 7. Outputs of PV array under low irradiance condition and mismatch faults

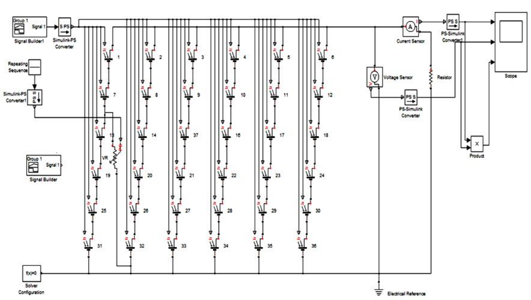

Fig. 8. Solar PV array under night-to-day transition faults

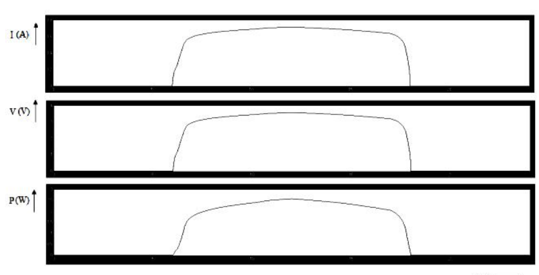

Fig. 9. Output of PV array under night-to-day transition fault

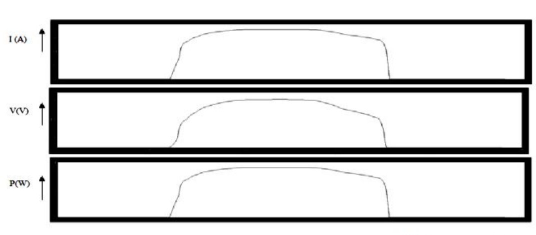

Fig. 10. Output of PV array under normal conditions

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The power output during normal conditions is 2.53 W (V = 3.6 V, I = 0.72 A, R_{sh} = 5 ohms). The power output during fault conditions (low irradiance and mismatch conditions in this case) is 0.34 W (V = 1.3 V, I = 0.26 A, R_{sh} = 5 ohms) and during night-to-day transition in this case is 2.45 W (V = 3.5 V, I = 0.7 A, R_{sh}= 5 ohms).

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