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Research Article

Linearization of Photovoltaic Cell Single Diode Equivalent Circuit Model Using Piecewise Linear Parallel Branches Model and Finding Fill Factor

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ABSTRACT

In this article, the linearization and analysis of the Photovoltaic (PV) cell single-diode equivalent circuit model have been performed. The diode element in the PV cell equivalent circuit model is a nonlinear component. The nonlinear PV cell single diode model has been linearized using the piecewise linear parallel branches model (PLPBM). In addition, the maximum power and fill factor (FF) of the PV cell have been determined based on the equivalent circuit parameters. Thevenin theorem was used in this analysis process. For this theorem to apply, the circuit must have a linear characteristic. In practice, the aim is to transfer the maximum power (Pmax) from the PV cell. Another important parameter of the PV solar cell is the FF. The FF describes the general behavior of a solar PV cell. This factor is used to determine the quality of the solar PV cell. The FF provides information about the quality and efficiency of the solar cell. In a low FF scenario, the value of the series resistance is high, while the value of the parallel resistance is low. The FF of typical PV cells ranges between 50% and 82%. In the analysis conducted in the article, the FF of the PV solar cell was found to be 74%.

Keywords: Fill factor, Maximum power transfer, PV cell single diode equivalent circuit, Piecewise linear parallel branches model, Thevenin equivalent circuit

Fotovoltaik Hücre Tek Diyot Eşdeğer Devre Modelinin Parçalı Doğrusal Paralel Dal Modeli Kullanılarak Doğrusallaştırılması ve Dolum Faktörünün Bulunması

ÖZET

Bu makalede Fotovoltaik (PV) hücre tek diyot eşdeğer devre modelinin doğrusallaştırılması ve analizi yapılmıştır. PV hücresi eşdeğer devre modelindeki diyot elemanı doğrusal olmayan bir bileşendir. Doğrusal olmayan PV hücresi tek diyot modeli, parçalı doğrusal paralel dallar modeli kullanılarak doğrusallaştırılmıştır (PLPBM). Ayrıca PV hücresinin maksimum gücü ve doldurma faktörü (FF)

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eşdeğer devre parametrelerine göre belirlenmiştir. Bu analiz sürecinde Thevenin teoremi kullanıldı. Bu teoremin uygulanabilmesi için devrenin doğrusal bir karakteristiğe sahip olması gerekir.
Uygulamada amaç, PV hücresinden maksimum gücü (Pmax) aktarmaktır. PV hücresinin bir diğer önemli parametresi FF'dir. FF, bir güneş PV hücresinin genel davranışını tanımlamak için kullanılır. Bu faktör solar PV hücresinin kalitesini belirlemek için kullanılır. FF, güneş pilinin kalitesi ve verimliliği hakkında bilgi sağlar. Düşük FF durumunda seri direncin değeri yüksek, paralel direncin değeri ise düşüktür. Tipik PV hücresinin FF'rü %50 ile %82 arasında değişir. Makalede yapılan analizde PV güneş pilinin FF %74 olarak bulunmuştur.

Anahtar Kelimeler: *Dolum faktörü, Maksimum güç aktarımı, PV hücresi tek diyot eşdeğer devresi, Parçalı doğrusal paralel dallanma modeli, Thevenin eşdeğer devresi*

I. INTRODUCTION

Renewable energy sources are increasingly being used day by day due to their inexhaustibility, lack of harm to the environment, and significantly lower cost compared to fossil fuels [1- 2]. The PV solar source holds significant importance among renewable energy sources. Solar energy is abundant and freely available in many regions of the world. Understanding the behavior of PV cells is crucial for optimizing their performance and increasing their efficiency. Photovoltaic cells, often called solar cells, are devices made from semiconductor materials such as silicon. When sunlight strikes the semiconductor material, it excites electrons, creating a flow of electricity. This phenomenon is known as the photovoltaic effect. The basic structure of a photovoltaic cell typically includes layers of semiconductor materials with different electronic properties. When photons from sunlight are absorbed by the semiconductor material, they transfer their energy to electrons, allowing them to flow through an external circuit as electric current. This flow of electrons is what we harness as electricity from solar panels. Solar PV cells come in various types, each with unique materials and mechanisms, influencing their efficiency and suitability for different applications. These cells are made from single-crystal silicon. Solar PV cell types and their efficiencies are given below:

A. MONOCRYSTALLİNE SİLİCON SOLAR CELLS

These are made from single-crystal silicon. They have high efficiency due to the purity of the silicon, typically ranging from 15% to 22% [3]. Monocrystalline silicon cells are widely used in residential and commercial installations.

B. POLYCRYSTALLİNE SİLİCON SOLAR CELLS

These are made from silicon crystals that are melted together. They are less expensive to produce compared to monocrystalline cells but have slightly lower efficiency, typically ranging from 13% to 18% [4].

C. THİN-FİLM SOLAR CELLS

Thin-film solar cells use thin layers of semiconductor materials deposited on a substrate. There are several types. Depending on the production type, efficiency varies between 5% and 13% [5].

D. PEROVSKİTE SOLAR CELLS

Perovskite cells have gained significant attention in recent years due to their rapid efficiency improvements and potential for low-cost production. Efficiency levels have quickly risen from below 10% to over 25% in laboratory settings, but commercialization is still underway, and long-term stability remains a challenge [6].

E. ORGANİC PHOTOVOLTAİC CELLS (OPVS)

OPVs are made from organic (carbon-based) materials and can be produced using low-cost printing techniques. Efficiencies for OPVs have been steadily improving, with recent achievements reaching around 15% [7].

It's worth noting that these efficiency figures are approximate and can vary depending on factors such as manufacturing techniques, materials' quality, and environmental conditions. Additionally, enhancing the durability and reliability of solar cells is crucial for long-term performance and reducing maintenance costs. This includes developing materials and coatings that can withstand harsh environmental conditions and degradation over time. While the efficiency of silicon solar cells and the effect of ambient temperature on solar modules were examined in ref. [8- 9], photovoltaic cell open circuit voltage and fill factor were examined in ref. [10].

When photovoltaic cells are connected in series, their voltages add up while the current remains same. In ref. [11], series-connected photovoltaic cell modeling and analysis were carried out. This configuration increases the overall voltage output of the system. It's similar to stacking batteries end-to-end in a flashlight to increase the total voltage. However, it's essential to note that the current. Remains the same throughout the series circuit, so if one cell is shaded or underperforming, it can significantly affect the performance of the entire string. Connecting cells in parallel increases the total current output while maintaining the same voltage as a single cell. This can be advantageous in situations where higher current is required, such as in low-light conditions or when powering devices with higher current demands. Additionally, in parallel connection of solar cells, the performance of other cells is less affected if one cell is shaded or malfunctions. When solar cells are connected in series, the current flowing through the cells remains the same, while the voltages of the cells are summed. As seen in Figure 1, the solar PV module consists of series-connected solar cells [12] .

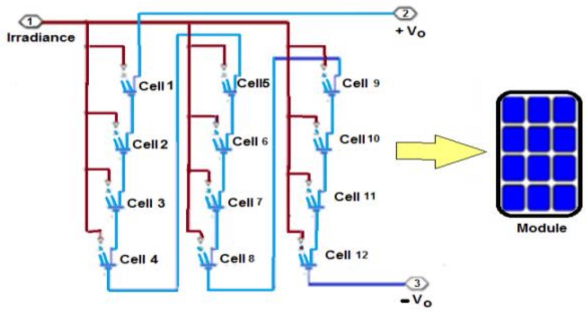

Figure 1. *A typical module has 12 cells connected in series*

In Figure 1, the total output voltage increases in this configuration group due to the series connection of solar cells. When solar cells are connected in parallel, the currents are added up and the voltage value remains the same as the voltage of a single cell group. This configuration increases the overall current output of the system. This setup allows for the optimization of both voltage and current levels, which is crucial for various applications, including solar panel systems. In this article, we explore the process of linearizing the PV cell single diode equivalent circuit model using the PLPB model. Validate the piecewise model by comparing it against the full nonlinear model, ensuring that the linearization captures the key behaviors of the PV cell, especially around critical points like the maximum power point (MPP).

In ref. [13], a new piecewise linear simulation algorithm using key-level model dynamics was studied. The I-V curve of the diode is typically divided into segments that correspond to different operating conditions, such as forward bias, reverse bias, and breakdown. For each segment, the slope (conductance) and intercept (bias voltage) are determined based on the local characteristics of the diode at that operating point. By linearizing the diode's output characteristics with the PLPBM, the overall behavior of a PV system can be modeled more accurately, enabling designers and engineers to analyze and optimize system performance under various operating conditions. In ref. [14], modeling of solar cells and modules was performed using a piecewise linear parallel branch model. Using PLPBM for linearizing the single diode PV cell model simplifies the complex nonlinear equations while maintaining sufficient accuracy for most practical purposes. This approach is especially useful in applications where computational resources are limited, but accurate real-time modeling is necessary, such as in MPPT (Maximum Power Point Tracking) algorithms or power electronics simulations .

We examine the theoretical basis in depth of the PLPB model and its application in characterizing PV cell behavior. Furthermore, we investigate the implications of linearization on the calculation of maximum power and FF, essential parameters for assessing the performance of PV systems [15]. To overcome this limitation, researchers have developed various techniques to linearize the model and facilitate mathematical analysis.
The Thevenin equivalent model is a powerful tool for simplifying complex circuits, and it can be applied to model PV solar cells. In ref. [16], Thevenin Equivalent of Solar PV Cell Model and Maximum Power Transfer has been studied.The Thevenin equivalent model is useful for understanding how the PV cell interacts with external loads, especially when trying to match the maximum power point (MPP) of the cell to an external circuit. At the MPP, the Thevenin equivalent circuit provides an intuitive understanding of how the internal characteristics of the PV cell (such as the series resistance and diode behavior) impact the overall performance [17- 19]. The effective Thevenin resistance (Rth) influences how much voltage is dropped internally within the cell, and Thevenin voltage (Vth) defines the potential power that can be delivered.To analyze the MPP of a photovoltaic (PV) cell using the Thevenin equivalent model, we need to focus on the point at which the PV cell delivers maximum power to a load [18- 20].

II. MODELİNG AND ANALYSİS OF PV CELL SİNGLE DİODE EQUİVALENT MODEL

A. SİNGLE-DİODE EQUİVALENT CİRCUİT MODEL

The single-diode equivalent circuit model is a commonly used method to represent the behavior of a PV cell. It simplifies the complex physical processes occurring within the cell into a more manageable form, allowing for easier analysis and design of PV systems [21, 22]. The single-diode equivalent circuit model provides a valuable tool for modeling and analyzing the behavior of PV cells. It simplifies the complex physics of solar cells into a more manageable form, allowing engineers and researchers to design and optimize PV systems effectively. However, it's essential to recognize that the model has limitations and may not capture all aspects of the cell's behavior under various conditions.
Modeling and analysis of solar PV cells using the single diode equivalent model is widely used in analyzing and understanding the performance of solar cells. This model simplifies the complex physical processes within a solar cell into a single equivalent circuit, making it easier to analyze and design PV systems [23, 24]. The analysis involves solving the circuit equations derived from the fundamental equations governing the behavior of the solar cell, such as the Shockley diode equation and Kirchhoff's laws. Techniques such as numerical simulation and analytical methods are often employed to study the behavior of the PV cell and optimize its performance. The single-diode equivalent circuit for a solar PV cell is shown in Figure 2.

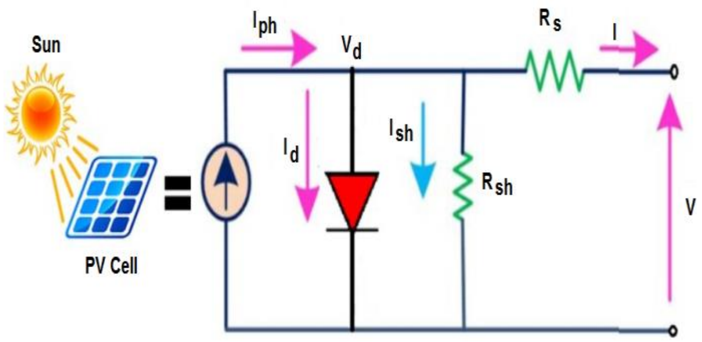

Figure 2. *PV cell single diode equivalent circuit model*

The single-diode model provides a good balance between simplicity and accuracy in describing the current-voltage (I-V) characteristics of a solar cell. It captures the essential physics of the cell without excessive complexity, making it suitable for practical simulations and analyses. Additionally, It serves as the foundation for designing and optimizing PV systems, including module and system-level analysis. The model helps in predicting the performance of solar cells under different conditions, such as varying irradiance and temperature, which are crucial for system design.

The single-diode equivalent circuit model given in Figure 2 is the general static equivalent circuit of the PV solar cell. This causes the circuit to have a nonlinear characteristic. The PV cell model given in Figure 2 is also referred to as a five unknown parameters model. These five parameters are Iph, Io, Rs, Rsh, and n. The variables you've mentioned are key parameters in the equivalent circuit model of a PV cell, often used to describe its behavior. PV cell equivalent circuit parameters are given below:

- Iph: This represents the photocurrent generated by the PV cell due to incident light. It is the current that flows through the external circuit connected to the solar cell when illuminated.
- Io: The reverse saturation current of the diode in the PV cell. This parameter characterizes the diode-like behavior of the solar cell, indicating the current that would flow through the cell in the absence of illumination.
- Rs: Series resistance of the PV cell. This resistance accounts for losses due to the internal resistance of the semiconductor materials and the interconnections within the cell.
- Rsh: Shunt resistance of the PV cell. This resistance represents leakage paths across the solar cell, which can reduce the efficiency of the cell if too low.
- n: The ideality factor (also known as the diode factor) of the PV cell. It is a dimensionless factor that represents deviations from ideal diode behavior due to recombination losses and other non-idealities within the semiconductor material.

These parameters are typically used in models such as the single-diode model or the double-diode model, which describe the current-voltage (I-V) characteristics of a solar cell under different operating conditions (illumination levels, temperature, etc.). These models help in understanding and predicting the performance of PV systems and optimizing their design for maximum efficiency.

B. ANALYSİS OF SINGLE DIODE EQUİVALENT CİRCUİTS

The single-diode model simplifies the complex behavior of a PV cell into a single-diode equation, which is relatively straightforward compared to the physical intricacies of the actual cell. Additionally, it allows for easier mathematical analysis and simulation compared to more detailed models. This makes it useful for quick calculations and initial design considerations.

The nonlinearity of the photovoltaic cell equivalent circuit presents several disadvantages, such as increased complexity in tracking the Maximum Power Point, sensitivity to environmental conditions, and partial shading issues. These challenges require sophisticated power electronics, complex control algorithms, and advanced design strategies to ensure optimal performance, leading to higher costs and system complexity. However, with effective management, the impact of nonlinearity can be minimized to improve overall system efficiency and reliability. Nonlinear characteristics make it difficult to maintain the MPP, especially in changing conditions like cloudy weather or shading.

The model provides a clear relationship between the output current and voltage of the PV cell, making it easier to estimate key parameters such as the fill factor, maximum power point, and efficiency. Researchers can use the model to optimize the design of PV systems by predicting how changes in environmental conditions (like sunlight intensity and temperature) affect the electrical characteristics of the PV module. The unknown parameters in this model depend on the intensity of the irradiation and the temperature. Therefore, the irradiation and temperature levels must be known for each output value to be calculated. The single-diode equivalent circuit model offers a balance between accuracy and simplicity, making it a practical choice for various stages of PV system design, analysis, and education. Its advantages lie in ease of use, parameter estimation, design optimization, and its widespread acceptance and compatibility within the field of photovoltaics. The output current to be produced by the photovoltaic cell is found in Equation (1).

$$\mathrm{I_{sc}} = \mathrm{I_{ph}} - \mathrm{I_D} - \mathrm{I_{sh}} \tag{1}$$

The formula to calculate diode current it is as below:

$$\mathrm{I_D} = \mathrm{I_0}\left[\exp\left(\frac{\mathrm{q(V+IR_s)}}{\mathrm{nkT_c}}\right) - 1\right] \tag{2}$$

The equation of the current flowing through the parallel resistor is as given below.

$$\mathrm{I_{sh}} = \frac{\mathrm{V+IR_s}}{\mathrm{R_{sh}}} \tag{3}$$

The output current of the Kyocera KC200GT module PV cell depends on various factors such as the amount of sunlight (irradiance), temperature, and the load connected to the module. The output current of the photovoltaic cell is found as follows.

$$\mathrm{I} = I_{ph} - I_0\left[exp\left(\frac{q(V+IR_s)}{nkT_c}\right) - 1\right] - \frac{(V+IR_s)}{R_{sh}} \tag{4}$$

Where:
k - The Boltzmann constant (J/K)
Iph- Photocurrent (A).
q - The elementary electron charge (C)
I_0 - Diode reverse saturation current.
n -Ideality factor of diode.
Rs - Equivalent series resistance (Ω)
Rsh - Equivalent shunt resistance (Ω)
Tc - Cell temperature (K)

The I-V (current-voltage) curve of a PV module, such as the Kyocera KC200GT, represents the relationship between the current and voltage output of the module under varying conditions. Analyzing the I-V curve helps designers understand the performance of PV modules under different conditions and design optimal systems for various applications, whether it's for grid-tied solar installations, off-grid systems, or other solar-powered devices. The I-V curve is affected by environmental factors such as temperature and solar irradiance. Higher temperatures generally reduce the voltage output of the panel, while increased irradiance (sunlight intensity) increases both the current and voltage outputs. The I-V curve of the Kyocera KC200GT module is given in Figure 3.

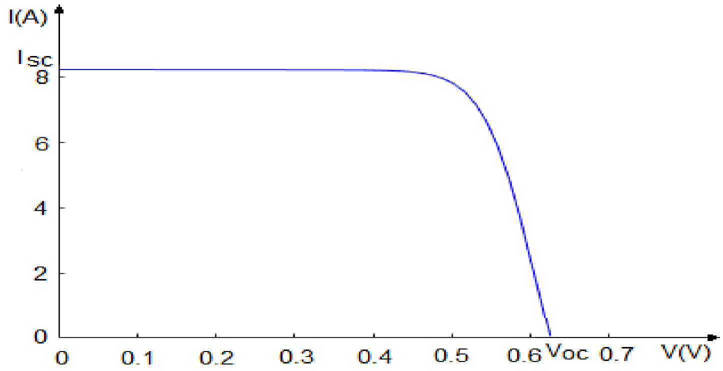

Figure 3. *I-V curve of the PV cell (at 25 °C, 1000 (W/m²)*

The I-V curve of a PV cell plays a crucial role in the design, analysis, optimization, and operation of PV systems. It provides valuable insights into the electrical characteristics of the cell, enabling efficient energy production, system monitoring, and maintenance. The short-circuit current (I_{SC}) of a PV cell refers to the current that flows through the cell when the circuit is short-circuited, meaning there is no external load connected to the cell. The formula to calculate the short circuit current of the PV cell is as below:

$$I_{sc} = I_{ph} - I_0 \left[\exp\left(\frac{I_{sc}R_s}{nV_t}\right) - 1\right] - \frac{I_{sc}R_s}{R_{sh}} \quad (5)$$

This occurs when the voltage across the terminals of the cell is zero, causing the maximum current to flow through the circuit. PV cells convert absorbed solar irradiation into electrical energy through the photovoltaic effect. Standard Test Conditions (STC). These are measured under lab conditions of 1000W per sq meter of "sunlight" with a standard spectrum etc. The photocurrent generated by the cells is highest under optimal sunlight conditions (such as in sunny weather and under STC) and decreases under reduced irradiance levels (such as in cloudy or overcast weather). Understanding these dynamics helps in predicting and optimizing the performance of solar energy systems under different environmental conditions [25, 26]. The formula to calculate PV cell photocurrent is as below:

$$I_{ph} = [I_{sc} + K_i(T - T_n)]\frac{G}{G_n} \quad (6)$$

Where, Iph is photocurrent, G is irradiation value, Gn is the irradiation value accepted under STC, T is PV cell temperature, Tn is nominal temperature, Ki is temperature coefficient of current. The PV cell photo-current depends on the solar irradiation and temperature. The current at the Maximum Power Point (MPP) defined by Equation (7).

$$I_{mp} = I_{pf} - I_0 \left[\exp\left(\frac{q(V_{mp} + I_{mp}R_s)}{nkT_c}\right) - 1\right] - \left(\frac{V_{mp} + I_{mp}R_s}{R_{sh}}\right) \quad (7)$$

This is the current that the PV cell produces when it is operating at its MPP. The diode reverse saturation current is a fundamental parameter that characterizes the behavior of semiconductor diodes, including those used in photovoltaic cells. It plays a significant role in determining the efficiency and performance characteristics of PV modules in converting solar energy into electrical power. The diode reverse saturation current is found by the following equation (8).

$$I_0 = I_{0ref}\left(\frac{T}{T_{ref}}\right)^3 \exp\left[\frac{qE_q}{nk}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \tag{8}$$

Where Ioref is diode saturation reverse current in the referred cell temperature condition. Eg is the band gap energy of the diode and T is the absolute temperature. During the design phase of a PV system, optimizing FF is critical to ensuring the system delivers maximum power output under varying environmental conditions. FF is influenced by the internal resistances of the solar cell, both series resistance (which lowers FF) and shunt resistance (which increases FF). High FF values generally indicate lower power losses due to resistance. The FF would slightly increase or decrease depending on the density of the irradiance and the influence of parasitic resistance [25, 26]. The FF is essentially a measure of the quality of the solar cell. The formula to calculate FF is as below:

$$FF = \frac{P_{max}}{I_{sc}V_{oc}} = \frac{V_{mp}I_{mp}}{I_{sc}V_{oc}} \tag{9}$$

The FF is calculated by dividing the maximum power obtained from the solar cell by the theoretical power obtained by multiplying the open circuit voltage by the short circuit current. PV cell efficiency is a critical parameter that determines how effectively solar energy can be converted into electrical power. Advances in materials, manufacturing processes, and design continue to drive improvements in PV cell efficiency, making solar energy an increasingly competitive and viable renewable energy option worldwide. PV cell efficiency is the ratio of electrical output power P(out) to solar input power P(in). The formula to calculate the efficiency of the solar PV cell is as below:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{FF * I_{sc}V_{oc}}{G * A} \tag{10}$$

Where, FF is the fill factor, A is the area of the solar cell and G is solar irradiance. From the equation (10), as the FF value increases, the efficiency of the PV cell increases. Increasing the efficiency of photovoltaic (PV) cells is a key goal in solar energy research and development. High-Quality Semiconductor Materials: Using materials with optimal band gaps for absorbing sunlight can increase efficiency. Traditional silicon-based cells have limitations, so researchers are exploring materials like perovskites, multi-junction solar cells, and thin-film technologies. Tandem or multi-junction cells can achieve efficiencies higher than single-junction cells by capturing a wider range of wavelengths. Additionally, using perovskite solar cells. Perovskites offer high absorption efficiency and tunable bandgaps, and they have gained attention for their potential to outperform traditional silicon cells. The formula to calculate the open circuit current of the PV cell it is as below:

$$V_{oc} = \frac{nkT_c}{q} Ln\left(\frac{I_{ph}}{I_0} + 1\right) \tag{11}$$

Where, Iph is photocurrent, and Tc is cell temperature. By examining the above equation, it is seen that the open circuit voltage does not increase linearly with temperature. The open-circuit voltage shown on the I-V curve below is obtained when the current flowing through the cell is zero. Variation in PV cell temperature occurs due to changes in the ambient temperature as well as changes in the intensity of solar irradiation. The PV cell temperature is defined as:

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$$T = T_{amb} + \left(\frac{NOCT - 20^{0}C}{0.8}\right)G \quad (12)$$

Where Tamb is ambient temperature, NOCT is nominal operating cell temperature, and G is solar irradiation. An increase in solar cell temperature of about 1°C results in an efficiency decrease of about 0.45%. The specifications of PV modules provide the foundational information necessary for the successful design, installation, operation, and maintenance of solar power systems. The specifications of the PV Module (KC200GT) are given in Table 1.

***Table 1.** The specification of the PV module used in study (PV Module KC200GT)*

Parameters	Value
Maximum Power (Pmax)	200W (＋10%／－5%)
Maximum Power Voltage (Vmp)	26.3 (V)
Maximum Power Current (Imp)	7.61 (A)
Open Circuit Voltage (Voc)	32.9 (V)
Short Circuit Current (Isc)	8.21 (A)
Temperature Coefficient of Voc	－1.23×10-1 (V/C)
Temperature Coefficient of Isc	3.18×10-3 (A/C)
Number of cells in series (Ns)	54

The PV module KC200GT refers to a specific model of photovoltaic module typically used in solar energy systems. PV modules like the KC200GT are used in various applications, including residential, commercial, and utility-scale solar installations, contributing to renewable energy generation worldwide.

III. LİNEARİZATİON OF PV CELL SİNGLE DİODE EQUİVALENT CİRCUİT MODEL USİNG PLPBM

The PV cell single-diode equivalent circuit model helps explain the electrical behavior of PV cells. However, due to the diode element in this model, the circuit has a nonlinear characteristic. The nonlinear characteristic makes it difficult to accurately model and analyze the single equivalent circuit of the PV cell. Traditional analytical methods are insufficient to directly solve the nonlinear equations of the single diode model, and require the development of special numerical techniques. Despite its complexity, the single-diode model is still the most widely used model for characterizing PV cell behavior and predicting performance under varying operating conditions. The Piecewise Linear Parallel Branch Model linearizes the diode characteristic in a photovoltaic cell by breaking it into several linear regions, each represented by a resistor in parallel. This approximation allows for easier analysis and simulation, particularly in modeling the behavior of the PV cell's equivalent circuit. In circuit simulation tools, the piecewise linear model is implemented by adding parallel resistor branches corresponding to different operating regions of the diode. This approach simplifies the nonlinear diode behavior into a more manageable form for analysis.

The linearization of the PV cell single-diode equivalent circuit model using the PLPBM represents a significant advance in the field of PV technology. The piecewise linear parallel branches model is based on the principle of linearization by dividing the nonlinear curve of the diode into linear sections. This simplification enables mathematical analysis and supports the development of efficient numerical algorithms for simulation and optimization. By dividing the nonlinear diode equation into multiple linear parts, the PLPBM significantly simplifies the computational complexity. Moreover, the piecewise linear parallel branches model provides a more intuitive understanding of how changes in operating conditions such as irradiance and temperature affect PV cell performance.

Based on the outlined criteria, the advocated approach appears to be technically correct and scientifically sound, provided it is rigorously formulated and validated through simulations and, ideally, experimental data. As with any scientific work, thorough documentation of assumptions, methodologies, and validations is essential for establishing credibility. If these aspects are adequately addressed in your paper, it would significantly contribute to the understanding and modeling of photovoltaic systems. Ensure that the mathematical equations used to describe the linear segments are correctly derived from the Shockley diode equation. The linearization should accurately reflect the slopes of the I-V curve in each segment. The equivalent of the diode circuit is given in Figure 4.

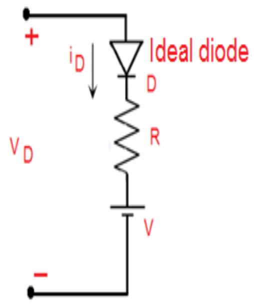

Figure 4. *The equivalent circuit of diode*

The equivalent circuit of a diode typically includes an ideal diode and a series resistance. The ideal diode represents the diode's one-way conduction behavior, conducting current when forward-biased and blocking current when reverse-biased. The series resistance accounts for the non-ideal behavior of real diodes, causing a voltage drop across the diode when it conducts in the forward direction. This simplified circuit model is commonly used in electronic circuit analysis to approximate the behavior of diodes. Higher irradiance levels result in higher current and power output from the solar cell, whereas lower irradiance levels result in lower outputs. These changes are reflected in both the I-V and P-V curves. The changes in the I-V and P-V curves at different irradiance values are given in Figure 5.

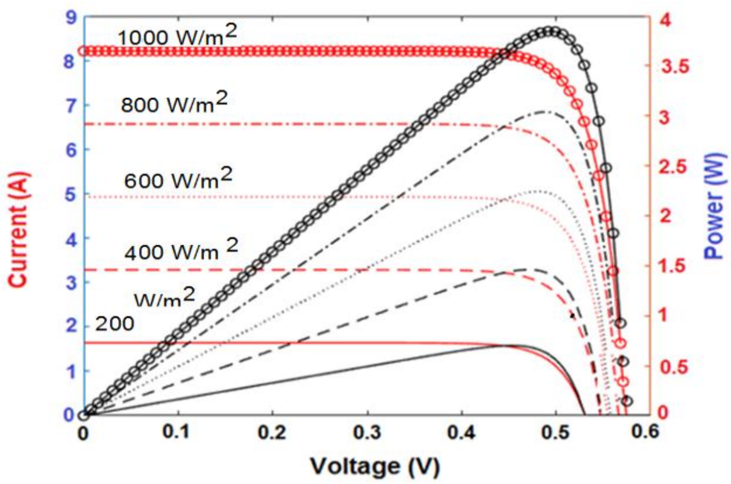

Figure 5. *The I-V and P-V solar cell curves at (200, 400, 600, 800 and 1000 (W/m^2)) irradiation values*

The piecewise linear parallel branches model of a diode is a simplification used in circuit analysis to approximate the behavior of a real diode. In this model, the diode characteristic curve (which relates the voltage across the diode to the current flowing through it) is approximated using multiple linear segments. The linearization of the diode with the PLPBM method is given in Figure 6.

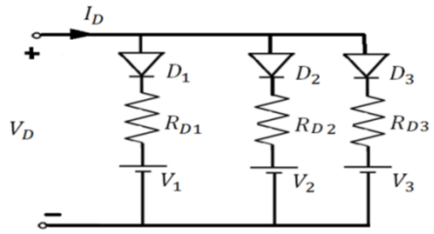

Figure 6. *Piecewise linear parallel branches model of diode*

The principle diagram of the piecewise linearization of non-linear characteristic of diode is given In Figure 7. In this method, the current-voltage curve of the diode is divided into several regions [27] .

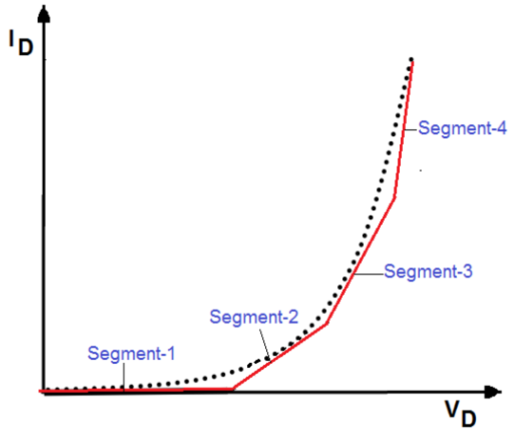

Figure 7. *Four segment piecewise diode model*

The PV cell equivalent circuit has a nonlinear characteristic due to the diode element. Using the PLPBM, the PV cell equivalent circuit can be linearized. This linearized model simplifies analysis and enables larger circuit simulations. The linearization of the PV cell with the PLPBM method is given in Figure 8.

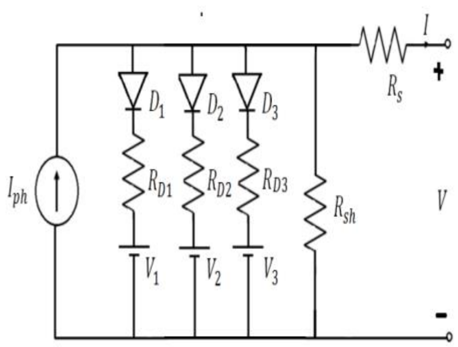

Figure 8. *Linearization of the PV cell equivalent circuit with the PLPBM method*

PV cell piecewise linearized model vertex points are located at:

$$0.9 * V_{MPP} \leq V_{amb} \leq 1.1 * V_{MPP} \quad (13)$$

<u>Segment 1</u>: ($V_D < V_1$) (V_1 = 0.9* MPP = 23.67 V). All diodes are in the off position. For this reason, almost all of the light current produced from the PV cell flows through the load and a small part flows through the shunt resistor.

<u>Segment 2</u>: ($V_1 < V_D < V_2$). D_1 diode is in the on position. In this range, the PV cell current decreases from 8.21 A to 7.61 A. In this case, 0.6 A current flows through D_1 diode. The value of R_{D1} resistance is found from Eq. (14) given below.

$$R_{D1} = \frac{V_{max} - 0.9V_{max}}{I_{D1}} \tag{14}$$

It is found as given below.

$$R_{D1} = 4.3833\ \Omega$$

<u>Segment 3</u>: ($V_2 < V_D < V_3$). In this range, D_1 diode and D_2 diode are in the on position. The current passing through D_1 diode is found with the Equation (15).

$$I_{D1} = \frac{1.1V_{max} - 0.9V_{max}}{R_{D1}} \tag{15}$$

The PV output current is 6.65 A, the current through D_2 diode:

$$I_{D2} = I_{ph} - I_{D1} - 1 \tag{16}$$

$$I_{D2} = 0.35\ A$$

ıs found. Resistance R_{D2} is calculated from Equation (17):

$$R_{D1} = \frac{1.1V_{max} - 0.9V_{max}}{I_{D2}} \tag{17}$$

$$R_{D2} = 7.514\ \ \Omega$$

ıs found.

<u>Segment 4</u>: ($V_3 < V_D < V_{OC}$). In this range, all diodes are in the on position. PV cell load current is zero. The open circuit voltage is 21.8 V. The current passing through D1 diode is found from equation (18).

$$I_{D1} = \frac{V_{oc} - 1.1V_{max}}{R_{D1}} \tag{18}$$

$$I_{D1} = 0.9057\ \text{A}$$

Is found. The current through D_2 diode is computed from Equation (19)

$$I_{D2} = \frac{V_{oc} - 1.1V_{max}}{R_{D2}} \tag{19}$$

($V_3 < V_D < V_{OC}$). In this range, since the PV output current (I) is zero, the current passing through D_3 diode is calculated from equation**:**

$$I_{D3} = I_{ph} - I_{D1} - I_{D2} - \quad (20)$$

$I_{D3} = 6.766$ A

is found. R_{D3} resistance is calculated from Equation (21):

$$R_{D3} = \frac{V_{oc} - 1.1V_{max}}{I_{D3}} \quad (21)$$

$R_{D3} = 0.5867\ \Omega$

is found. The maximum cell voltage at the MPP point is found from Equation (22)

$$V_{mpcell} = \frac{V_{mp}}{N_s} \quad (22)$$

$V_{mpcell} = \frac{26.3}{54} = 0.478\ V$

is found. The equivalent of the voltages in Fig. 9 is calculated from Equation (23).

$$0.9 * V_{MPP} < V_{MPP} < 1.1 * V_{MPP} \quad (23)$$

The voltage values of V1, V2, and V3 are found in Equation (22). As a result, V1, V2, and V3 are 0. 4302 V, 0.478 V, and 0,5258 V are calculated as. Since all PV cells are connected in series, the same current flows through all PV solar cells. The equivalent circuit parameters of the diode are given in Table 2.

***Table 2**. Equivalent circuit parameters of the diode*

Parameters	Values	Parameters	Values
I_{D1}	0.9057 (A)	R_{D1}	4.3833 (Ω)
I_{D2}	0.35 (A)	R_{D2}	7.514 (Ω)
I_{D3}	6.766 (A)	R_{D3}	0.5867 (Ω)
Vmpcell	0.478 (V)	V_1	0.4302 (V)
I	6.65 (A)	V_2	0.478 (V)
		V_3	0.5258 (V)

In the piecewise linear parallel branches model, the diode within the equivalent circuit of a PV cell is often linearized around its operating point to simplify analysis. By linearizing the diode model in this way, the equivalent circuit becomes easier to analyze using linear circuit analysis techniques, facilitating the design and optimization of PV systems. However it's essential to remember that this linearization is only valid around the operating point and may introduce inaccuracies outside this region.

The contributions of the paper can significantly advance the understanding and application of photovoltaic technology. By introducing a more accessible and efficient modeling approach, it has the potential to impact research, education, and practical implementations in the renewable energy sector, ultimately leading to more efficient energy systems and better integration of solar power into the energy grid.

A. DETERMİNİNG THE MAXİMUM POWER OF THE SOLAR PV CELL

To determine the maximum power output of a PV cell, we usually need to find the operating point at which the product of voltage and current is maximized. This point is called the Maximum Power Point (MPP). Locate the point on the IV curve where the product of current and voltage is maximized. Mathematically, this point corresponds to the maximum power output (Pmax) of the PV cell. It's important to note that the operating conditions, such as solar irradiance and temperature, can significantly affect the maximum power output of the PV cell. Additionally, the maximum power point may shift due to changes in these conditions. Therefore, it's often necessary to consider the real-world operating environment when determining the maximum power output of a PV cell. According to Thevenin's theorem, any linear electrical network with voltage and current sources and resistances can be replaced by a single voltage source (Thevenin voltage) in series with a single resistor (Thevenin resistance). This equivalent circuit represents the original circuit as seen from two terminals. To transfer the maximum power from a PV cell to the load, it is necessary to determine the Thevenin equivalent of the PV cell. Thevenin equivalent. Voltage sources are short-circuited and current sources are open-circuited to find Thevenin equivalent resistance. The aim here is to simplify the complex circuit, allowing the circuit to be analyzed more easily. Thevenin voltage and resistance values are given below.

$$V_{Thi} = V_i + R_{Di}\left(\frac{I_{ph}R_{sh} - V_i}{R_{sh} + R_{Di}}\right) \quad (24)$$

$$R_{Thi} = R_s + \left(\frac{R_{sh}R_{Di}}{R_{sh} + R_{Di}}\right) \quad (25)$$

V_{Thi} is the open circuit voltage between two points. The R_{Thi} resistor is the input or equivalent circuit resistor when independent sources are disabled. Thevenin's equivalent circuit is shown in Figure 9.

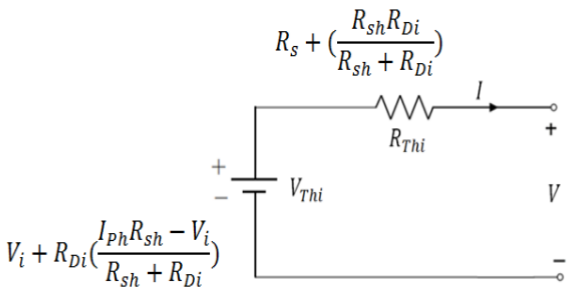

Figure 9. *Derivation of Thevenin equivalent model of solar PV cell*

Where V_{Thi} and R_{Thi} are Thevenin's equivalent voltage and resistance of the model of Figure 9 at region i (i = 1, 2, 3....number of regions). Thévenin's theorem states that any linear electrical network can be replaced by an equivalent circuit consisting of a single voltage source Vth in series with a single resistor Rth, where Vth is the open-circuit voltage at the terminals of the network, and Rth is the equivalent resistance seen from those terminals when all independent sources are turned off (replaced by their internal resistances). Thévenin's theorem provides a useful theoretical framework for understanding and optimizing the power output of PV modules by identifying the conditions under which maximum power transfer occurs. This theorem is fundamental in PV system design and operation, facilitating efficient energy conversion from sunlight to electrical power. The equivalent of this circuit is given in Figure 10.

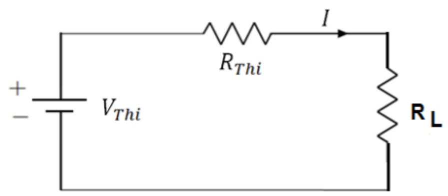

Figure 10. *Development of Thevenin equivalent model PV cell with RL loaded*

The current through the load for any value of load resistance is

$$I_L = \frac{V_{Thi}}{R_{Thi} + R_L} \tag{26}$$

The power transferred to the load is

$$P = I_L^2 * R_L \tag{27}$$

When we take the derivative of equation (26), the following expression is obtained.

$$\frac{dP}{dR_L} = V_{Th}^2 \left[\frac{(R_{Thi} + R_L)^2 - 2R_L + (R_{Thi} + R_L)}{(R_{Thi} + R_L)^2} \right] = 0 \tag{28}$$

The result of equation (28) is found as follows.

$$R_L = R_{Thi} \tag{29}$$

This principle ensures that the maximum amount of power is transferred from the source to the load. When the load resistance matches the source resistance in the Thevenin equivalent circuit, the circuit operates most efficiently, maximizing power transfer. The maximum power transferred to the load is found using the following formula.

$$P_{max} = \left(\frac{V_{Thi}}{R_{Thi} + R_L} \right)^2 * R_L \tag{30}$$

The change of cell output power depending on the load resistance is given in Figure 11.

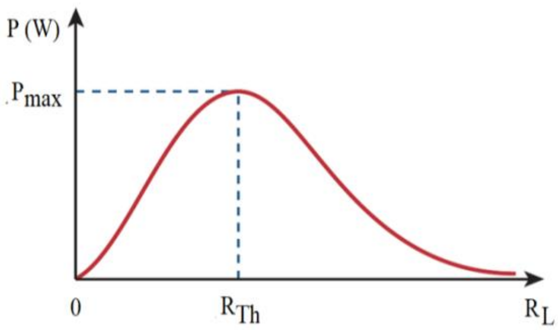

Figure 11. *Output power dependent on load resistor*

As a result, the maximum power value is obtained as:

$$P_{max} = \frac{V_{Thi}^2}{4R_{Thi}} \tag{31}$$

The value of the Thevenin voltage given in equation (32).

$$V_{Thi} = V_i + R_{Di}\left(\frac{I_{ph}R_{sh} - V_i}{R_{sh} + R_{Di}}\right) \quad (32)$$

The formula to calculate the Theremin resistance of the PV cell it is as below:

$$R_{Thi} = R_s + \left(\frac{R_{sh}R_{Di}}{R_{sh} + R_{Di}}\right) \quad (33)$$

Maximum power to be transferred from the PV cell to the load from equation (31).

$$P_{max} = \frac{\left[V_i(R_{sh} + R_{Di}) + R_{Di}\left(I_{ph}R_{sh} - V_i\right)\right]^2}{4(R_{sh} + R_{Di})[R_s(R_{sh} + R_{Di}) + R_{sh}R_{Di}]} \quad (34)$$

Maximum power transfer is the finding of the load value that provides the greatest power transfer from a PV cell to the connected load. The goal of a photovoltaic (PV) system is to convert sunlight into electrical energy as efficiently as possible. Ensuring maximum power transfer from the PV cell to the load is crucial.Maximizing power transfer from a photovoltaic cell is essential for ensuring the efficiency, reliability, and economic viability of solar energy systems. The Maximum Power Point Tracking **(MPPT)** technique is the most effective method to ensure maximum power transfer, along with proper system design, impedance matching, and load management. These strategies allow PV systems to capture and utilize the highest possible amount of energy from the sun, improving the overall performance and efficiency of solar power systems.

IV. DEVELOPMENT OF THE ANALYTICAL EXPRESSION OF THE MAXIMUM POWER AND FILL FACTOR BASED ON EQUIVALENT CIRCUIT PARAMETERS

The value of the fill factor gives information about the ideality of the PV cell. In an ideal PV cell, the fill factor is equal to one. Therefore, the fill factor should be close to one in any PV cell. The parameters shown in Table 1. are used in the simulation and are given by the manufacturer's PV module..

$$P_{max} = \frac{\left[V_1(R_{sh} + R_{D1}) + R_{D1}\left(I_{ph}R_{sh} - V_1\right)\right]^2}{4(R_{sh} + R_{D1})[R_s(R_{sh} + R_{D1}) + R_{sh}R_{D1}]} + \frac{\left[V_2(R_{sh} + R_{D2}) + R_{D2}\left(I_{ph}R_{sh} - V_2\right)\right]^2}{4(R_{sh} + R_{D2})[R_s(R_{sh} + R_{D2}) + R_{sh}R_{D2}]} + \frac{\left[V_3(R_{sh} + R_{D3}) + R_{D3}\left(I_{ph}R_{sh} - V_3\right)\right]^2}{4(R_{sh} + R_{D3})[R_s(R_{sh} + R_{D3}) + R_{sh}R_{D3}]} \quad (36)$$

Solar PV cells are exposed to non-uniform solar irradiation throughout the day. Shadowing in PV panels can significantly reduce energy production and efficiency. Proper design, including the use of bypass diodes and careful system layout, along with ongoing monitoring and maintenance, is essential to mitigate the impact of shading and maximize the performance of photovoltaic systems over their operational lifetime. The P-V characteristic curve of the PV module is given in Figure 12.

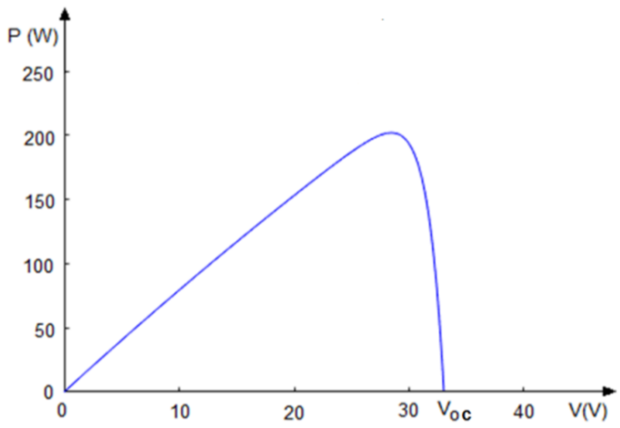

Figure 12. *P-V curve of the PV module (at 25 °C, 1000 W/m²)*

The measurement of the maximum power value produced by photovoltaic cells under different irradiation intensities and operating conditions is important as it reflects the system's performance. Because the power output of photovoltaic panels depends on radiation intensity, operating temperature, and other climatic parameters. In this study, a piecewise linear diode model has been developed to obtain a characteristic close to the nonlinear characteristic of a single diode of the PV cell. From equation (9), the fill factor of the solar system is as given in Equation (36).

$$FF = \frac{\frac{[V_1(R_{sh}+R_{D1})+R_{D1}(I_{ph}R_{sh}-V_1)]^2}{4(R_{sh}+R_{D1})[R_s(R_{sh}+R_{D1})+R_{sh}R_{D1}]}+\frac{[V_2(R_{sh}+R_{D2})+R_{D2}(I_{ph}R_{sh}-V_2)]^2}{4(R_{sh}+R_{D2})[R_s(R_{sh}+R_{D2})+R_{sh}R_{D2}]}+\frac{[V_3(R_{sh}+R_{D3})+R_{D3}(I_{ph}R_{sh}-V_3)]^2}{4(R_{sh}+R_{D3})[R_s(R_{sh}+R_{D3})+R_{sh}R_{D3}]}}{I_{sc}V_{oc}} \tag{36}$$

The value of the Fill Factor is found as follows from the results of the Equation (36).

FF=74 %

is found. The value of the FF gives information about the ideality of the PV cell. In an ideal PV cell, the fill factor is equal to one. Therefore, the fill factor should be close to one in any PV cell. For the fill factor to be large, the series resistance (Rs), the ideality factor of the diode (n), the reverse saturation current density (Io), and the temperature (T) in the PV cell equivalent circuit should be small. However, the band gap energy (Eq) and the shunt resistance (Rsh) must be large.

IV. CONCLUSION

Since there is a diode element in the PV cell equivalent circuit, this model is not linear and Thevenin's theorem cannot be applied to this equivalent circuit. However, the Thevenin equivalent was found after linearizing the nonlinear PV cell equivalent circuit with the piecewise linear parallel branches model. The proposed new PV cell model is widely used in the analysis and simulation of PV systems. In this study, we focused on modeling and simulation of PV cell single diode equivalent circuits, taking into account linearized equivalent circuit parameters.

Maximizing power transfer from PV modules is essential for achieving high energy conversion efficiency, optimizing system performance, and ensuring the economic viability and longevity of solar energy installations. Advanced technologies and careful system design play crucial roles in achieving these goals in solar power applications. Proper system design, including module orientation, tilt angle, shading analysis, and optimal wiring configuration, contributes to maximizing power transfer efficiency.

The fill factor is directly affected by the series and shunt resistors and diode losses in the equivalent circuit of the PV cell. The fill factor is a critical parameter in assessing the efficiency, performance, and quality of photovoltaic devices. It plays a vital role in maximizing the energy conversion efficiency of solar cells and modules, thereby contributing to the overall success and adoption of solar energy technologies. As a result, the efficiency of the PV cell increases, and the output power approaches its maximum value.

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