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REVIEW ARTICLE

Advancements in Modeling, Estimation Techniques, and Fault Analysis in Solar Photovoltaic Systems: A Comprehensive Review

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Abstract
Advanced monitoring necessitates employing fault diagnostics in solar photovoltaic (SPV) systems, as these diagnostics can alert users to potential catastrophic failures or heightened risks. Analyzing various flaws in photovoltaic systems is essential because these defects can cause energy shortfalls, system malfunctions, and fire hazards, which are often challenging to avert. To provide green and clean energy through solar power, this work aims to enhance efficiency by conducting further research. This includes modeling the Solar Photovoltaic system, estimating its parameters, and examining the different types of Solar Photovoltaic failures.

Keywords: Photovoltaic, Solar Panel, Matlab Simulation, Solar Panel Mathematical Modelling, Simscape

Introduction

Solar photovoltaic (PV) systems have developed as one of the utmost auspicious renewable energy source, offering significant potential to address the escalating energy demands while mitigating environmental concerns associated with conventional energy generation (Ramos et al., 2023). However, the efficient operation and management of solar Photovoltaic systems necessitate robust modeling, accurate estimation techniques, and reliable fault analysis methods to ensure optimal performance, longevity, and safety (Hossain et al., 2022). In recent years, substantial progress has been made in these areas, driven by advancements in technology, methodologies, and interdisciplinary research efforts (Chowdhury et al., 2024).

This comprehensive review synthesizes the latest developments and insights into modeling, estimation techniques, and fault analysis in solar Photovoltaic systems. Drawing from a diverse range of scholarly works published up to 2024, this paper provides a comprehensive overview of the state-of-the-art approaches, methodologies, and challenges in these critical areas. The modeling of solar Photovoltaic systems plays a pivotal role in understanding their behavior, optimizing their performance, and facilitating system design and integration (Mekhilef et al., 2020). Recent research has witnessed significant advancements in both analytical and computational modeling techniques, encompassing aspects such as solar irradiance modeling, photovoltaic device characteristics, system-level modeling, and dynamic simulation (Alonso et al., 2021). These models serve as invaluable tools for predicting energy generation, assessing system performance under varying conditions, and informing decision-making processes.

Estimation techniques are indispensable for accurately assessing the performance and health status of solar Photovoltaic systems, particularly in real-time or near-real-time applications (Khalid et al., 2023). The latest research has seen the development of advanced estimation algorithms and methodologies for parameters such as solar irradiance, temperature, module degradation, and system efficiency (Huang et al., 2024). These techniques leverage data-driven approaches, machine learning algorithms, and sensor technologies to enhance their accuracy, reliability, and efficiency of performance estimation in solar Photovoltaic system. Fault analysis and diagnosis are crucial for ensuring the reliability, safety, and longevity of solar Photovoltaic systems, especially in the face of potential faults and failures (Zhang et al., 2022). Recent, studies have been focused on the developments of fault detection, localization, and prognosis techniques using various monitoring, diagnostic, and prognostic tools (Mishra et al., 2023). These approaches encompass both hardware-based solutions, such as sensor networks and embedded diagnostics, and software-based algorithms for anomaly detection and fault classification.

In light of the rapid advancements in modeling, estimation techniques, and fault analysis, this review aims to provide a comprehensive synthesis of the current state-of-the-art, identify emerging trends and challenges, and offer insights into future research directions. By elucidating the latest developments and methodologies in these critical areas, this paper seeks to contribute to the ongoing efforts aimed at enhancing the efficiency, reliability, and sustainability of solar Photovoltaic systems.

The growing energy needs of the world's population require the use of all energy sources. Over the last ten years, the fastest expansion in power generation has come from solar energy, mostly due to policymakers' worries about supply dependability, energy diversification, and climate difficulties. There is a critical need to reconsider how we use the energy resources we still have and investigate different renewable energy sources as pollution increases and fossil fuel supplies decline. This review article draws inspiration from the National Action Plans on Climate Changes. Solar photovoltaic (PV) systems are susceptible to a range of errors and malfunctions, including problems with grid connection, maximum power point tracking (MPPT), Photovoltaic arrays, grounding, batteries, and utility hook-up, even though they have stationary parts and require no maintenance ([] Y. Zhao et al., 2013).

Due to their constant solar output during the day, Photovoltaic modules are particularly difficult to fully shut down during failures, particularly on the DC sides. Any breakdown among the several solar based photovoltaic (PV) module coupled in to a series parallel architecture might affect the Solar Photovoltaic system's overall productivity. What's more concerning from a safety standpoint is that one malfunction can compound into several more, which might spell tragedy. The voltage and current ratings of a typical series-parallel Photovoltaic system are increased, which raises the possibility of large defect currents or DC arcs.

A lack of knowledge about the many types of flaws in Solar Photovoltaic systems has been the main cause of a number of disasters in recent years, including fire dangers. Frequently, these flaws remain unnoticed until they result in disastrous fires, as the ones that occurred in the 2009 383 kW Solar Photovoltaic plant in Bakersfield and the 2011 1 MW Solar Photovoltaic plant in Mount Holly (T. B. Brooks,2011) (SEPA,2011). These occurrences demonstrate the inadequacies of conventional Solar Photovoltaics array fault detection and safety methods, emphasizing the pressing need for substitutes to address these problems. For professionals to identify, isolate, and troubleshoot defects in Solar Photovoltaic systems, fault diagnosis is essential. When Solar Photovoltaic parameters are not within limits, the system monitors them, sounds an alarm, and starts counteractions.

The varieties of Solar Photovoltaic systems and their operational procedures are not covered in this study. Rather, it is organized as follows: A thorough analysis of modern modeling and parameter estimation techniques for solar photovoltaic systems, including ODM and TDM modeling, is provided in Section 2.1. Different types of Photovoltaic faults are covered in Section 2. 2, with the conclusions in Section no. 3.

An examination of fault types, modeling, and estimation in solar photovoltaic (SPV) systems

Evaluation of Solar Photovoltaic System Modeling and Estimation

It is difficult to deal with an Solar Photovoltaic system's nonlinear output characteristics since they change with solar irradiation (SIL) levels, the Sun geometric (SGP) position, and ambient (AT) temperature. The output of the Solar Photovoltaic system usually decreases between 12 PM and 3 PM because of the rising cell temperatures. Partial shading causes the array to receive nonuniform irradiance, which complicates the I-V and P-V characteristics and produces many peaks. Since the early 1990s, industrialization in both industrialized and developing nations has resulted in a great deal of experience with Solar Photovoltaic systems on buildings. For instance, shadowing was found to damage 41% of installed Photovoltaic systems, that resulting in to 10.00% energy losses, according to the German 1000 Roofs Photovoltaic Programs, which was launched in the year 1990 (M. Drif et al., 2005). Up to 70% of power can be lost due to poorer MPPT convergences, which leads to local peaks rather than their global peaks (G. Petrone et al.,2008). Regardless of the electrical load characteristics or weather, a buck-type DC/DC converter and microcontroller-based MPPT approach has been proposed to maximize efficiency (E. Koutroulis et al., 2001). The approach's efficiency in fluctuating temperature and insolation levels was proved by a MATLAB-based parameter extraction and model evaluation for a 60 W solar panel (G. Walker, 2001). The modest advantage of the boost converter at low light levels was demonstrated by comparisons of buck & boost MPPT; shading effects were not engaged into account in the study. For efficient power transmission from the Photovoltaic array to the load lines in the face of quickly varying weather, the incremental conductance technique (ICM) was examined as a solution to the traditional perturb and observe method (POM)'s drawbacks (K. H. Hussein et al.,1995). To guarantee a seamless and speedy transitions to their maximum power points without the need for a Photovoltaic array's DC current sensors, the power feedback method (PFM) was created by V_{mpp} and I_{mpp} (K. June-Min et al., 2006). In comparison to POM and PFM, a minor fractional change in order of the incremental conductance technique was suggested to their maximum power tracking in Solar Photovoltaic systems, providing superior performance under changing load and ambient conditions. Photovoltaic efficiency may be raised by around 5% using enhanced incremental conductance techniques [C.-H. Lin et al., 2011][A. Belkaid et al., 2016].

The performance of a Solar Photovoltaic system is influenced by variations in solar irradiation levels, bypass ideal/ practical diodes, individual solar cells connections, and solar cell properties. Efficiency loss from hot spots and performance loss from bypass diode deterioration have both been predicted (F. J. Vorster et al., 2002) (D. D. Nguyen and B. Lehman et al., 2006). under order to solve the problem of differentiating between local and global peaks under partially darkened situations, array designs in series and parallel were studied (H. Patel and V. Agarwal, 2008). The temperature characteristics of Solar Photovoltaic arrays under fault situations have been studied using thermal cameras (P. Parinya et al., 2007) (T. Trupke et al., 2006) (C. I. Buerhop et al., 2012), yet it is rare to explore the connection between electrical and thermal properties. To close this gap, a parameter-based model that integrates thermodynamic and electrical properties was put forth (Y. Hu, 2013). Despite the fact that lumped parameter modeling frequently does not convert directly to power generation, research on Solar Photovoltaic system parameter estimate has developed. The operational data provided by manufacturers is usually restricted to standard test conditions (STC) and does not correspond to real-world operations. In order to create realistic simulations, parameter estimation entails assessing the Solar Photovoltaic model parameters using sample data. This requires precisely determining circuit parameters like I_{ph}, I_o, R_s, and R_{sh}.

Conventional parameter estimation techniques include numerical methods, which are thought to be more accurate but rely on the fitting algorithm, cost function, and initial parameter values (C.-C. Liu et al., 2008) (F. Nakanishi et al., 2000), and analytical methods, which use important components in the I-V characteristic curve to represent model parameters mathematically (W. De Soto et al., 2006) (F. Nakanishi at al., 2000) (A. Ortiz-Conde et al., 2006). With some suggesting indirect ways to modify I-V curves, intelligent computing approaches have drawn attention for managing nonlinear functions without derivative information (J. A. Gow and C. D. Manning, 1999) (R. Gottschalg et al, 1999). For parameter estimation, evolutionary methods like bacterial foraging algorithms

(BFA) and particle swarm optimization (PSO) have been investigated [28]. For accurate parameter retrieval, methods such as cuckoo search, penalty-based (P- DE) differential evolutions, and simulated annealing (SA) have also been developed (F. Giraud and Z. Salameh, 1999) (M. T. Elhagry et al., 1997). Determining and fixing faults in Solar Photovoltaic systems requires mathematical modeling. A decrease in output power is the first indication of a problem with photovoltaic modules, and it may be examined using typical I-V and P-V curves. Examining various failure types requires an understanding of the I-V characteristics of Solar Photovoltaic modules (X. H. Nguyen et al., 2015) (C.-T. Sah et al, 1957).

The Perfect Photovoltaic Cell

The photon energy from solar radiation is absorbed by semiconductor materials when they are exposed to sunshine. This results in a potential difference that drives a flow of charge carriers via the external circuit. Photocurrent is produced by this photovoltaic effect (Iph). This behavior is described by the mathematical equation for I-V characteristics and the equivalent circuits of an ideal Solar Photovoltaic cell, which are based on semiconductor theory [49].

$$I_{pv} = I_{ph} - I_o[e^{(\frac{qV_{pv}}{\alpha k T_m})} - 1] \qquad \text{......................... (1)}$$

Their magnitudes of I_{ph} is directly related to their flux of insolation's and their absorptions capabilities of the semiconductor materials. As seen in equation (1.1.1), the models require three major parameters (I_{ph}, I_o and α) to completely described IV characteristic curves. Figure. 2 illustrates the IV and PV characteristic curves with few notable points (Voc, 0), (0, Isc), and (V_{mpp}, I_{mpp}).

The Solar Photovoltaic cell has a distinctive feature, acting as both a constant current and voltage source. The smaller section of the constant current lines at (0, I_{sc}) on the V-I characteristics curve indicates the slopes for the constant current portions, suggesting a higher values of shunt resistance (R_{sh}) across a constant current source. Similarly, the small section of the constant voltage lines at (V_{oc}, 0) indicates the slopes for constant voltage portions, implying the presence of series impedance (R_s) with their terminal.

The One Diode Model (ODM)

The values obtained of I_{pv}, I_{ph} from basic equation (1.1.1) of the basic Solar Photovoltaic cell does not accurately depict the I -V characteristics of a practical Solar Photovoltaic array. The basic lumped parameter (LPE) equivalent circuit model and their various parameters are shown in Figure 3. The (ODM) One Diode Model is typically used model for envisaging Solar Photovoltaic cell energy production. This solar cell model is characterized as a light generated current sources shunted with a reverse negative baised polarity bypass diode to avoid hotspot emergence throughout open circuit or few supplementary module faults.

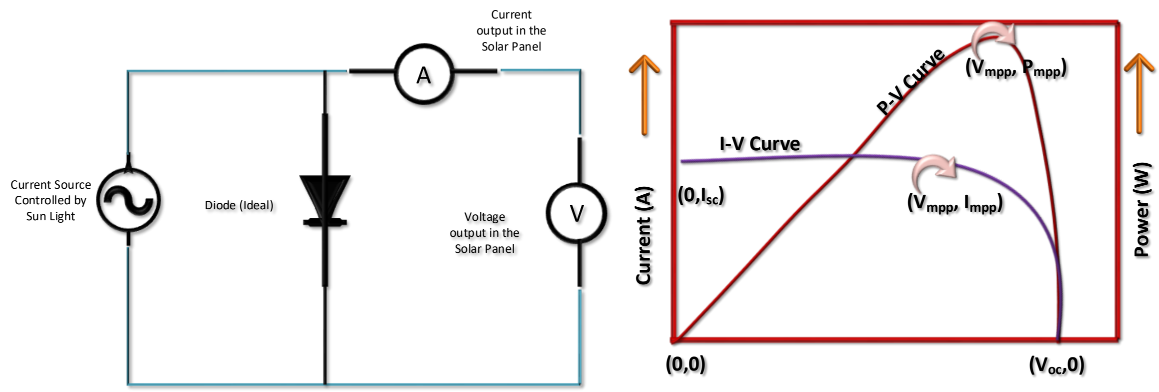

Figure 2: The Basic Characteristic P-V and I-V curve.

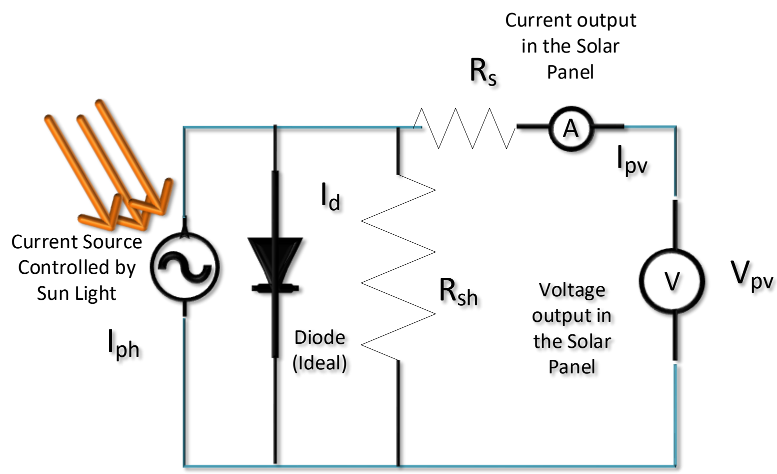

Figure 3: The Fundamental Circuit of equivalence – One Diode Model [ODM].

Solar Photovoltaic (SPV) cells can be associated in to the series to form modules, which however arranged in a parallel to series configuration to create array. These mathematical equations that describes the I – V characteristics of the practical Solar Photovoltaic array is provided by:

$$I_{pv} = I_{ph} - I_d = I_{ph} - I_o[e^{\frac{(V_{pv} - R_S I_{pv})}{V_t \alpha}} - 1] \text{ .... (2)}$$

where , $$I_d = I_o[e^{\left(\frac{V_{pv} + R_s I_{pv}}{V_t \alpha}\right)} - 1] \text{ .... (3)}$$

The I–V characteristic curve may be characterized by four parameters (Iph, Io, α, and Rs), as shown by equation (2) for the one-diode Rs model (R. Chenni et al, 2007) [50]. However, the accuracy of the Rs model declines when Kv causes the Solar Photovoltaic cell to undergo considerable temperature changes. By adding the shunt resistance, Rsh, to the circuit, the temperature sensitivity may be increased (Y. T. Tan et al, 2004) (S. Liu et al, 2002). The model with the additional shunt resistance (Rsh) is shown in equation (3).

$$I_{pv} = I_{ph} - I_o[e^{\frac{(V_{pv}-R_S I_{pv})}{V_t\alpha}} - 1] - \left(\frac{V_{pv} + R_S I_{pv}}{V_t\alpha}\right) \text{......................... (4)}$$

These thermodynamic voltages of the arrays with a series connection of Ns cells are given by Vt = Ns*k*Tm/q. Solar Photovoltaic cells connected in series produce higher output voltage, while those connected in to the parallel generate higher current. With the inclusion of R_{sh} in the one diode model (ODM), the number of retrievable parameters increases to five: R_{sh}, I_{ph}, R_s, I_o, and α.

2.1.3. The Two-Diode Model (TDM)

More complex and precise models with various applications have been developed by several researchers (K. Ishaque et al, 2012). The previously discussed one-diode models inherently overlook the effect of recombination current loss, especially at low voltage. To address this, a two diode (TDM) model was developed, as illustrated in Figure 4. In this model, the diode ideality constant is set to two, and a second diode is connected to the first to account for junction recombination. The characteristic equations for the two diode (TDM) model is provided by:(J. Ma et al, 2013) (K. Ishaque et al, 2011) (N. Enebish et al, 1993)

$$I_{pv} = I_{ph} - I_{d1} - I_{d2} - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} = I_{ph} - I_{o1} \cdot \left[\exp\left(\frac{V_{pv} + I_{pv}R_s}{V_{t11} * \alpha_1}\right) - 1\right] - I_{o2}\left[\exp\left(\frac{V_{pv} + I_{pv}R_s}{V_{t2} * \alpha_2}\right) - 1\right] - \frac{V_{pv} + I_{pv}R_s}{R_{sh}}, \text{......................... (5)}$$

Where, $I_{d1} = I_{o1}\left[\exp\left(\frac{V_{pv} + I_{pv}R_s}{V_{t1} * \alpha_1}\right) - 1\right]$ 燼nd營 $_{d1}$ $= I_{o2}\left[\exp\left(\frac{V_{pv} + I_{pv}R_s}{V_{t2} * \alpha_2}\right) - 1\right].$ .... (6)

Seven factors in all need to be retrieved for two-diode circuit modeling: I_{ph}, I_{o1}, I_{o2}, R_s, R_{sh}, α_1, and α_2. Operating circumstances such as the temperature of the Solar Photovoltaic module (T_m) and the irradiance on the module's surface (G) affect some of the components in equation (4). The following equations express these dependencies (N. Enebish et al, 1993).

$$I_{ph} = \left(I_{ph\_STC} + K_I * \Delta T\right) * \frac{G}{G_{STC}} \text{......................... (7)}$$

The following is a more accurate equation that accounts for temperature fluctuation when describing the saturation current for a TDM [55]:

$$I_{\mathrm{ol1}} = \frac{(I_{\mathrm{sc}S\mathrm{STC}}+K_I*\Delta\mathrm{T})}{(exp(V_{\mathrm{oc}S\mathrm{STC}}+K_V*\Delta\mathrm{T}/\alpha_1*V_{t1})-1)},$$
$$I_{o2} = \frac{(I_{\mathrm{sc\_STC}}+K_I*\Delta\mathrm{T})}{(exp(V_{\alpha\_\mathrm{STC}}+K_V*\Delta\mathrm{T}/\alpha_2*V_{t2})-1)}, \quad .... (8)$$

where $V_{t1} = V_{t2} = N_s \mathrm{kTT}_m/\mathrm{q}$ and $\Delta\mathrm{T} = T_m - T_{\mathrm{STC}}$. .... (9)

The parameters and variables in equations (6) through (8) have been measured at STC. The levels of Io1 and Io2 in the TDM have been determined through iterations in a number of investigations.

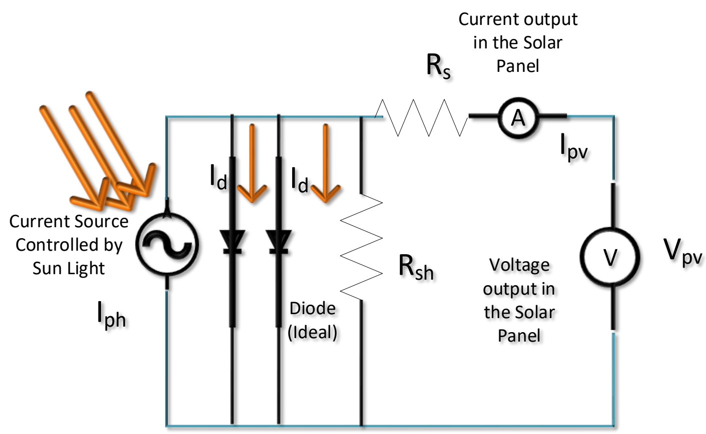

Figure 4: The Fundamental Circuit of equivalence– Two Diode Model [TDM.]

Because of inappropriate beginning assumptions, the iterative approach will lengthen the calculation time (N. Enebish et al., 1993). It was suggested in (M. G. Villalva et al., 2009) that the reverse saturation current magnitudes, Io1 and Io2, be identical. This may be done by combining equations (7) and (8) as follows:

$$I_{o1} = I_{o2} = I_o = \frac{(I_{\mathrm{sc}S\mathrm{STC}}+K_I*\Delta\mathrm{T})}{(exp(V_{\mathrm{oc\_STC}}+K_V*\Delta\mathrm{T}/(\alpha_1+\alpha_2/p)*V_t)-1)} .... (10)$$

Iteration is not necessary for the combined equation shown in (9) since the outcome may be assessed analytically. Shockley's diffusion theory (C.-T. Sah et al, 1993) states that the diffusion current component, α1, needs to equal unity. ὕα1 + α2Þ/p ≥ fied equa-1 yields the recombination current component, α2, where p can be set to a greater than 2.2 value. The selection of α1 and α2 values will be clear and unambiguous (10).

$$\mathrm{I_{pv}} = \mathrm{I_{ph}} - \mathrm{I_o}\left[\exp\left(\frac{\mathrm{V_{pw}}+\mathrm{I_{pv}R_s}}{\mathrm{V_t}}\right)+\exp\left(\frac{\mathrm{V_{pw}}+\mathrm{I_{pv}R_s}}{(\mathrm{p}-1)\mathrm{V_t}}\right)+2\right]-\left(\frac{\mathrm{V_{pw}}+\mathrm{I_{pv}R_s}}{\mathrm{R_{sh}}}\right) .... (11)$$

Neglecting Rs (Rs = 0) simplifies the TDM without compromising accuracy. As a result, there are now six parameters instead of seven (Iph, Io1, Io2, Rsh, α1, α2). Equation (4) can therefore be made simpler as

$$I_{pv} = I_{ph} - I_{o1}\left[\exp\left(\frac{V_{pv}}{V_{t1} * \alpha_1}\right) - 1\right] - I_{o2}\left[\exp\left(\frac{V_{pv}}{V_{t2} * \alpha_2}\right) - 1\right] - \frac{V_{pv}}{R_{sh}} \quad (12)$$

Over the past decade, numerous scholars have focused on estimating Solar Photovoltaic parameters; Table 1 provides references for parameter estimation in solar photovoltaics. Generally, the ODM approach is the simplest for creating an Solar Photovoltaic cell model, especially during rapidly changing weather conditions (M. A. de Blas et al, 2002). However, under normal weather conditions, the TDM approach is preferred as it produces better results than the ODM approach. The next section covers various Photovoltaic fault classes.

The Basic Review on Faults in Solar Photovoltaic (SPV) System

The primary causes of efficiency decline and self-based degradation in Solar Photovoltaic devices are faults. These faults can stem from defective engineering parts or natural causes. While few studies have been conducted on different Solar Photovoltaic system problems, most published papers on SPVs focus on higher cell level usage, circuit-level optimization, electrical systems modeling, panel engineering and MPPT. This section discusses several fault types that occur on the Direct Current and Alternate Current sides of the solar photovoltaic (SPV) system. Direct Current faults originate at the string connections and end before the inverter, while AC faults start from the inverter and extend to the grid connections.

The Direct Current Side Faults

1. Open-Circuit Faults

An open circuited fault may result when one of the most current carrying paths in series connected with the load is broken or opened (M. Davarifar et al, 2013). Even though an open circuit might not be a malfunction, it can be considered a system outage that reduces overall efficiency. These issues can be recognized using a conventional Direct Current shunt, which takes a little amount of the current as input and outputs 0.00 to 75.00 mV for measurements purposes. To ensure that no string is unutilized, a shunt resistance is connected to respective string to track its contribution. Direct Current shunts, made of strong copper bars, are used in high Direct Current (DC-current) applications as current measurement devices in Direct Current loads. The shunt provides 0.00 mV (i.e., the systems are opened circuit) if the output current is zero.

Figure 5 depicts a real-time open-circuit failure. In the figure, the potential location of an open-circuit fault is indicated by the letter X. An open-circuit error can develop within the string amongst Solar Photovoltaics and in the bus communication between strings. It is very clear that this string is not much contributing to their respective loads, if any of the shunt values approach zero. Moreover, string monitoring circuits can be used to precisely determine which Solar Photovoltaic is disconnected.

2. The (L2L) Line to Line Faults

The Line to line (L2L) faults in Solar Photovoltaic arrays can result from short circuits or double ground faults (when two potential differences accidentally make low-resistance contact). Figure 6 shows a Line to line (L2L) fault circuit.

Analyzing Line to line (L2L) faults requires monitoring the voltage of each string separately. If there are any differences between the strings, the amount separating a normal string from an abnormal string needs to be analyzed to determine how various internal Photovoltaic arrays are by passed, causing Line to line (L2L) faults. Pinpointing the exact location of a line-to-line fault is more challenging; however, this can be done in both ungrounded and grounded systems by using indirect measurements with a double ground fault and a short circuit fault, correspondingly. Additionally, (Y. Zhao et al,2011) examined how to protect Solar Photovoltaic systems from overcurrent damages and investigated Line to line (L2L) faults through the night and day transition and low sunlight incidence with a 40% position discrepancy. (M. K. Alam et al, 2013).

3. The Bypass Diode Faults

Semiconductor diodes operate on forward (FB) bias from photovoltaic to application circuits. Compared to a diode short circuit failures, an open-circuit diode failure's contribution is zero, making it a safe failures. When a diode short circuits, isolation turns into...

Table 1: The References for general estimating parameters of Solar Photovoltaic [SPV.]

Estimating Parameter	Model	References
Series Resistance (Rs)	Single Diode Model	(Ishaque, K., Salam, Z., Taheri, 2011) (Villalva, M. G., Gazoli, J. R. et al, 2009) (Gow, J. A., Manning, C. D., 1999)
Shunt Resistance (Rsh)	Single Diode Model	(Villalva, M. G., Gazoli, J. R., et al, 2009) (Townsend, T. U. 1989)
Diode Ideality Factor (n)	Single Diode Model, Double Diode Model	(Walker, G. R. 2001)
		(De Soto, W., Klein, S. A., et al, 2006)
Photocurrent (Iph)	Single Diode Model, Double Diode Model	(Villalva, M. G., et al, E. F. 2009) (Ishaque, et al. 2011)

Saturation Current (I0)	Single Diode Model, Double Diode Model	(De Soto, et al. (2006).
		(Villalva, M. G., et al (2009).
		(Jiang, J., et al. (2006).
Temperature Coefficient	Single Diode Model, Double Diode Model	(Skoplaki, E., et al. (2009).
		(Evans, D. L., et al. (1978).
		(Duffie, J. A., et al. 2013).
Short-Circuit Current (Isc)	Single Diode Model, Double Diode Model	(Walker, G. R. 2001).
		(De Soto, et al. 2006).
Open-Circuit Voltage (Voc)	Single Diode Model, Double Diode Model	(Villalva, M. G., et al 2009)
		(Gow, J. A., Manning, C. D. 1999).
Maximum Power Point (MPP)	Single Diode Model, Double Diode Model	(Ishaque, K., et al. (2011)
		(Villalva, M. G., et al. 2009)
		(Femia, N., et al. 2005)
Fill Factor (FF)	Single Diode Model, Double Diode Model	(Walker, G. R. (2001)
		(Sera, D., Teodorescu, R., et al. 2007)
Module Efficiency (η)	Single Diode Model, Double Diode Model	(Skoplaki, E., Palyvos, J. A. 2009)
		(Duffie, J. A., Beckman, W. A. 2013)
		(King, D. L., Kratochvil, J. A., aet al, 2004)

When a bypass diode short circuits, one string may become a load for another, lowering the efficiency of both strings and casting doubt on the integrity of the strings. By comparing the shunt output values used to diagnose open-circuit issues, this may be found. Figure 7 shows an example of a bypass diode failure. A diode open-circuit failure (D1) may be indicated if a shunt output is zero. An imbalance in the current flowing through the shunts may indicate that the diodes have shorted circuited (D2).

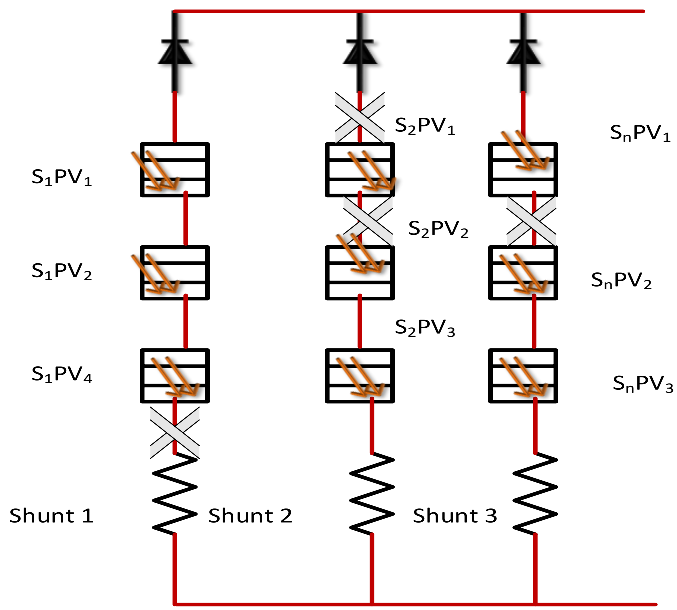

Figure 5: The First Open circuit fault Analysis and Comparison

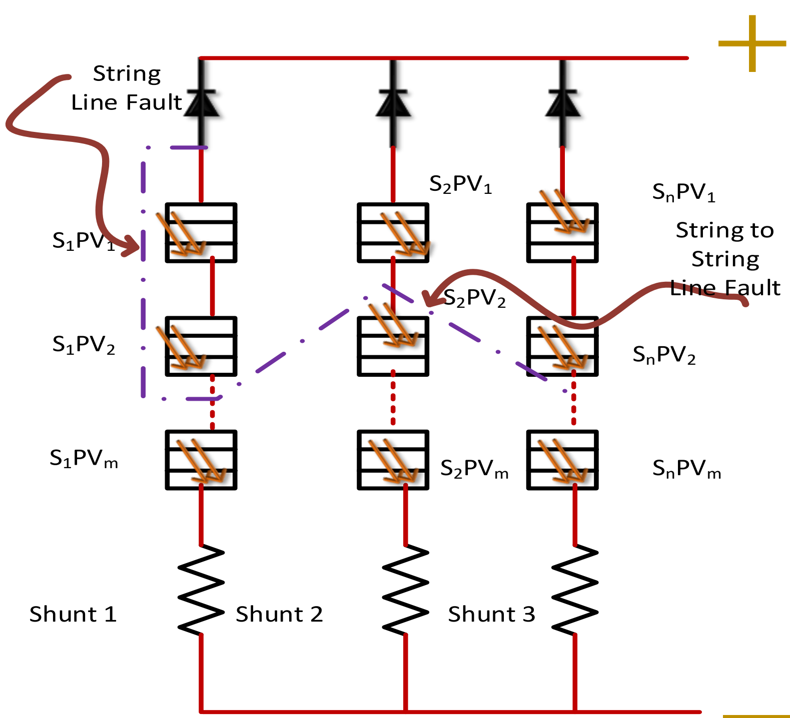

Figure 6: The Line-line fault Analysis and Comparison

A bypass diode can be used to lessen the potentially dangerous consequences of hotspot heating. Bypass diodes lower module voltage losses by allowing current to travel over shaded cells (M. Miyatake et al, 2011). On the other hand, partial shading or positional mismatch can cause long term energies dissipation in the bypass diodes, which can exacerbate the thermal effects on the diodes and its neighboring component and eventually result in bypass diode failure (E. Koutroulis and F. Blaabjerg, 2012).

4. Problems with Charge Controllers

An Solar Photovoltaic system's charge controller is essential because it increases efficiency using high-frequency switching systems and a variety of tracking approaches. Low conversion efficiency is mostly caused by unwanted load current and elevated operational temperature from nonlinear solar radiation levels. In order to resolve these problem, the maximum power operating points of the Photovoltaic system is followed by using offline/ online algorithms, which force the system to operate closer to this ideal state. Regardless of the load or the weather, MPPT continually modifies Solar Photovoltaic systems to draw the greatest amount of electricity.

Along with the inverter unit, the charge controller is an electrical device that is connected in to series to accept input from numerous strings. A charge controller-based fault monitoring system is depicted in Figure 8. A redundancy controller keeps an eye on the charge controller to ensure optimal safety and dependable data collection. In the event that the active controller fails, redundancy controllers take over the functions of the charge controllers and turn on a standby controller (R. Platon et al, 2015). Hardware -based MPPT techniques for non-uniform irradiance operations employing dynamic reconfigurations of Solar Photovoltaic modules are included in literature reviews (M. Miyatake et al, 2011) (E. Koutroulis and F. Blaabjerg, 2012). A straightforward high-frequency charge controller that functions almost similarly can be used to circumvent charge controller failure, according to research on the subject (M. Boztepe et al, 2014) (M. Oulcaidet al, 2016).

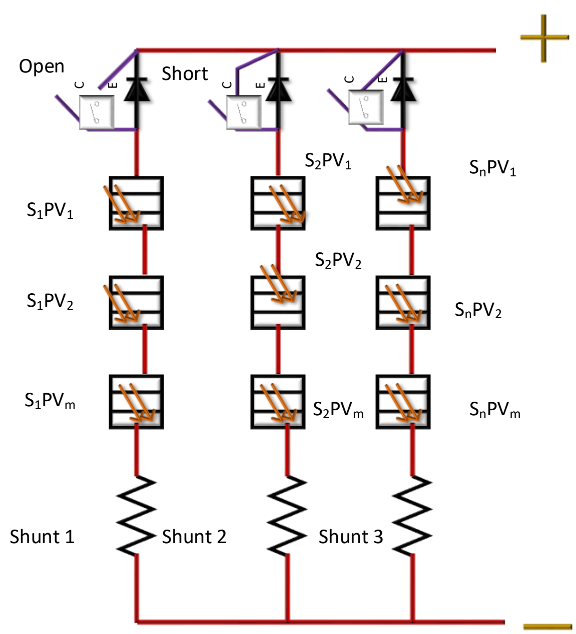

Figure 7: The Bypass diode fault Analysis and Comparison

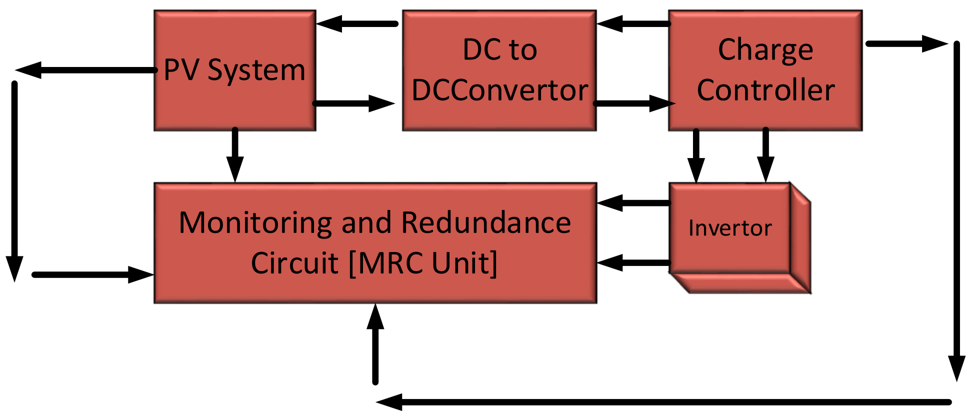

Figure 8: Basic Charge controller and fault monitoring system.

5. Ground Faults

Unintentional electrical short circuits, caused by various adverse environmental factors like strong winds, heavy rain, fog, and high temperatures, can result in ground faults, the most common type of defect in photovoltaic systems. Ground faults have the potential to generate massive fault currents and lead to fires if left unprotected. These faults, both lower and higher ground faults, can be analyzed using meters-based instruments(Y. Zhao et al, 2011) (M. S. Arani and M. A. Hejazi, 2016).

6. Arc Faults

Arc faults occur when electrical lines are poorly shunted, leading to arcs that can produce smoke and fire. They occur when a string is connected too loosely to another string, another PV, or a charge controller. Solar Photovoltaic systems are vulnerable to both parallel and serial arc faults, necessitating the de-energization of the system to protect against fire risks. Sealing the contacts in perfectly springed connections can help alleviate this issue (J. Johnson et al, 2012)9(E. D. Spooner and N. Wilmot, 2008).

7. Inconsistency Issues

Mismatch faults occur when one cell in an Solar Photovoltaic module has markedly different electrical characteristics from the other cells, resulting in significant power loss and potentially irreparable damage to Photovoltaic modules. However, they are difficult to identify with conventional safety mechanisms because they rarely produce significant fault currents. Several categories of mismatch faults include:

(a) Modest Shading

Partial shading on Solar Photovoltaic module surfaces caused by various factors such as trees, moving clouds, adjacent buildings, and mobile towers can significantly alter the P-V curve, leading to multiple local peaks (M. Miyatake et al, 2011) (E. Koutroulis and F. Blaabjerg , 2012) (M. Boztepe et al, 2014) (B. Shiva Kumar and K. Sudhakar,2015)

(b) Distribution of Nonuniform Irradiance:

Variations in the sun's irradiance strength over the day can cause some parts of the Photovoltaic cell to receive excessive light, resulting in high currents and heating, while other areas receive insufficient light, reducing the electrical output of the Photovoltaic system (S. Das et al,2018) (J. P. Vargas et al, 2015).

(c) Hotspot and Snow Covering:

Various factors like cell failure, partial shading, interconnectivity failure, and variations in insolation between cells can lead to the formation of hot spots or localized heating in Solar Photovoltaic modules. Snow cover on Photovoltaic arrays is caused by extreme temperatures, which vary depending on weather and geographic location (N. Heidari et al,2015) (E. Molenbroek et al, 1991).

(d) Soiling:

Accumulation of bird droppings and dust particles on Solar Photovoltaic module surfaces can significantly affect system performance. Wind speed and relative humidity are important climatological factors related to soiling (A. Massi Pavan et al,2011).

(e) Deterioration Errors:

Factors such as moisture intrusion, color tarnish, bubbles in the solar module, cell cracks, flaws in the antireflective coating, loss of binding, delamination over the cells, and connections can lead to degradation and an increase in internal series resistance (G. Makrides et al, 2014).

8. Fault in DC-DC Converter

The DC-DC converter is a critical circuit in every photovoltaic system, reducing cable thickness, minimizing losses, and ensuring secure wire connections. Various electrical components, including diodes, MOSFET switches, and a controller arc, are used in this circuit, but they often fail due to unfavorable environmental conditions. Standard enclosures can help prevent fire and moisture-based failures common in Photovoltaic installations (E. Ribeiro et al, 2013) (S. Sukumaran and K. Sudhakar,2017).

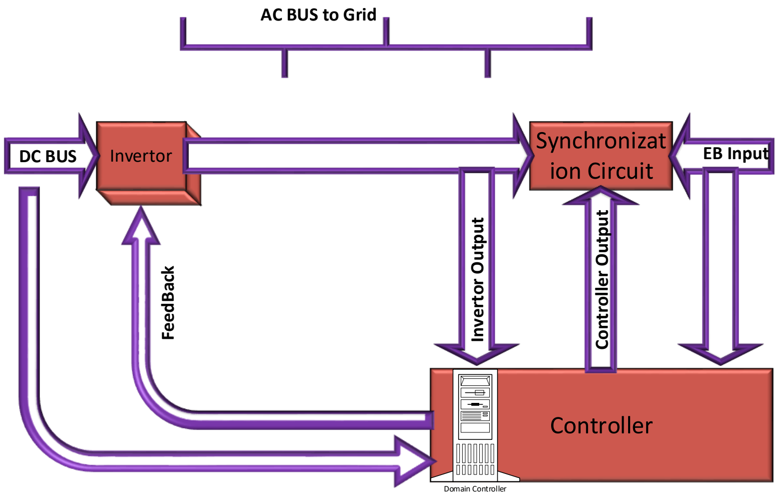

Figure 9: The Fundamental Control scheme for an inverter and a synchronizer fault.

AC Side Faults

1. Inverter Issues: An inverter, responsible for converting DC voltage to suitable AC voltage, can adjust voltage, current, and frequency to meet specific output requirements. Comprising various electronic controlled systems, waveform generators, tiny transformers, and multileg MOSFET switches, these devices offer direct output to the grid, albeit with a remote chance of failure, often triggered by uncertainties in the load. (A. M. Omer et al,2007) (W. Chine et al, 2014)

2. Synchronizer Problems: In on-grid applications, ensuring synchronization between inverter outputs and the current grid power line is crucial. To achieve perfect synchronization, parameters from the power line guide the inverter settings. Synchronizers typically include a live comparator that checks line and inverter voltages, frequencies, and phase sequences. If settings match, the synchronizer relay activates, combining both sources into a single one, thereby avoiding desynchronization issues. (W. Chine et al,2014) (A. Luna et al, 2015) (L. Hadjidemetriou et al, 2016)

3. Imbalanced Frequency, Voltage, and Current: Maintaining equal three-phase voltages is essential to prevent imbalanced errors, which can stem from improper loading techniques. Balanced loads across phases ensure uniform current distribution and voltage stability. Unbalanced frequency results if voltage and current fall out of balance, leading to unnatural current oscillation. Implementing uniform distribution strategies can mitigate this issue. (A. Sahu et al, 2016) (M. C. Falvo and S. Capparella, 2015)

4. AC Side Overload: Overloading on the AC side disrupts AC component characteristics, causing power to be maintained despite increased current and decreased voltage. This deterioration can damage cable lines and induce anomalous power factor (lag) in electronic equipment. While a mitigating system can handle minor overloads,

detecting large overloads is crucial for maintaining system stability, necessitating partial or full load termination. (A. Elkholy et al,2016) (O. M. Arafa et al, 2017)

Conclusion

Solar power generation not only provides electricity but also mitigates the negative impacts of greenhouse gas emissions from fossil fuel burning. In countries like India, where rural populations require access to power, solar energy plays a vital role. Ensuring efficient power generation systems deliver the required energy to loads or storage systems is essential. However, persistent flaws can decrease electricity generation efficiency. This comprehensive review provides insights into modeling Solar Photovoltaic systems, parameter estimation, and various fault types, serving as a valuable reference for researchers and practitioners alike. (W. T. da Costa et al, 2010) (K. Ishaque et al, 2011).

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Authors contribution: Author 1& 2 : Conceptualization, Methodology, Writing - Original Draft. Author 3 & 4: Data Curation, Formal Analysis, Writing - Review & Editing. Author 4 5: Software, Validation, Visualization. Author 6 : Supervision, Project Administration, Funding Acquisition

Data availability: The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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