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TOKAT GAZİOSMANPAŞA UNIVERSITY

GRADUATE EDUCATION INSTITUTE

DEPARTMENT OF ELECTRICAL ENGINEERING

MASTER DEGREE

COMPARISON OF THE MODELS DEVELOPED FOR PV MODULE/CELL PARAMETER EXTRACTION

MASTER THESIS

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Supervisor: Prof. Dr. Ulaş EMİNOĞLU

TOKAT- 2022

SCIENTIFIC ETHICS PAGE

According to the thesis writing guide of Tokat Gazoosmanpasa University Natural and Applied Sciences, I declare that my Master thesis titled " Comparation of the Models developed for PV Module/Cell Parameter Extraction", which I have prepared under the consultancy of *Prof. Dr. Ulaş EMİNOĞLU*, is an original study that complies with scientific ethical values and rules, and I will accept all kinds of legal sanctions if it is determined otherwise.

Mona İbrahim HUSSEIN

17/06/2022

ÖZET

FOTOVOLTAİK (PV) HÜCRELERİN/MODÜLLERİN EŞDEĞER DEVRE PARAMETRELERİNİN BELİRLENMESİ

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Haziran 2022, ix + 34 sayfa

Bir fotovoltaik (PV) modül için elektrik devresi parametrelerinin belirlenmesi ve akım-gerilim eğrilerinin çizilmesi verimlilik analizi açısından büyük önem taşımaktadır. Bu nedenle mevcut çalışmada, tek diyot devre modelinin bilinmeyen değişkenlerinin belirlenmesi için önerilen analitik çözüm yöntemlerinin performans analizleri yapılmıştır. Modellerin doğruluğu tek, çift ve üç diyotlu eşdeğer devre modelleri için elde edilen sonuçlarla test edilmiştir. Karşılaştırma amacıyla, analitik, kısmi arama tabanlı ve meta-sezgisel yöntemler uygulanarak ilgili literatürde yaygın olarak çalışılan birçok PV Modülü kullanılmaktadır. Karşılaştırmalarda çıkış gücü ve akımına (P-V ve I-V) ait sistem eğrileri de dikkate alınmıştır. Hesaplanan ve gerçek veriler arasındaki Hata Ortalama Karekök Hata Değeri (Root Mean Square Error; RMSE) ve Belirleme Katsayısı (Coefficient of Determination; R2) değerleri de karşılaştırma için kullanılmıştır. Yapılan analizler sonucunda parametre tahmininde avantaj sağlayan model/modeller saptanmıştır.

Anahtar Kelimeler: Analitik Yöntemler, Güvenilirlik Analizi, Parametre Kestirimi, PV Modül.

ABSTRACT

COMPARİSON OF THE MODELS DEVELOPED FOR PV MODUL/CELL PARAMETER EXTRACTİON

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For a photovoltaic (PV) module, determination of its electrical circuit parameters and plotting their current-voltage curves is of great importance in terms of efficiency analysis. Therefore, in present work, performances analysis of analytical solution methods suggested for determining the unknown variables of single-diode circuit model have been done. The accuracy of the models is tested through the results obtained for single-, double- and three-diode equivalent circuit models. Several PV modules, which are widely studied in the related literature by applying analytical, partly-search based, and meta-heuristic methods are used for comparison purposes. The system curves that belong to the output power and current (P-V and I-V) are also considered in comparisons. The Root Mean Square Error (RMSE) and the Coefficient of Determination (R2) values between calculated and real data are also used for comparison and the model/models which has advantage for parameter estimation is founded.

Keywords: Analytical Methods, Reliability Analysis, Parameter Estimation, PV Module.

ACKNOWLEDGEMENT

To God, for giving the wisdom, strength, support and knowledge and blessing me with this education. I would like to express my deep gratitude to my thesis supervisor, Prof. Dr. ULAŞ EMİNOĞLU, for his guidance, support, and constant supervision as well as for providing necessary information regarding this thesis. I'm extremely grateful for my parents for their love, support and prayers. I'm very much thankful for my dear and beloved husband, his love and support gave me strength to complete this thesis. Last but not least, my warm and heartfelt thanks go to my sisters for their support, prayers and hope that they had given to me.

MONA IBRAHIM HUSSEIN

17 Haziran 2022

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1. INTRODUCTION

PV modules have become preferred energy sources in energy production systems in independent or interconnected networks as a result of the reduced production costs of PV cells in line with the advances in technology today; and a realistic modeling is very important for effective evaluation (Lehtola & Zahedi, 2019: 25-31). Furthermore, in terms of design and dimensional properties, system curves that belong to the output power and current (P-V and I-V) in accordance with equivalent circuit parameters are very important. In the literature, two types of electrical circuit models which has five and seven parameters are generally used. For example, in Reference (Chan & Phang, 1987: 286-293), a PV cell was examined separately with both five-parameter and seven-parameter models using experimental data. There are analytical and numerical solutions for both models, where various methods can be applied (Shongwe & Hanif, 2015: 938-946). In the study of two commercial PV modules, different methods, which were developed for determination of single-diode five-parameter equivalent circuit model parameters, were compared. The shunt and series resistance model, which takes into account the standard test conditions (STC) and temperature-dependent saturation current, of the equivalent circuit is given in (Sera, et al., 2007: 2392-2396) , and some terms were neglected in the equations set. However, analytical solutions for such systems are not feasible due to the nonlinear equations and the large number of unknown variables. Therefore, a solution method for single-diode model is given in (Reis, et al., 2017: 634-639) and it was showed that the Newton-Raphson method can easily be used for the solution. However, despite its results with high accuracy, the Newton-Raphson method is disadvantaged here, because of to the increased number of steps required for the solution, which increases the execution time. (Patel, 2016: 7034-7039), who included Lambert W function in his study, have reduced the execution time by a new method, which incorporates analytical methods together with numerical methods. (Kareem & Saravanan, 2016: 2028-2041), the Gauss-Seidel method was used for the solution in determining the equivalent circuit parameter, and the initial values were determined by analytical approaches since the initial conditions affect the performance of the Gauss method considerable. Similarly, an analytical method consisting of three equations using the equivalent circuit was developed (Atay & Eminoglu, 2019: 3026-3039) and validated with the help of the results given in the literature for many of the commercial PV modules. In addition to these studies, different sets of equations were also created for the single-diode model, in which one of the parameters is considered constant. For example, other parameters were determined according to the shunt resistance (Chaibi, et al., 2018: 376-386). But it is well-known that the shunt resistance is one of the basic parameters and is unknown initially. In other words, it was assumed that the shunt resistance can be initially obtained by experimentally. A similar equivalent circuit based analytical model was given in Reference (Cubas, et al., 2013: 873-877) and the results obtained for the two known commercial PV modules were tested by making comparisons with the results available in the literature. Although the diode ideality factor is a main unknown variable, it is defined as an input parameter. And its value is considered in the range of 1-1.5. (Eminoglu & Atay, 2021), an analytical solution method is suggested for determining the unknown variables of single-diode circuit model. Firstly, a mathematical relation is established using the curve fitting method between the photon current (I_{pv}) and short-circuit current (I_{sc}) for several PV modules available in the literature. Then, an analytical model consisting of a set of equations with three unknowns (R_p, R_s and a) is developed using this developed relation between the currents. The accuracy of the model is tested through the results obtained for single-, double- and three-diode equivalent circuit models.

In addition to these models, it is also possible to model the variables depending on the ambient temperature. In the temperature-dependent model, however, solar heat becomes an important factor in the measurement results (I-V, P-V characteristic) given by the manufacturer, and makes analysis difficult (Farivar & Asaei, 2010: 929-934). The main difference between the double- and the single-diode model is related to the differences in the number of parameters and the accuracy of the calculated parameters. A comparative review of both main models was carried out in Reference (Shannan, et al., 2013: 210-214). When the analysis of the differences between the models was performed by considering the accuracy and execution times, it was found from the calculations that the double-diode model with seven parameters provided a better accuracy but asked for a higher execution time. Similarly, in their study, (Yahfdhou, et al., 2016: 247-260)simulated a PV cell in a hybrid system by solving both models with a numerical solution method. As a result of the analysis, it was concluded that the unknown parameters could be determined in a shorter time thanks to the fewer parameters, but the double-diode model was found to be more favorable in terms of accuracy. It is well-known that initial values are difficult to determine in numerical studies. For this reason, the validity of different commercial PV cells was tested by using the experimental data in approximate analytical solutions (Hejri, et al., 2014: 915-923) to determine the initial values of the double-diode model. Additionally, the single-diode model was also analyzed in (Hejri, et al., 2014: 915-923). In the model, some small-valued terms and diode saturation current in the set of equations were neglected to decrease the unknown parameters. (Mohapatra, et al., 2017: 2392-2400), five non-linear basic equations were created from the PV equivalent circuit and these equations were solved for a commercial PV module using a solution technique in the MATLAB platform. The model was validated by an experimental system.

Meta-heuristic methods are widely used to achieve optimal solutions in multi-parameter complex systems. Therefore, many studies are available in the literature using this type of optimization techniques to find equivalent circuit parameters of PV modules [18-24, 28-30]. Using the genetic algorithm (Kennedy & Eberhart, 1995: 1942-1948), unknown parameters of the single-diode model were calculated in Reference (Zagrouba, et al., 2010: 860-866), and it was concluded that this meta-heuristic method is very favorable for such problem. In a study where the Particle Swarm Optimization Algorithm (Storn & Price, 1997: 341-359) was first applied for this problem (Sandrolini, et al., 2010: 442-451) , double-diode equivalent circuit model parameters were determined using experimental measurement data for the PV module. This optimization algorithm was also applied to determine the parameters of the single-diode circuit (Muralidharan, 2017: 509-513), single- and double-diode circuits (Ishaque & Salam, 2011: 2349-2359) with a similar approach. The results obtained in both studies were tested with the help of experimental data and the results available in the literature. Another optimization technique, called differential development algorithm (Saravanan & Panneerselvan, 2013: 16-19), was applied for the estimation the value of five parameters (Li, et al., 2019: 465-474). The developed model was tested with the help of experimental data and the reliability of the results was presented. The Memetic Adaptive Differential Evolution technique was used for parameter estimation in Reference (Elazab, et al., 2020: 1-15). In the study, the value of seven parameters were determined for the PV modules which are commonly used in the literature, and the reliability of the model was demonstrated by comparing the obtained V-I characteristic with the measured data. In addition, the three-diode circuit model was used in Reference (Goldberg, 1989) instead of the single- and double-diode equivalent circuits. The validity of the model was tested using experimental data by determining the equivalent circuit parameters and V-I characteristics for the PV modules. The Grasshopper Optimization Algorithm was applied to determine the parameters of the equivalent circuit model, and the Root Mean-Square Error (RMSE) value, which was determined using V-I characteristic values calculated according to experimental data and circuit parameters, was used as the target function. In addition to single optimization-based algorithms, parameter estimation studies using multiple optimization-based methods are also available in the literature. In the study in Reference (Castro, 2018: 230-238), a GA-PSO-based hybrid algorithm was used to determine single-diode circuit model parameters. In their analysis, it was concluded that the hybrid approach was more advantageous than the GA-based method. In Reference (Hamid, et al., 2016: 1-21), Artificial Neural Network (ANN) was applied for parameter estimation, and its performance was compared with an analytical method. Results shows that the ANN-based model was unfavorable in terms of computational time and applicability, although the ANN-based model seems to give more favorable results for the parameters and maximum power estimation. An algorithm developed using both Nelder-Mead and PSO methods was implemented in reference (Tong & Pora, 2016: 104-115) for the two-diode equivalent circuit model. The developed algorithm was validated for some commercial PV modules with the help of results which were obtained by using meta-heuristic methods.

Besides the use of meta-heuristic methods, parameter estimation for PV modules using search-based algorithms are also stated in the related literatures which used in this study. For the single-diode model, an equation reduced to a resistor in series (R_s) is given in the algorithm (Rasool, et al., 2017: 519-530). Where other equivalent circuit parameters were determined according to the parameter values that satisfies the equality found by making a search for the diode ideality factor for values in the range of 1-2. Another study (Bencherif & Benouaz, 2018: 1-18) performs a similar parameter estimation, where the equations were reduced to the equivalent circuit shunt resistance (R_p) parameter. For each diode ideality factor (a) value taken in the study, R_p and the remaining parameters are calculated. The termination of the algorithm is done by considering the error value defined between the maximum power and its actual value. An approach for the two-diode model with seven parameters is given in Reference (Vilalva, et al., 2009: 1198-1208). In the proposed algorithm, serial resistance (R_s) is defined as an independent parameter, and the remaining parameters are calculated according to the selected serial resistance in each iteration. Operations are repeated until the calculated value of the selected series resistance becomes equal to its value in the algorithm. Similarly, (Pelap, et al., 2016: 84-92) provides a search-based algorithm that searches for the real solution, according to the equivalent circuit serial resistance (R_s). In the algorithm, the value of the unknown parameters is searched in accordance with the maximum power point. The validity analysis of the model was performed using experimental output current and output power data for numerous PV modules.

2. GENERAL INFORMATION ABOUT PV MODULES

2.1 PV Module

In 1839, Alexandre-Edmond Becquerel finds out that when some materials are exposed to light, they create an electrical charge. Even though the original solar panels were inefficient enough to power only basic electrical equipment, they were used as a light meter. Becquerel's finding was not repeated until 1873, when Willoughby Smith found that the charge could be created by light striking selenium. Following Smith's discovery, William Grylls Adams and Richard Evans Day published "The effect of light on selenium" in 1876, detailing the technique they performed to repeat Smith's findings. In 1881, Charles Fritts created the first commercial solar panel, describing it as "continuous, consistent, and of great force not only by exposure to sunshine but also by exposure to dim, dispersed lighting." These solar panels, however, were inefficient when compared to coal-fired power plants. In 1939, Russell Ohl developed the solar cell idea that is now utilized in solar panels. He was granted a patent for his invention in 1941. In 1954, Bell Labs exploited this concept to create the first commercially effective silicon solar cell. Mohamed M. Atalla pioneered the silicon surface passivation by thermal oxidation process at Bell Labs in 1957. Since then, surface passivation has been critical to solar cell efficiency.

Solar photovoltaic (PV) systems are one type of renewable energy system that is essential for generating electricity from solar radiation. It is the main unit of a PV array and is made up of numerous PV cells. Its function is to generate direct current electricity in the presence of un-concentrated sunlight, as the solar panel acts as a receptacle for sunlight and transforms incident photons to electric power. A solar inverter converts the energy produced by the panel from direct current (DC) to alternating current (AC). A photovoltaic module is a device that connects a number of solar cells electrically and mounts them in a support structure or frame. Solar PV systems are a highly stable and clean source of power that may be used for a variety of purposes including dwelling, industry, agriculture, livestock, and so on.

Solar PV systems are made up of several components that should be chosen based on your system type, site location, and uses.

Solar charge controller, inverter, battery bank, auxiliary energy sources, and loads are the primary components of a solar PV system (appliances).

- Solar charge controller - controls the voltage and current from the PV panels to the battery, preventing overcharging and extending battery life.
- Inverter - transforms the DC output of PV panels into a clean AC current that may be used in AC appliances or supplied back into the grid line.
- Battery - When there is a demand for energy, it is stored and used to power electrical equipment.
- Load - is any electrical device that is linked to a solar PV system, such as lights, radios, televisions, computers, refrigerators, and so on.
- Auxiliary energy sources - is a diesel generator or another form of renewable energy.

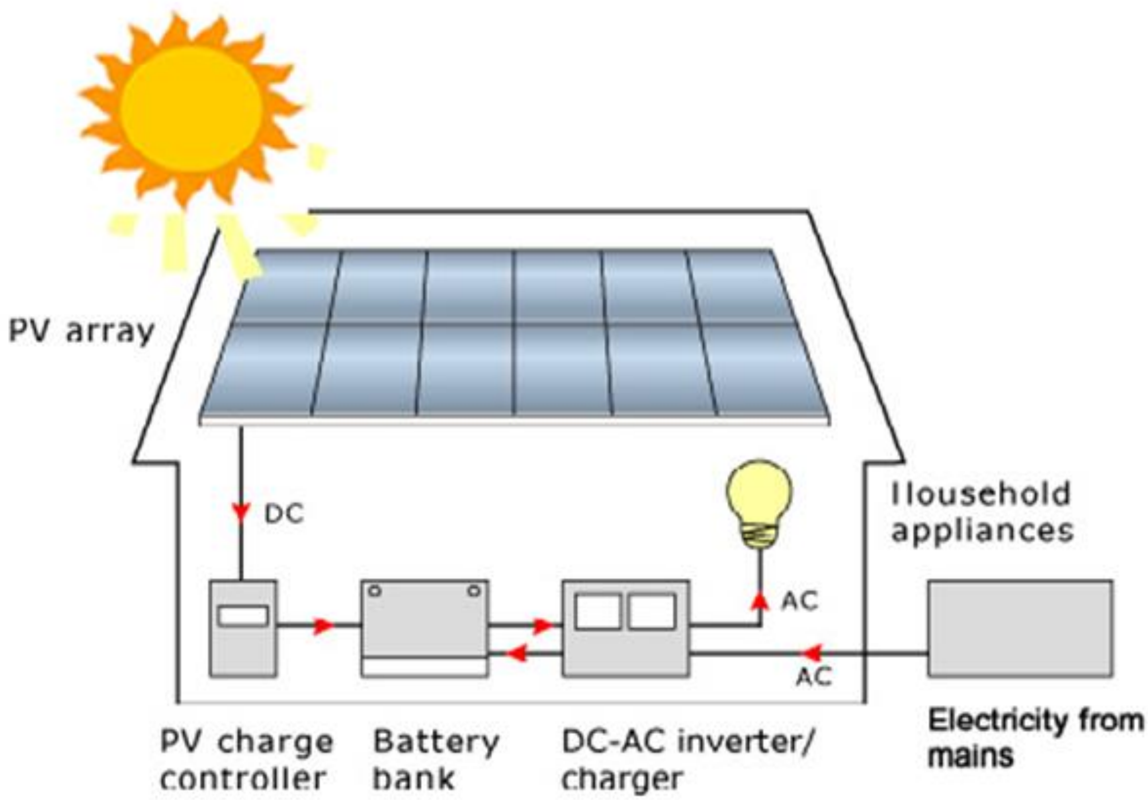

Figure 2.1 Solar PV system components

2.2 Types of PV Panels

Solar panels are classified into three types: monocrystalline, polycrystalline, and thin-film. Each of these solar cells is manufactured uniquely and has a distinct appearance.

2.2.1 Monocrystalline panels

are the most sophisticated and oldest form of solar panels. Monocrystalline Solar Panels, as the name implies, are constructed of one (mono) crystal (crystalline) silicon solar cells. Pure silicon is made into bars and sliced into wafers to produce these solar cells. The cell edges are chopped off, smoothed, and rounded during this operation to assist the solar cells produce even more power. Although time-consuming and inefficient, this provides the monocrystalline cells a distinct look. Monocrystalline Solar panels are high-quality panels made from the purest silicon. Although monocrystalline cells are more costly, they have a longer lifespan and greater efficiency. Because the cells are made of a single crystal, they produce more power. Furthermore, Monocrystalline cells have a black and uniform finish. As a result, they are the clear choice for anybody seeking for a modern black solar panel.

2.2.2 Polycrystalline panels

Polycrystalline panels, sometimes known as "multi-crystalline" panels, are frequently regarded as the mid-range panel. Polycrystalline solar panels are the less expensive choice, but being less efficient. Polycrystalline cells, like monocrystalline panels, are constructed of silicon. Polycrystalline cells, on the other hand, are created from multiple (Poly) pieces of silicon crystal fused together. As a result, polycrystalline solar panels are less efficient and have a shorter lifespan. That is, they do not generate as much power from the sun as Monocrystalline panels for as long. Because there are numerous crystals in each cell, the electrons have less flexibility to travel. Polycrystalline cells, unlike their monocrystalline counterparts, do not require each of the four sides to be sliced. This is better for the environment because it reduces waste. Overall, the method is quicker and less expensive than producing monocrystalline panels. These wafers are then joined to make a polycrystalline panel. Polycrystalline cells are distinguished by their blue appearance, rectangular form, and speckles. They seem blue and speckled because each cell contains several crystals and the sunlight reflects off these crystals.

2.2.3 Thin-film solar panels

Thin-film solar panels, as opposed to monocrystalline and polycrystalline solar panels, are thin, flexible, and have a low profile. This is due to the fact that the cells within the panels are about 350 times thinner than the crystalline wafers used in monocrystalline and polycrystalline solar panels. Thin-film solar panels are created by layering semiconducting materials including silicon, cadmium telluride, and copper indium gallium selenide. The semi-conductor layer is sandwiched between two transparent conducting layers, with a glass layer on top to assist catch sunlight. Although silicon is used to manufacture thin-film solar panels on occasion, it is not the same as solid silicon wafers. It is, instead, a non-crystalline silicon. When compared to crystalline panels, thin-film solar panels have poorer efficiency and power capabilities. With efficiency of roughly 11%, they require a lot more roof space to generate a lot of solar energy. They also tend to decay faster than crystalline panels, resulting in the shortest warranties. Nonetheless, thin-film panels have a position in the solar business. Thin-film panels, since they are more flexible, may be employed for a wide range of applications. Solar panels may also be formed into shingles or solar roof tiles, allowing property owners who dislike the look of solar panels to go solar.

Figure 2.2 Three types of PV panel.

2.3 Types of Solar Power System

Solar power systems are broadly classified into three types:

2.3.1 Grid-tied solar power system

This is the most prevalent sort of solar power system. A grid-tied or grid-connected solar power system, as the name implies, is one that is linked to both the home and the regular electrical utility grid. There is no storage battery in this sort of solar power system.

All of the appliances utilize the solar power generated by the solar panels in real time. If the solar power system produces more energy than the residence consumes, the extra energy can be sold back to the utility company through a process known as net-metering. When the solar power system does not produce enough electricity, the appliances take balancing power from the utility grid. This system involves a few panels, wire boxes, disconnects, and an inverter.

Advantages:

1. The initial cost of purchasing a solar power system for your house might be rather high. However, grid-tied systems are substantially less expensive than other forms of rooftop solar electricity since they need less equipment.
2. Low running costs: Grid-connected systems have relatively low operating costs. Solar panels are warranted for 20 to 25 years.
3. Grid-connected systems are easy and have no downtime (without electricity).
4. You have the option of designing your system with both an alternative energy source and a utility source. This allows you to modify the system in the future to match your needs.

Disadvantages:

The disadvantage of this form of solar power system is that when the sun goes down, you cannot use any of the energy produced by the solar panels. If your power goes out, your solar panels will be turned off automatically, leaving you without power. This will undoubtedly affect your daily existence.

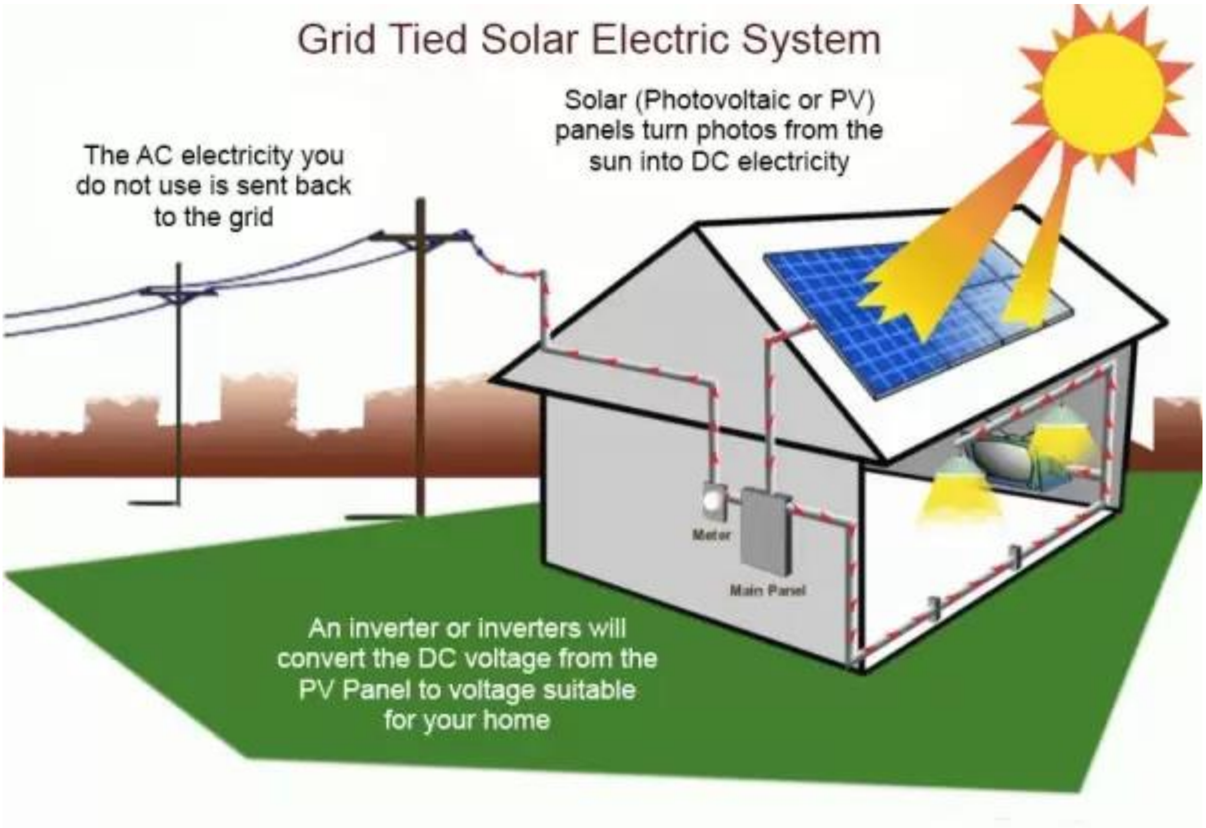

Figure 2.3 Grid-tied solar power system.

2.3.2 Off-grid solar power system

As the name implies, an off-grid solar power system is a totally autonomous solar power system with energy storage that is not linked to the main utility grid. In an off-grid solar power system, the only source of electricity is the solar panels. This energy is either sent to the appliances or saved in the battery for later use. Off-grid solar power systems are suited for isolated rural locations or applications where traditional sources of electricity are either unavailable or prohibitive. Off-grid solar power systems can be either AC-based, which contain an inverter that converts the energy stored in batteries to AC power and feeds it to AC appliances, or DC-based, which are less expensive since they do not require an inverter but can only power DC products. Because it is not connected to the electric grid, this sort of system is more costly. This necessitates the installation of more solar panels and batteries.

Advantages:

1. One of the finest aspects of this form of solar power system is that you are not reliant on a utility provider. You are not bound by the utility company's terms and conditions.

2. No blackouts: Another advantage is that even if everyone else's power goes off, your home will remain fully operational. This is critical for persons with medical issues who necessitate the use of electronic equipment or refrigerated medications.

3. No more utility bills: Because you generate your own power, you will never have to pay a utility bill again.

Disadvantages:

1. Higher initial cost: If you do not have a utility connection, you will require a backup battery when there is no sun. Adding this backup source will raise your costs.

2. You may run out of stored electricity if the weather is gloomy or wet for a few days.

3. Energy efficiency is essential: You must be extremely cautious with your energy consumption, or your home may not have adequate electricity.

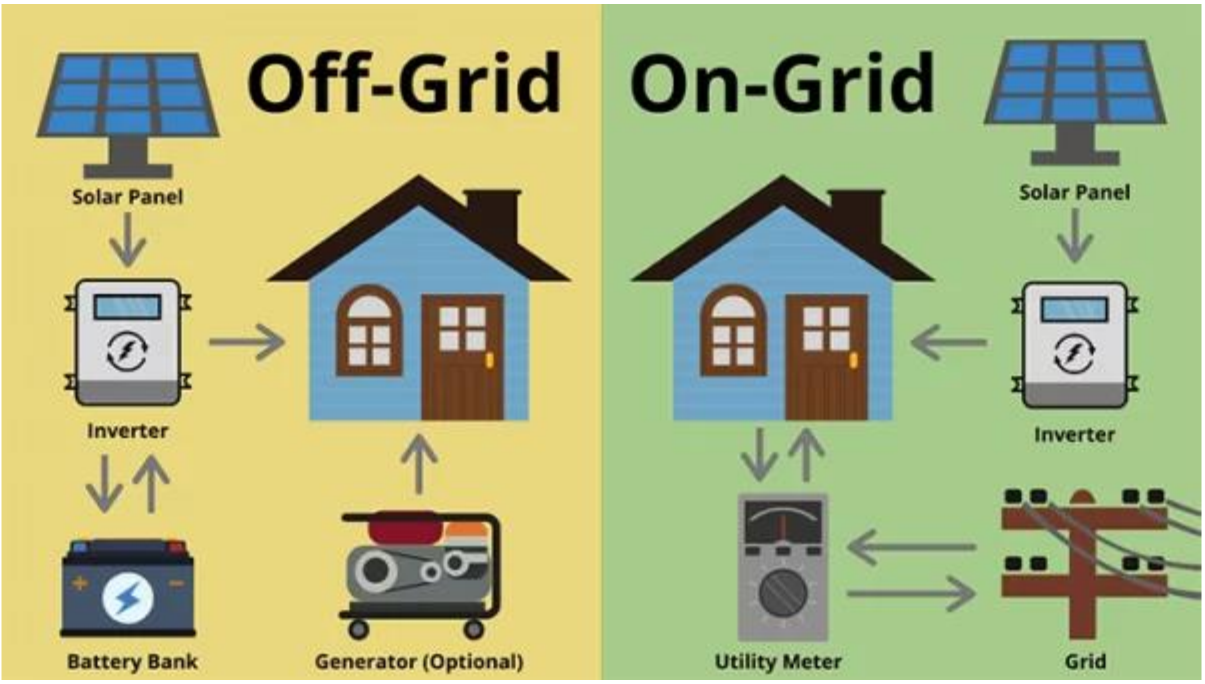

Figure 2.4 Off-grid and on-grid solar power system.

2.3.3 Hybrid solar power system

A hybrid solar power system is a solar power system with energy storage that is comparable to a grid-tied solar power system but includes an energy storage system, often in the form of battery backup. Even though it is more expensive, this form of solar power system has grown in popularity in recent years. When solar energy output exceeds demand, the excess is used to charge batteries and stored for later use. When production falls short of demand, the stored energy in the batteries is utilized to make up the difference. A well-designed hybrid solar power system offers you the dual advantage of lowering your electricity costs while also providing you with the security of having backup power during a power outage. A hybrid system includes of a PV array, a charge controller, a battery bank and inverter, and, in certain cases, a tertiary power source such as a wind turbine or a gas engine.

Advantages:

1. Excess energy from your solar power system may be stored in the battery. So, you can power your home even when there is no sunlight. If there is a power outage, your house will remain operational for several hours.
2. Save money: The battery can give extra possibilities to save money since your energy storage system can ensure that you are utilizing its power rather than grid electricity.

Disadvantages:

1. Cost: The system is more expensive because the batteries must be changed on a regular basis. Although the price of batteries has decreased in recent years, they must still be changed at some time.
2. High-level expertise: Because this solar power system is more sophisticated, it may necessitate the services of a solar installer with a higher degree of skill to design and install it. So, check with your solar power business to see whether they install this sort of system.

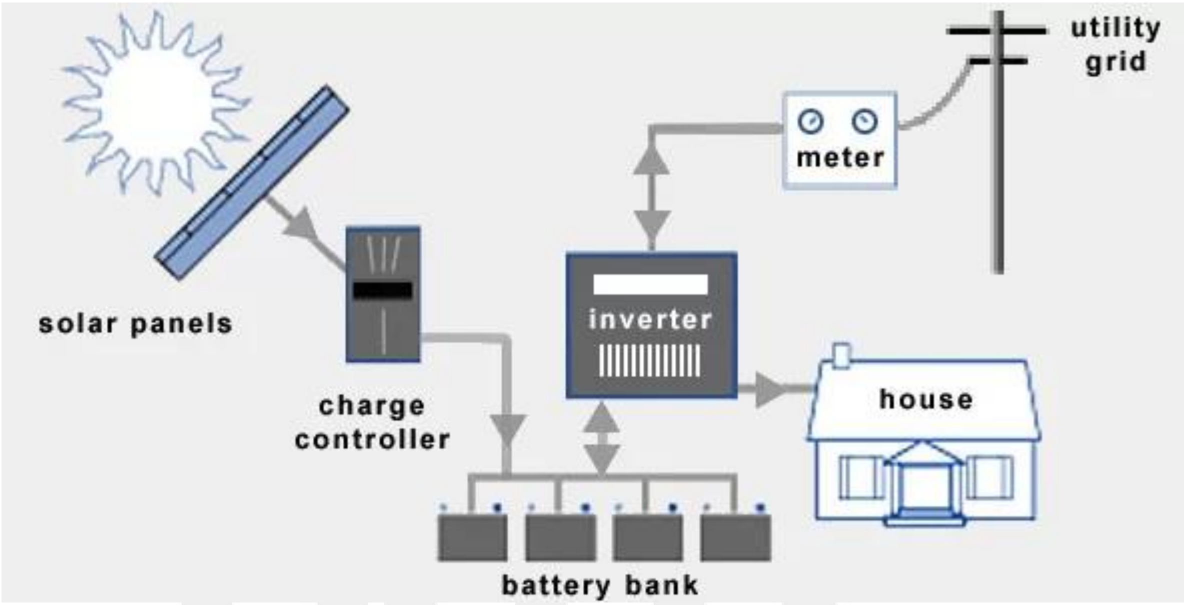

Figure 2.5 Hybrid Solar Power System.

2.4 Photovoltaic Cell Voltage

Regardless of size, a single photovoltaic solar cell may produce a "Open Circuit Voltage" (VOC) of roughly 0.5 to 0.6 volts at 25oC (usually around 0.58V). This cell voltage is relatively constant as long as there is sufficient irradiance light, ranging from dim to bright sunshine. Open circuit voltage indicates that the PV cell is not linked to any external load and so does not generate any current flow. When connected to an external load, such as a lamp, the output voltage of the individual cell reduces to roughly 0.46 volts or 460 mV (460 millivolts) as the electrical current flows, and will remain around this voltage level regardless of the intensity of the sun. This drop in output voltage is produced by resistance and power losses inside the cell structure, as well as metallic conductors placed on the cell surface. The output voltage of a solar cell is also affected by temperature. As the cell degrades under hot conditions, the output voltage of the cell decreases as the temperature rises. As a result, under full daylight, the output voltage drops by around 5% for every 25° C rise in cell temperature. In order to counterbalance power production losses caused by high temperatures, solar panels and modules with more photovoltaic cells are advised for very hot regions than for colder climates.

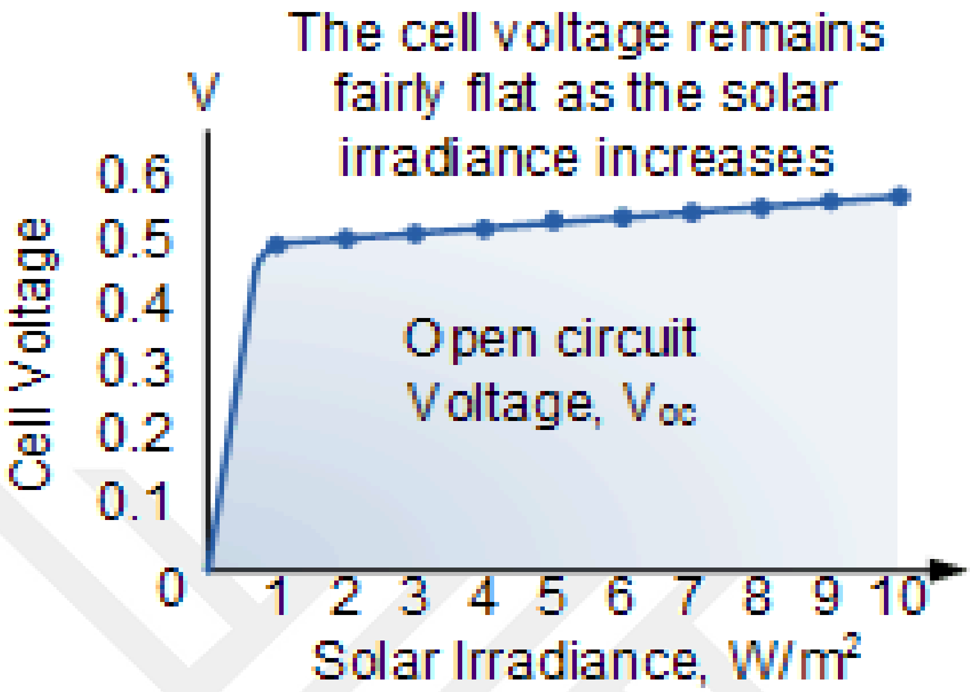

Figure 2.6 Photovoltaic cell voltage

2.5 Photovoltaic Cell Current

Unlike the voltage of a photovoltaic cell, the output DC current (I) varies in direct proportion to the amount or intensity of sunshine (photon energy) falling upon the PV cell's face. Furthermore, the output current is directly proportional to the cell surface area, as the larger the cell, the less energy enters it. The more sunlight that enters the cell, the more current it generates. Photovoltaic cells with high current outputs are more desired in general, however the greater the current output, the higher the cost.

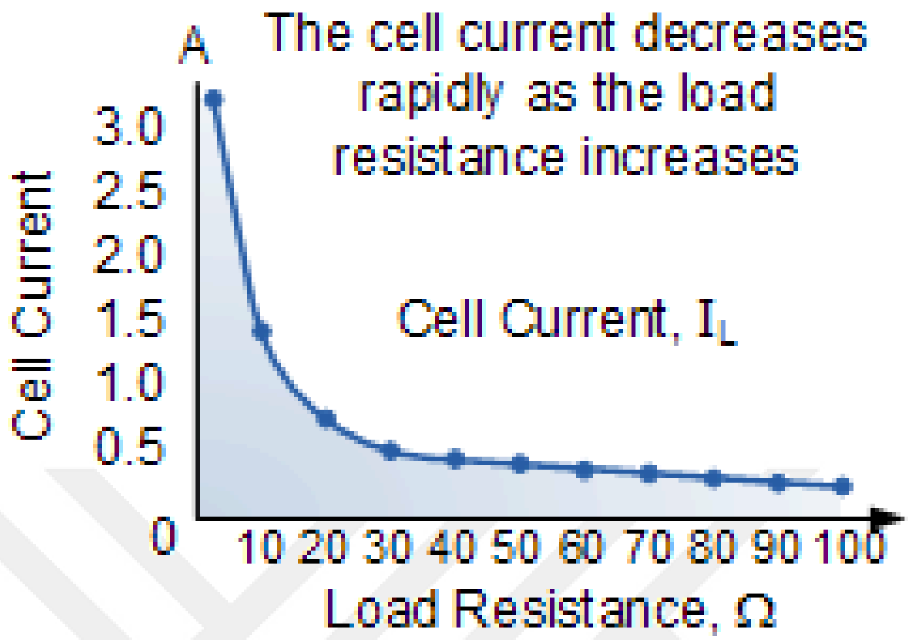

Figure 2.7 Photovoltaic cell current.

2.6 PV Panel Power Output

The power output of a photovoltaic solar cell is expressed in watts and equals the product of voltage times current (V x I), which is correct. At typical operating temperatures, the optimal working voltage of a PV cell under load is around 0.46 volts, providing a current of roughly three amps in full sunshine. Power (P) equals voltage times current = V x I = 0.46 x 3 = 1.38 watts. While 1.38 watts of solar electricity may be sufficient to operate a tiny electrical item such as a phone charger or attractive garden light, it is insufficient to perform any useful job. Individual solar photovoltaic cells, on the other hand, can be electrically linked in series (daisy chained) to obtain the necessary voltage as series voltages accumulate, or connected in parallel (side by side) to produce the desired current as parallel currents add. Then, any combination of two or more PV cells may be linked in series and/or parallel to produce any desired voltage, current, and power output, resulting in a photovoltaic panel. In practice, the solar cell runs in the linear portion of its I-V characteristic curve, supplying roughly the same current as a short circuit. P = V x I is the power provided by the PV panel to a battery and load connected in parallel with the panel.

3. PARAMETER ESTIMATION MODELS FOR PV CELLS/MODULES

Figure 3.1 refers the single-diode model with five unknown parameters for one PV cell/module (Hejri, et al., 2016: 396-410). Here I_{pv} is photon current produced by the cell, serial and parallel resistances are referred by R_s and R_p, respectively. Diode current in equivalent circuit is defined by

$$I_d = I_o(e^{\frac{V_d}{aV_t}} - 1) \tag{3.1}$$

where I_o is diode leakage current, diode ideality factor is showed by a, and V_d is diode terminal voltage. The thermal voltage on the diode is referred by V_t ($V_t = kN_sT/q$). The number of cells for one module is denoted by N_s, the Boltzmann constant is showed by k, and q shows the electron load. The final term, T shows the cell temperature (Hejri, et al., 2016: 396-410).

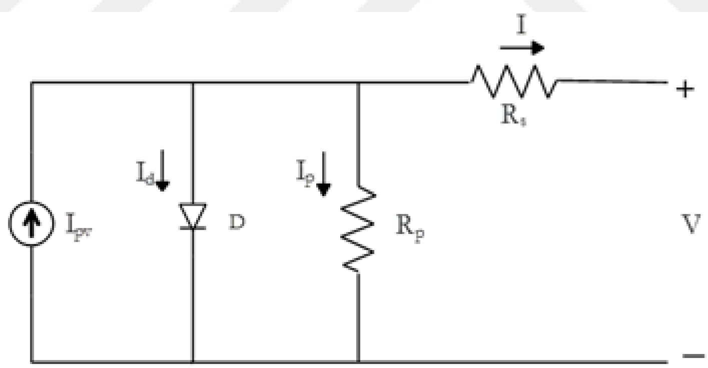

Figure 3.1 Single-diode five parameters equivalent circuit model for PV Modules/Cells

As the solar energy systems become popular nowadays, determining the parameters of a PV Cell/Module using experimental data is important for designing and evaluating the efficiency of the PV panels that indicated in literatures. Therefore, the validity of the models was analyzed for numerous PV modules. The test data, presented with the results, for the PVs used were taken from the studies given in the literature. Newton-Raphson method (Matlab, 2010) was used to solve the equations related to the developed model, and calculations were performed in Matlab (M. khalid, et al., 2019: 1-12). Table 3.1-3.3 show single-diode equivalent circuit parameters obtained under standard test conditions for SW255, KC200GT and MSX120 PV modules, respectively, using the models given in literatures. The results obtained by some of the analytical methods in the literature are given separately for comparison purposes. As shown in Table 3.1, the equivalent circuit parameters set for the SW255 PV module do not exactly correlate with the parameters given in Reference (Chaibi, et al., 2018: 376-386). This is due to the parallel resistance (R_p), determined by experimental measurements and used as input parameter in Reference (Chaibi, et al., 2018: 376-386). The parameter values obtained by the model given in the Reference (Chaibi, et al., 2018: 376-386) using the value of R_p=2245 Ω as an input parameter are given in the last line in Table 3.1, and it is observed that they completely match the results of the model (Sera, et al., 2007; Kareem & Saravanan, 2016; Atay & Eminoglu, 2019; Cubas, et al., 2013 and Eminoglu & Atay, 2021). In Table 3.2, the equivalent circuit parameters extracted for the KC200GT are given together with the parameter values specified in Reference (Cubas, et al., 2013: 873-877). The reason for the difference between the results obtained by other analytical methods is due to the diode ideality factor (a), considered a known parameter and used as input data in Reference (Cubas, et al., 2013: 873-877). The parameter values determined by using a=1.376 as an input parameter in the model given in Reference (Cubas, et al., 2013: 873-877) are stated in the last column in Table 3.2. In this case, it is clear that the results obtained from the methods given in (Sera, et al., 2007; Kareem & Saravanan, 2016; Atay & Eminoglu, 2019; Chaibi, et al., 2018; Cubas, et al., 2013) correlate with each other. Table 3.3 shows the extracted parameters for the BP-MSX120. The parameter values calculated in the Reference (Hejri, et al., 2016: 396-410) for this PV module, and the parameter values obtained by applying the proposed analytical methods in the Reference (Kareem & Saravanan, 2016; Atay & Eminoglu, 2019; Chaibi, et al., 2018; Cubas, et al., 2013; Eminoglu & Atay, 2021 and Mohapatra, et al., 2017)are given separately for comparison purposes. As can be seen from Table 3.3, the determined parameter values and the parameter values obtained by using other models (Kareem & Saravanan, 2016; Atay & Eminoglu, 2019 and Mohapatra, et al., 2017), and the results given in Reference (Hejri, et al., 2016: 396-410) are completely consistent. However, these models were found to have some disadvantages when compared with the models (Kareen & Saravanan, 2016 and Atay & Eminohlu, 2019) in practice. For example, when the results given in Reference (Hejri, et al., 2016: 396-410) are substituted in the equations in the model, it is seen that the equations are not satisfied. Therefore, it is possible to state that the equations of the model are incorrect. The parameters of the model given in Reference (Mohapatra, et al., 2017: 2392-2400) was found to be quite dependent on the initial values, and requires functional software/tool to achieve realistic results under initial conditions, which are not too close to the solution. Although the same results are obtained using the models given in the References (Sera, et al., 2007; Chaibi et al, 2018 and Cubas, et al., 2013), these methods have some handicaps. The model given in (Sera, et al., 2007: 2392-2396) needs initial values for a, R_s and R_p parameters. In addition, the model developed in (Chaibi, et al., 2018: 376-386) uses the value of R_p as an input parameter but it is an unknown parameter and that are not available in estimation application. Similarly, the model given (Cubas, et al., 2013: 873-877) uses the diode ideality factor as an input parameter which is unknown and must be determined. Therefore, it is possible to say that these methods are more unfavorable as compared to methods proposed in(Kareen & Saravanan, 2016 and Atay & Eminohlu, 2019). On the other hand, it is seen from the tables that the methods given in (Eminoglu & Atay, 2021) and (Tong & Pora, 2016: 104-115) do not give fully realistic results for some PVs.

Table 3.1 Extracted parameters for SW255 PV Module

PV Module	SW255 PV Module (Chaibi, et al., 2018)										
Parameters	V_{oc} (V)	I_{sc} (A)	V_{mpp} (V)	I_{mpp} (A)	N_s	P_m (W)	R_s (Ω)	R_p (Ω)	a	I_o (nA)	I_{pv} (A)
(Chaibi, et al., 2018)	38	8.88	30.9	8.32	60	255	0.203	6300	1.264	0.304	8.8800
Model (Sera, et al., 2007)	38	8.88	30.9	8.32	60	255	0.210	2570	1.248	23.17	8.8807
Model (Kareem & Saravanan, 2016)	38	8.88	30.9	8.32	60	255	0.210	2570	1.248	23.17	8.8807
Model (Atay & Eminoglu, 2019)	38	8.88	30.9	8.32	60	255	0.210	2570	1.248	23.17	8.8807
Model (Chaibi, et al., 2018)	38	8.88	30.9	8.32	60	255	0.211	2245	1.244	21.66	8.8808

Model (Cubas, et al., 2013)	38	8.88	30.9	8.32	60	255	0.211	2233	1.244	21.59	8.8808
Model (Eminoglu & Atay, 2021)	38	8.88	30.9	8.32	60	255	0.211	2245	1.244	21.66	8.8808
Model (Hussein, 2017)	38	8.88	30.9	8.32	60	255	0.191	812.7	1.264	29.67	8.8821

Table 3.2 Extracted parameters for KC200GT PV Module

PV Module	KC200GT PV Module (Cubas, et al., 2013)										
Parameters	V_{oc} (V)	I_{sc} (A)	V_{mpp} (V)	I_{mpp} (A)	N_s	P_m (W)	R_s (Ω)	R_p (Ω)	a	I_o (μA)	I_{pv} (A)
(Cubas, et al., 2013)	32.9	8.21	26.3	7.61	54	200	0.231	594.8	1.300	0.096	8.213
Model (Sera, et al., 2007)	32.9	8.21	26.3	7.61	54	200	0.217	951.9	1.342	0.171	8.2119
Model (Kareem & Saravanan, 2016)	32.9	8.21	26.3	7.61	54	200	0.217	951.9	1.342	0.171	8.2119
Model (Atay & Eminoglu, 2019)	32.9	8.21	26.3	7.61	54	200	0.217	951.9	1.342	0.171	8.2119
Model (Chaibi, et al., 2018)	32.9	8.21	26.3	7.61	54	200	0.217	951.9	1.342	0.171	8.2119
Model (Cubas, et al., 2013)	32.9	8.21	26.3	7.61	54	200	0.217	948.9	1.342	0.170	8.2119
Model (Eminglu & Atay,	32.9	8.21	26.3	7.61	54	200	0.217	1862	1.376	0.265	8.2109

2021)											
Model (Hussein, 2017)	32.9	8.21	26.3	7.61	54	200	0.201	396.9	1.342	0.170	8.2142

Table 3.3 Extracted parameters for BP-MSX120 PV Module

PV Module	BP-MSX120 PV Module (Hejri, et al., 2016)										
Parameters	V_{oc} (V)	I_{sc} (A)	V_{mpp} (V)	I_{mpp} (A)	N_s	P_m (W)	R_s (Ω)	R_p (Ω)	a	I_o (µA)	I_{pv} (A)
(Hejri, et al., 2016)	42.1	3.87	33.7	3.56	72	120	0.473	1365	1.396	0.323	3.871
Model (Sera, et al., 2007)	42.1	3.87	33.7	3.56	72	120	0.472	1365	1.398	0.322	3.871
Model (Kareem & Saravanan, 2016)	42.1	3.87	33.7	3.56	72	120	0.472	1365	1.396	0.322	3.871
Model (Atay & Eminoglu, 2019)	42.1	3.87	33.7	3.56	72	120	0.472	1365	1.398	0.322	3.871
Model (Chaibi, et al., 2018)	42.1	3.87	33.7	3.56	72	120	0.472	1365	1.398	0.322	3.871
Model (Cubas, et al., 2013)	42.1	3.87	33.7	3.56	72	120	0.472	1364	1.398	0.322	3.871
Model (Eminoglu & Atay, 2021)	42.1	3.87	33.7	3.56	72	120	0.475	1339	1.395	0.322	3.871
Model (Mohapatra, et al., 2017)	42.1	3.87	33.7	3.56	72	120	0.472	1360	1.398	0.325	3.871
Model (Hussein, 2017)	42.1	3.87	33.7	3.56	72	120	0.437	833	1.396	0.315	3.872

Secondly, the validity of the models for the MSX60, STP6-120/36 and PWP201 PV modules, which are widely used in such studies and have experimentally obtained I-V characteristics, was analyzed. Two different error indices; Root Mean Square Error (RMSE) (Chapra & Canale, 1988) (M. khalid, et al., 2019: 1-12) and Coefficient of Determination (R^2) (M. khalid, et al., 2019: 1-12) were used in the analyses. The parameter values for the MSX60 PV module at T=25 °C are given together with the parameter values calculated by applying the PSO algorithm from meta-heuristics methods in Reference (Muralidharan, 2017: 509-513) are presented in Table 3.4. As shown in the table, the results obtained by both methods are close to each other. The I-V characteristics obtained using these parameter values are given in Figure 3.2 together with the experimental data. The system curve that belongs to the output current (I-V) obtained by using results in (Kareen & Saravanan, 2016 and Atay & Eminohlu, 2019) is more consistent with the experimental data as compared to the curve generated by the results of the meta-heuristic method. This is clearly seen in the error indices given in Table 3.7. In Table 3.7, the first column shows the error rates for MSX60 PV module output current values. The RMSE and R^2 values are 0.0384 and 0.9989, respectively, for the output currents obtained using our results, which are very close to ideal values (0 and 1, respectively). Therefore, it is possible to state that the results of the PSO-based algorithm are more consistent with the experimental data than the output current values determined by Reference (Muralidharan, 2017: 509-513)

The equivalent circuit parameters were determined for the STP6-120/36 and presented in Table 3.5 together with the results given in Reference (Tong & Pora, 2016: 104-115) The I-V characteristic generated using these results is shown in Figure 3.3, together with the experimental results and the output current values given in Reference (Tong & Pora, 2016: 104-115). As shown in Table 3.5, obtained parameter values differ with the results obtained by the search-based algorithm, based on the diode ideality factor in Reference (Tong & Pora, 2016: 104-115). On the other hand, it is seen that the current-voltage characteristic obtained by the results of the models (Kareen & Saravanan, 2016 and Atay & Eminoglu, 2019) using Figure 3.3 largely matches the experimental data and the current values given in Reference (Tong & Pora, 2016: 104-115). This is also seen from the RMSE, R^2 error values calculated for the corresponding PV module and given in the second row in Table 3.7. Although the error values for the output currents given in Reference (Tong & Pora, 2016: 104-115) were slightly more favorable, it was observed that the same current values could not be obtained when the given equivalent circuit parameter values were used. This can be seen from the fact that R_p=9.745 Ω is not a suitable value for heat losses for V_{oc}=19.21 V voltage level.

Table 3.6 shows the equivalent circuit parameters obtained at 45 °C for the PWP201 PV module using the model developed in (Kareen & Saravanan, 2016 and Atay & Eminoglu, 2019). For comparison purposes, double-diode equivalent circuit parameters determined using the PSO method in Reference (Nones, et al., 2018: 774-791) is given separately in Table 3.6. The parameter values obtained by both methods are close to each other. The curve that belongs to output current created by using the specified parameter values are shown in Figure 3.4 together with the experimental measurement results. The current-voltage characteristic curved by using the results given in (Kareen & Saravanan, 2016 and Atay & Eminoglu, 2019) is consistent with the experimental data and the current values of the double-diode equivalent circuit. This is also evident from the RMSE and R^2 error values, given in the third row in Table 3.7, calculated using experimental data. The error values for the results of both models indicate that output curve has a higher goodness of fit. Moreover, it can be stated that the output current values of the model results given in (Kareen & Saravanan, 2016 and Atay & Eminoglu, 2019) are slightly more favorable, compared to the double-diode equivalent circuit current values.

Table 3.4 Extracted parameters for MSX60 PV Module at 25 ^oC

PV Module	MSX60 PV Module (Sandrolini, et al., 2009)										
Parameters	V_{oc} (V)	I_{sc} (A)	V_{mpp} (V)	I_{mpp} (A)	N_s	P_m (W)	R_s (Ω)	R_p (Ω)	a	I_o (µA)	I_{pv} (A)
(Moralidharan, 2017)	21.1	3.8	17.1	3.5	36	60	0.146	561.6	1.331	0.15	3.802
Model (Kareem & Saravanan, 2016)	21.1	3.8	17.1	3.5	36	60	0.169	637.5	1.404	0.32	3.801
Model (Atay & Eminoglu, 2019)	21.1	3.8	17.1	3.5	36	60	0.169	637.5	1.404	0.32	3.801

Table 3.5 Extracted parameters for STP6-120/36 PV module at 55 ^{o}C

PV Module	STP6-120/36 PV Module (Tong & Pora, 2016)										
Parameters	V_{oc} (V)	I_{sc} (A)	V_{mpp} (V)	I_{mpp} (A)	N_s	P_m (W)	R_s (Ω)	R_p (Ω)	A	I_o (μA)	I_{pv} (A)
(Tong & Pora, 2016)	19.21	7.48	14.93	6.83	36	120	0.0049	9.745	1.207	1.20	7.483
Model (Kareem & Saravanan, 2016)	19.21	7.48	14.93	6.83	36	120	0.1819	281.7	1.304	0.89	7.484
Model (Atay & Eminoglu, 2019)	19.21	7.48	14.93	6.83	36	120	0.1819	281.7	1.304	0.89	7.484

Table 3.6 Extracted parameters for PWP201 PV module at 45 ^{o}C

PV Module	Photowat-PWP201 PV Module (Muralidharan, 2017)										
Parameters	V_{oc} (V)	I_{sc} (A)	V_{mpp} (V)	I_{mpp} (A)	N_s	P_m (W)	R_s (Ω)	R_p (Ω)	A	I_o (μA)	I_{pv} (A)
(Nunes, et al., 2018)	16.7785	1.0317	12.649	0.912	36	-	1.2392	744.71	1.3173/ 1.3169	2.5129/ $1x10^{-6}$	1.0323
Model (Kareem & Saravanan, 2016)	16.7785	1.0317	12.649	0.912	36	-	1.3130	582.3	1.3644	0.1671	1.0340
Model (Atay & Eminoglu, 2019)	16.7785	1.0317	12.649	0.912	36	-	1.3129	582.2	1.3644	0.1671	1.0340

Table 3.7 RMSE and R^2 values between experimental and calculated output current data for different PV modules

Model/ PV Module	Model (Kareem & Saravavan, 2016; Atay & Eminoglu 2019)		Model (Muralidharan, 2017)		Model (Tong & Pora, 2016)		Model (Nunes, et al., 2018)	
	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2
MSX60	0.0384	0.9989	0.0913	0.9941	-	-	-	-
STP6-120/36	0.0241	0.9995	-	-	0.0178	0.9997	-	-
PWP201	0.0024	0.9999	-	-	-	-	0.0033	0.9998

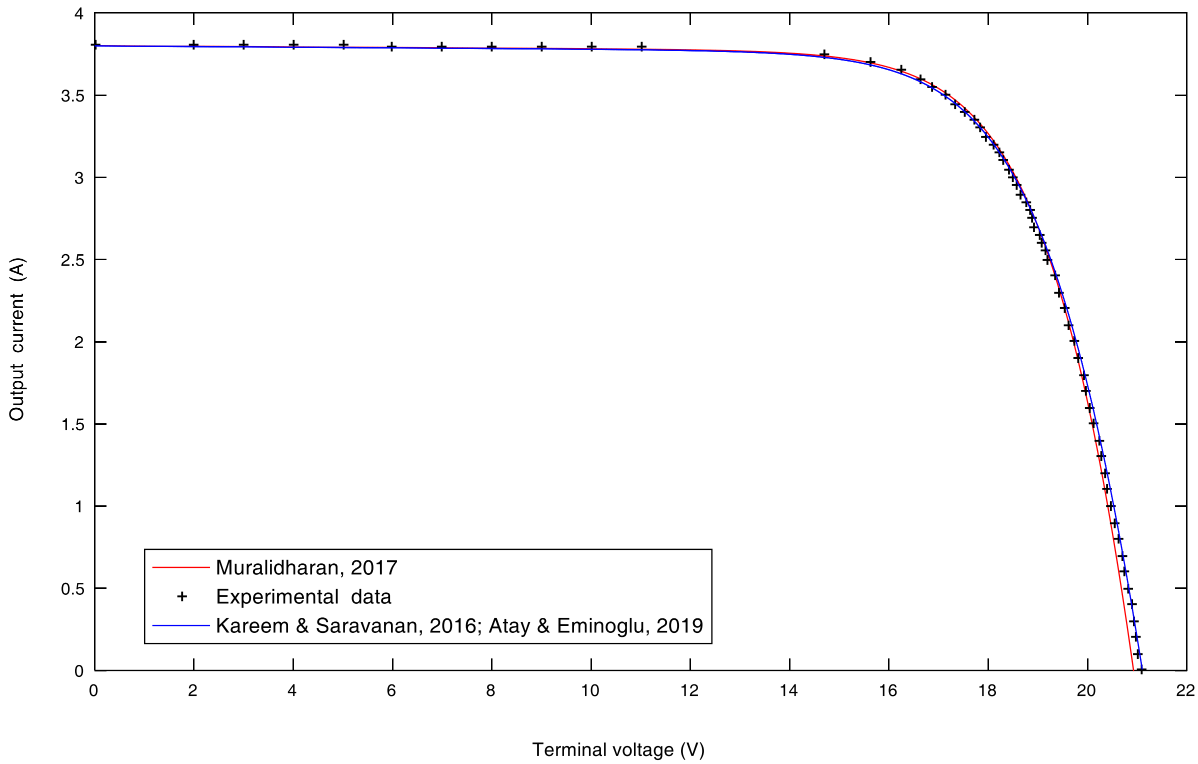

Figure 3.2 I-V curves of Solarex MSX60 PV module at 25 °C

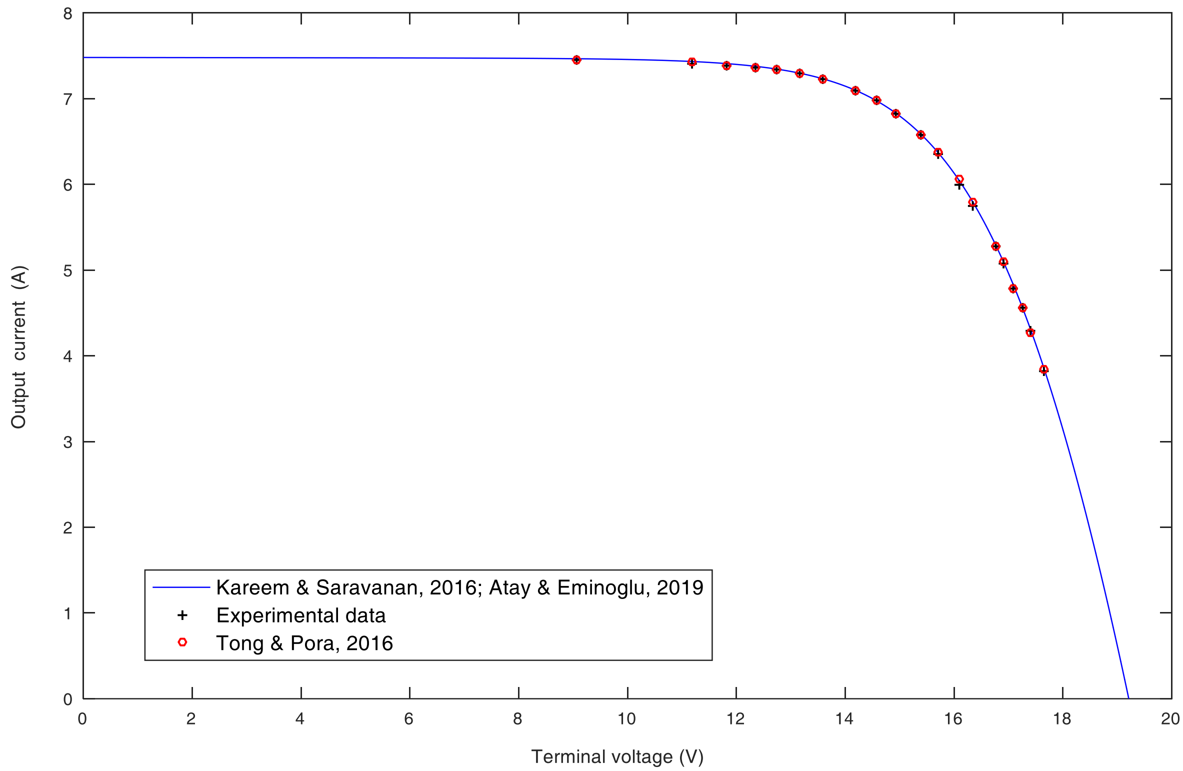

Figure 3.3 I-V curves of STP6-120/36 PV module at 55 °C

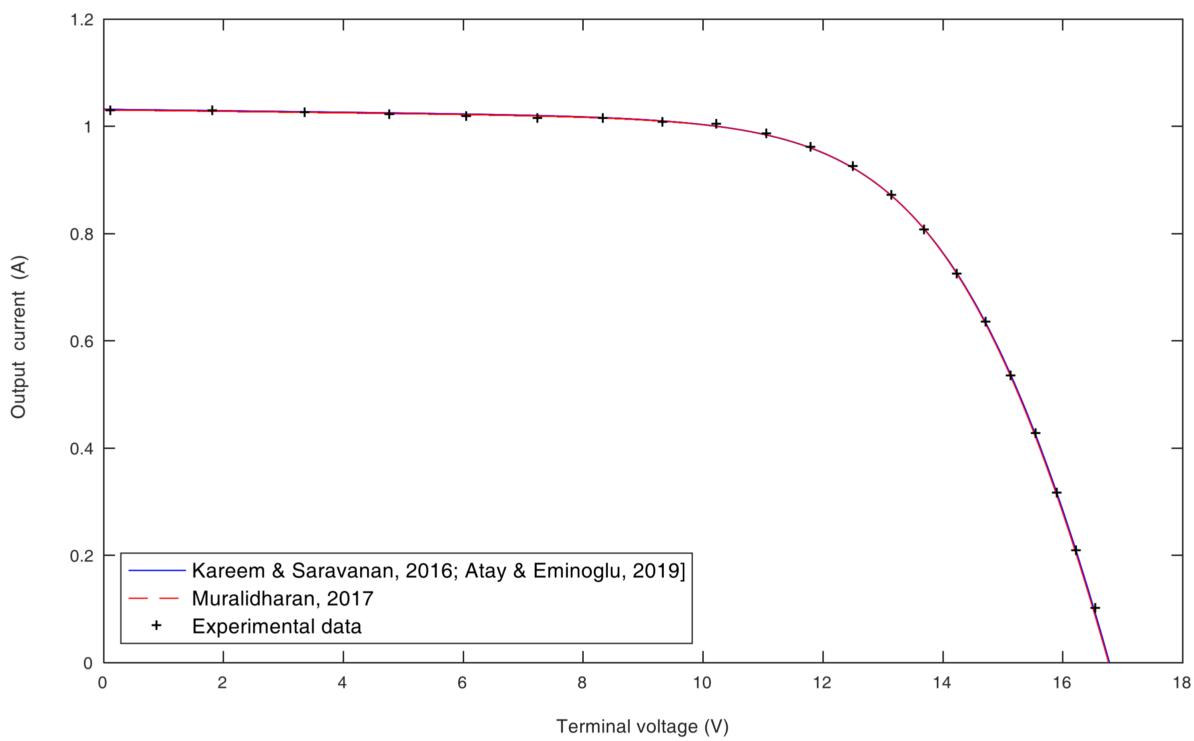

Figure 3.4 I-V curves of PWP201 PV module at 45 °C

Obtaining the output current-voltage characteristic and the resulting power-voltage curve of a PV-module realistically by using equivalent circuit parameters at a given temperature is of great importance for the efficient use of that module. Figure 12 depicts the P-V curve obtained using the equivalent circuit parameter given in Table 3.2, defined for the KC200GT with the developed model. Two different curves are also depicted in the figure for comparison purposes. The first one is based on the parameters obtained for the single-diode model by applying the search-based algorithm given in Reference (Vilalva, et al., 2009: 1198-1208) . And, the second one is based on the parameters obtained for the three-diode model by applying the meta-heuristic method (Grasshopper Optimization Algorithm) given in Reference (Elazab, et al., 2020: 1-15). As shown in the figure, curves related to all model results correlate highly at low voltages. However, the correlation reduces at higher values of output voltage. On the other hand, the power values determined by the models developed in (Kareen & Saravanan, 2016 and Atay & Eminoglu, 2019) completely correlate with the experimental data. Therefore, it could be stated that the equivalent circuit parameters obtained by the model gives more reliable results than the three-diode equivalent circuit parameters given in Reference (Elazab, et al., 2020: 1-15) and single-diode circuit with five parameters given in Reference (Vilalva, et al., 2009: 1198-1208).

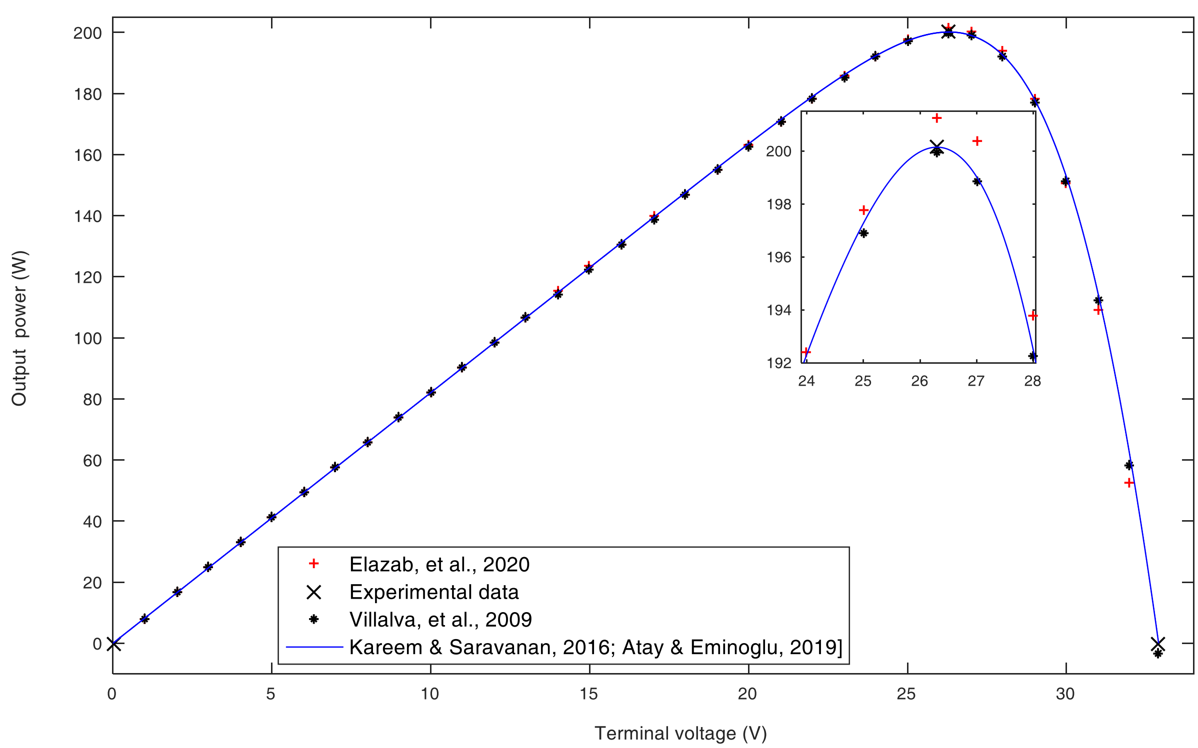

Figure 3.5 P-V curves of KC200GT PV module at 25 ^{o}C

4. CONCLUSIONS

In this study, six PV modules with various power and temperature characteristics were used to test the model's validity. Firstly, SW255, KC200GT and MSX120 practical PV Modules were taken into account at standard test conditions, and the results were found to be consistent with the results of similar analytical methods given in the literature indicating that the models given in (Kareen & Saravanan, 2016 and Atay & Eminoglu, 2019) are more reliable than the other models. Moreover, the existing mathematical models in the literature were found to have some disadvantages, such as incorrect mathematical relations(Hejri, et al., 2016: 396-410), determining the equivalent circuit parallel resistance (R_p) by experimental measurements to be used as input data (Chaibi, et al., 2018: 376-386), accepting the diode ideality factor (a) as a known parameter (Cubas, et al., 2013: 873-877), higher dependence of the parameters to the initial values due to the use of only the basic equations for the solution (Mohapatra, et al., 2017: 2392-2400), and the need to solve more complex set of equations, compared to the model in(Kareen & Saravanan, 2016 and Atay & Eminoglu, 2019), due to the equivalent circuit equations obtained by variable elimination method.

Although they are less practical in terms of application/use, compared to the analytical methods, the search and meta-heuristic algorithm-based methods are known to have high reliability. Therefore, model comparison was also achieved for the I-V and P-V curves created using the results stated in the related literature for the single-, double- and three-diode models. RMSE and R^2 error values calculated using experimental data and the datasheets were used for comparison purposes. As a result of the analyses, it was found that curves related to the results of the model developed in (Kareen & Saravanan, 2016 and Atay & Eminoglu, 2019) highly correlate with the experimental data, and that the output current error values were negligible. In addition, the model was found to provide more valid or very close results, compared to that of the search-based methods. On the other hand, compared to these types of search-based methods, it can be stated that the model is more advantageous in terms of usage/application.

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