



## Enhancing Photovoltaic Array Performance through Optimizing Power during Mismatch Conditions under Series-parallel (SP) and Total Cross-Tied (TCT) Configurations

Lahlou Abad <sup>a,\*</sup>, Salah Tamalouzt <sup>a</sup>, Kamel Djermouni <sup>b</sup>, Karim Fathi Sayeh <sup>a</sup>

<sup>a</sup> Laboratoire de Technologie Industrielle et de l'Information, Bejaia, Algeria.

<sup>b</sup> Laboratoire de maitrise des énergies renouvelables Bejaia, Algeria.

### ARTICLE INFO

#### Article history:

Received April 2, 2024

Accepted April 22, 2024

#### Keywords:

Photovoltaic systems  
PV array configuration  
Mismatch fault  
MPPT  
TCT Configuration  
SP Configuration

### ABSTRACT

Photovoltaic (PV) systems, harnessed from the sun's energy, serve as a vital component in the global shift towards sustainable energy sources. This paper presents a comprehensive investigation into the performance optimization of PV arrays operating under mismatched conditions, examining both Series-Parallel (SP) and Total Cross-Tied (TCT) configurations. The study explores the influence of variations in series and parallel resistances within PV modules on power generation. Two Maximum Power Point Tracking (MPPT) techniques are employed to enhance system efficiency. Our research unequivocally demonstrates the superiority of the TCT configuration, yielding a remarkable 28-watt advantage over the SP configuration when subjected to internal resistance changes. Additionally, the application of fuzzy logic-based MPPT exhibits exceptional responsiveness, surpassing the conventional Perturb and Observe (P&O) approach. These findings emphasize the pivotal role of system configuration and control strategies in optimizing PV array performance under varying operational conditions. This study contributes valuable insights to advance the harnessing of solar energy and underscores the significance of configuration and control methodologies in maximizing power output from PV systems.

## 1. INTRODUCTION

Photovoltaic (PV) systems are instrumental in the worldwide shift toward sustainable energy sources. By capturing solar energy, PV arrays demonstrate their reliability and renewability in generating electricity. Yet, numerous factors, notably the degradation of PV panels and system setup, significantly impact the performance of photovoltaic installations.

\* Corresponding author, E-mail address: [lahlou.abad@univ-bejaia.dz](mailto:lahlou.abad@univ-bejaia.dz)



Several comprehensive studies have delved into the intricate realm of mismatch losses within photovoltaic (PV) systems, highlighting the multifaceted nature of this critical issue. For instance, [1] conducted an insightful investigation into the mismatch problem, meticulously dissecting the deleterious effects stemming from partial shading scenarios, shedding light on the intricate mechanisms at play when shading phenomena disrupt the operation of PV arrays. Furthermore, [2] embarked on a rigorous exploration of the mismatch problem induced by partial shading conditions, coupling their investigation with a meticulous quantitative analysis of the ensuing power losses. [3] focuses on the primary factors that underpin the occurrence of mismatch problems in PV systems. Their research dissected the various elements, ranging from shading effects and module degradation to circuit configuration intricacies, that collectively contribute to mismatches. Moreover, [4] and [5] honed on improving power generation efficiency when dealing with value changes of both series and parallel- PV module resistances in a Series-Parallel (SP) configuration. Their investigations delved into the intricacies of power control strategies tailored to SP setups, acknowledging the unique challenges posed by mismatches in this specific configuration. By exploring strategies to maximize energy yield under mismatch conditions, collectively, these studies reflect a concerted effort within the research community to unravel the complexities of mismatch losses in PV systems, offering valuable insights and methodologies for optimizing performance and harnessing the full potential of solar energy.

This paper has the primary objective of introducing an in-depth investigation into the optimization of power generation in photovoltaic (PV) systems operating in the presence of mismatch conditions. The study is specifically focused on examining the impact of variations in both series and parallel resistances within PV modules when configured in both Series-Parallel (SP) and Total Cross-Tied (TCT) configurations. Furthermore, it aims to conduct a thorough comparative analysis between these two configurations to discern their respective performance characteristics. The optimization of power generation in these scenarios is achieved through the implementation of two Maximum Power Point Tracking (MPPT) techniques, which play a crucial role in ensuring that the PV system operates at its highest efficiency level.

## 2. PV SYSTEM MODELING

The mathematical representation of a photovoltaic (PV) cell relies on the underlying physical principles that govern its functionality. Through the photovoltaic effect, sunlight is directly converted into electrical energy within a PV cell. [6]. The primary mathematical model used to describe the behavior of a PV cell is the single diode model [7], [8] which is mostly used in literature. The selection of the one-diode equivalent circuit is based on its ability to provide faster numerical calculations while maintaining an acceptable level of accuracy. The optimal representation of a PV cell can be defined as a controlled current source, denoted as  $I_{pc}$ , which embodies the photocurrent, alongside a parallel diode, as illustrated in Figure (1-a). The corresponding current-voltage characteristics of this model are depicted in Figure (2). In contrast, the one-diode practical model encompasses both a controlled current source,  $I_{pc}$ , and a diode conducting current,  $I_d$ . Moreover, it incorporates internal resistances,  $R_s$  and  $R_{sh}$ , in series and shunt configurations, respectively, as shown in Figure (1-b).

$$I_{pv} = I_{pc} - I_d - I_{sh} \quad (1)$$

$I_{pv}$  is the PV module current.

$$I_{pc} = \left[ [(Suns - Suns_{ref}) * P_2] + [(T - T_{ref}) * P_3] + 1 \right] P_1 * Suns \quad (2)$$

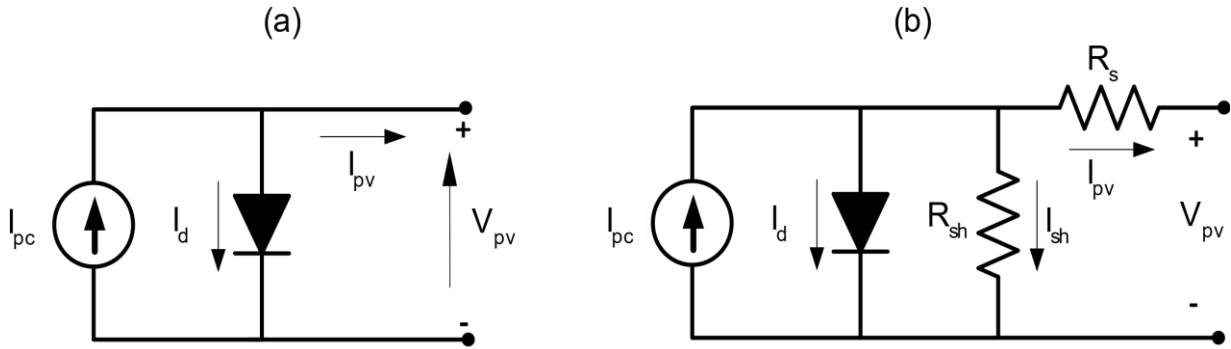


Fig 1. The equivalent electrical scheme of the PV cell

Where  $S_{uns}$  is the actual solar irradiation level ( $W/m^2$ ),  $S_{unref}$  is the nominal level of insolation,  $T$  and  $T_{ref}$  (k) are the ambient temperature and the nominal temperature, respectively, at STC  $S_{unref}$  is equal to  $1KW/m^2$  and  $T_{ref}$  is  $298.15$  k.  $P_1, P_2, P_3$  are parameters to be determined experimentally.

$$I_d = I_{sat} \left[ \exp \left( \frac{q(V_{pv} + (I_{pv} * R_s))}{A * n_s * K * T} \right) - 1 \right] \tag{3}$$

The diode current  $I_d$  represents the losses due to the recombination of charge carriers in the PV cell,  $V_{pv}$  and  $I_{pv}$  are the voltage and current generated by the cell,  $q$  (C) is the electron charge,  $K$  is the Boltzmann constant ( $J/k$ ),  $A$  is the diode ideality factor,  $n_s$  is the number of series connected cells,  $I_{sat}$  is the saturation current is highly temperature-dependent:

$$I_{sat} = P_4 T^3 \exp \left( \frac{-E_g}{K * T_j} \right) \tag{4}$$

$I_{sh}$  is the current running through the shunt resistor,  $R_s$  represents the resistance in series with the PV cell. It accounts for the resistive losses within the cell, such as the resistance of the semiconductor material and the interconnection of cells in a module,  $R_{sh}$  resistance represents the leakage paths in parallel with the PV cell. It accounts for the non-ideal behavior of the cell, such as surface defects or impurities that create unintended pathways for current flow [5]. This model can depict the characteristics of a photovoltaic (PV) module that incorporates a series connection of  $n_s$  individual cells (figure (2)).

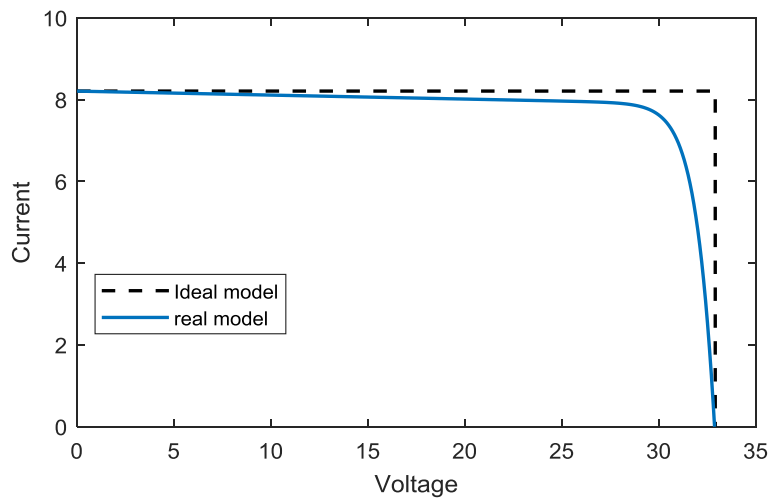


Fig 2. The I\_V curve of the PV cell

### 3. $R_s$ AND $R_{sh}$ EFFECT

Figures (3-a) and (3-b) visually illustrate the influence of series and shunt resistors on the output current of the PV cell. Upon thorough examination of these plots, a discernible trend becomes apparent: the gradient of the flat section in the PV cell's I-V curve shows an inverse correlation with the shunt resistance ( $R_{sh}$ ), while the slope of the steep section in the I-V curve shows a direct relationship with the series resistance ( $R_s$ ).

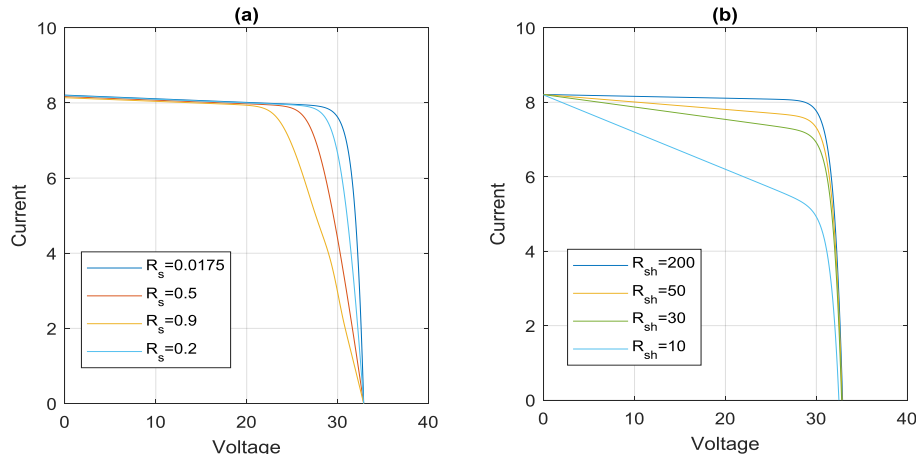


Fig 3. The I\_V curve of the PV cell

This astute observation is effectively encapsulated and depicted in Figure (4), offering a vivid portrayal of the inverse correlation between shunt resistance and the gradient of the horizontal I-V curve, alongside the direct correlation between series resistance and the gradient of the vertical I-V curve in the PV cell.

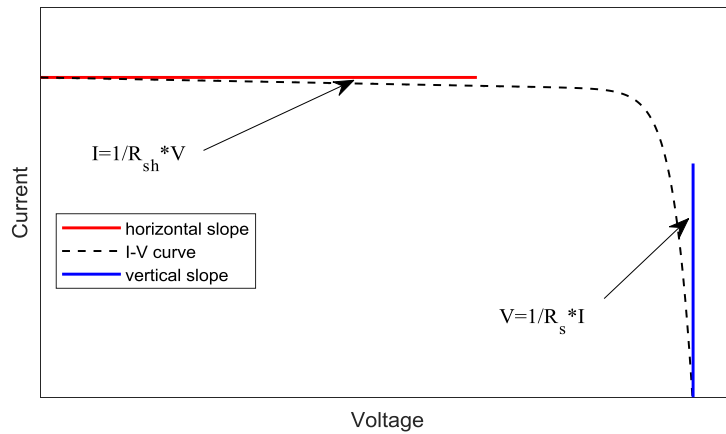


Fig 4. I\_V curve with horizontal and vertical slopes.

## 4. PV ARRAY CONFIGURATIONS

### 4.1 Series-Parallel (SP) configuration

In a Series-Parallel (SP) configuration of PV arrays (Figure 5-a), PV modules are initially linked in series to form strings, aiming to achieve a specific output voltage. Subsequently, these strings of modules are connected in parallel to attain the desired output current. The (SP) configuration offers several advantages, notably its simplicity in construction. It presents a straightforward and cost-efficient method for configuring PV arrays, reducing redundant connections, and streamlining the overall design. This

simplicity not only lowers installation expenses but also enhances system reliability, as fewer components translate to fewer potential points of failure[10].

#### 4.2 Total Cross-Tied (TCT) configuration

The Total Cross-Tied (TCT) connection scheme (Figure 5-b) involves integrating cross-ties into the series-parallel connected PV system. Widely recognized as one of the most prevalent and effective approaches in the photovoltaic industry, this configuration aims to counter the detrimental effects of partial shading on the PV array while minimizing losses compared to other standard connection schemes. By incorporating cross ties, the TCT configuration enhances overall performance, particularly in scenarios where sections of the PV array experience shading. This design optimizes the utilization of available solar energy, thereby maximizing power output. Consequently, the TCT connection scheme remains a favored option among PV practitioners seeking to boost the reliability and efficiency of their solar power systems [11].

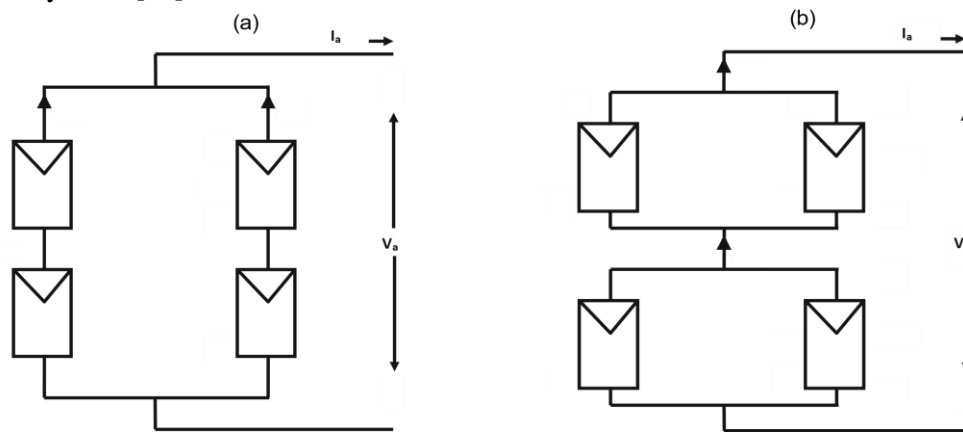


Fig 5. Schematic diagram of a PV array connected in SP and TCT

### 5. RESULTS AND DISCUSSION

In this section, we present the simulation results for four modules initially connected in a series-parallel (SP) configuration and then in a (TCT) configuration. During these simulations, two of the modules were subjected to a mismatch fault. The ideal series and parallel resistance values for the modules are set as  $R_s=0.221\Omega$  and  $R_{sh}=415.45 \Omega$ , respectively. To introduce the mismatch fault, we modified the resistance values of these two modules as follows:  $R_{s1}=1.5 \Omega$ ,  $R_{s2}=1.1 \Omega$ ;  $R_{sh1}=55 \Omega$ ,  $R_{sh2}=20 \Omega$ . A visual summary of these changes is provided in Figure (6).

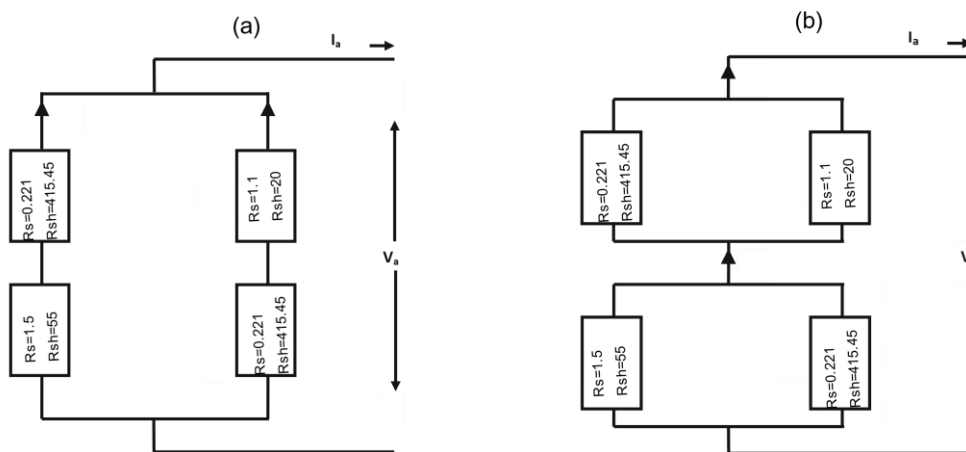


Fig 6. PV array configuration with resistance values.

Figure (7) illustrates the I-V (current-voltage) and P-V (power-voltage) curves during the occurrence of a mismatch fault in both the series-parallel (SP) and total cross-tied (TCT) configurations. It is evident from the graph that the TCT configuration outperforms the SP configuration. In TCT, the maximum power point (MPP) reaches approximately 1068.2 W. In contrast, the MPP for the SP configuration is 1040.6 W, indicating a difference of approximately 28 W. This discrepancy underscores the effectiveness of the TCT configuration.

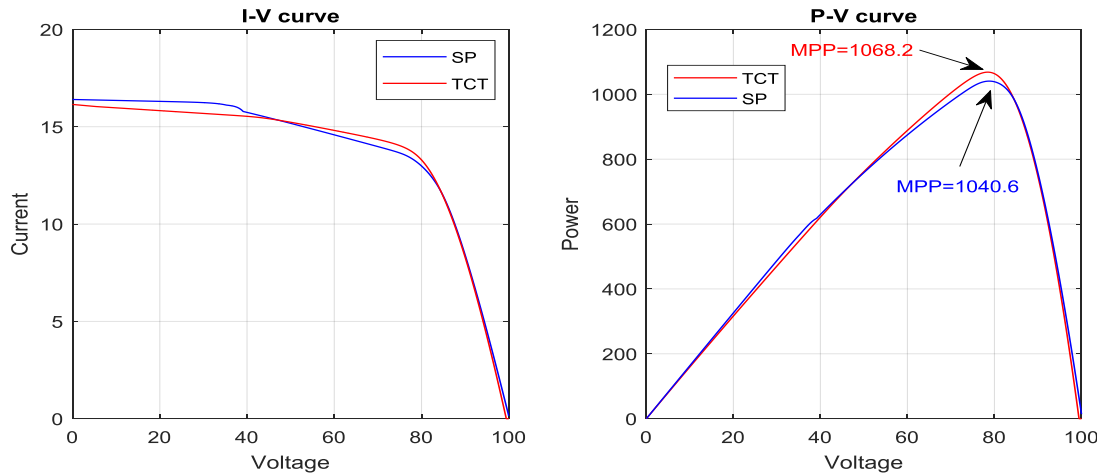


Fig 7. I\_V and P\_V curves with mismatch default

Figures (8) and (9) depict the power response of four modules in an SP and TCT configuration, connected to a load through a boost converter. This boost converter is controlled by an MPPT (Maximum Power Point Tracking) block, employing two different techniques for tracking the maximum power point (MPP): the conventional Perturb and Observe (P&O) method and a fuzzy logic approach with two input parameters, namely the error (E) and the rate of change of error ( $\Delta E$ ). The error is determined using the equation:

$$E = \Delta P / \Delta V \tag{5}$$

The output of this block is the duty cycle (D), triangular membership functions are employed for defining three membership functions for both inputs and the output.

In Figure (8-a), the power response of the modules in the SP configuration is shown for both P&O and fuzzy logic methods. Figure (8-b) provides a close-up view of the power response between 0.024 s and 0.035 s. Both methods converge to the MPP with 100% accuracy during this interval. Notably, the fuzzy logic method exhibits a quicker response time, achieving a time response of 0.025 s, while the conventional P&O method takes 0.028 s to respond. This discrepancy underscores the effectiveness of the fuzzy logic method.

Moving on to Figure (9-a), presents the power response of the modules in a Total Cross-Tied (TCT) configuration, utilizing both the P&O and fuzzy logic methods. Figure (9-b) zooms in on the power response between 0.022 s and 0.033 s. Both methods reach the MPP, however, there is a noticeable difference in response times, with the fuzzy logic method attaining an MPP of 0.025 s.

At last, the Total Cross-Tied (TCT) configuration has proven to be significantly more effective in generating power when compared to the Series-Parallel (SP) configuration, resulting in a noticeable

power increase of 28 watts. It is worth noting that the fuzzy logic-based method exhibited a considerably swifter response and performance compared to the Perturb and Observe (P&O) method.

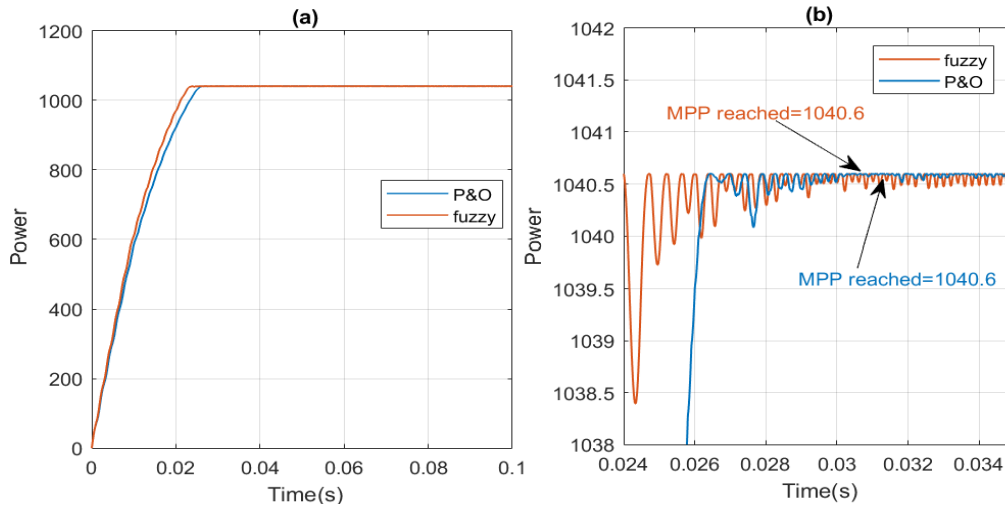


Fig 8. Power response in case of SP configuration.

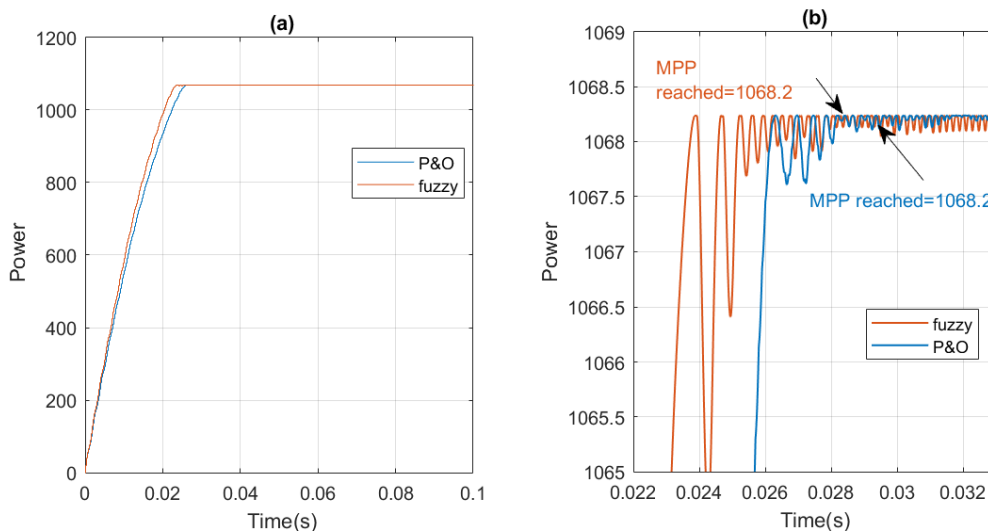


Fig 9. Power response in case of TCT configuration.

## 6. CONCLUSION

This paper delves into a comprehensive examination of a photovoltaic (PV) array's performance under mismatched conditions, conducted in both Series-Parallel (SP) and Total Cross-Tied (TCT) configurations. The findings unequivocally highlight the superiority of the TCT configuration when confronted with changes in internal resistances, manifesting as a substantial 28-watt discrepancy when compared to the SP configuration. Notably, the utilization of the fuzzy logic method exhibited remarkable efficiency, demonstrating significantly faster response times when compared to the conventional Perturb and Observe (P&O) approach. This study underscores the pivotal role of configuration and control techniques in optimizing the power output of PV arrays under varying operating conditions.

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