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Survey of Photovoltaic (PV) Technologies, PV Module Characteristics, Connection Forms and Standards

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Abstract

The effective utilization of energy has become a major concern in recent years on account of the rapidly increasing demand with population growth and industrialization. In parallel with this growing demand towards energy usage, the world-wide energy supply has been subjected to enormous stress. Therefore, energy efficiency and using alternative energy sources issues have become more crucial. Photovoltaic (PV) systems can be shown among the mostly used alternative energy sources and this technology is gaining remarkable popularity. However, PV systems suffer from low system efficiency, high initial cost and erratic atmospheric conditions. Presently, the studies are extended in order to improve the structural efficiency of the PV panels and provide energy efficiency solutions by qualifying the raw material. In this paper, it is aimed to make an investigation on the PV cells technology in terms of efficiency, cost and technical properties based on employed raw materials. On the other hand, a PV panel model is presented to achieve extraction of panel characteristic and for usage in power systems simulation in PSCAD/EMTDC program. This panel model is suitable for the purpose of realizing power system dynamic and transient analysis of both stand-alone and grid connected PV systems. Also an evaluation of grid connection standards and codes for Turkey is presented in detail.

Anahtar Kelimeler : Photovoltaic technology, Grid codes, Photovoltaic cell modelling, PV grid connection

Fotovoltaik (FV) Teknolojileri, FV Modül Karakteristiği, Bağlantı Formları ve Standartların İncelenmesi

Özet

Son yıllarda enerjinin etkin kullanımı, nüfus artışı ve sanayileşme ile birlikte hızla artan enerji talebine bağlı olarak çok önemli hale getirmiştir. Enerji kullanımında artan talebe paralel olarak dünya geneli enerji arzı çok büyük baskıya maruz kalmaktadır. Bu nedenle enerji verimliliği ve alternatif enerji kaynaklarının kullanılması çok önemli bir konu haline gelmiştir.

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Fotovoltaik sistemler (FV) en çok kullanılan alternatif enerji kaynakları arasında gösterilebilir ve bu teknoloji gün geçtikçe dikkat çekici popülerlik kazanmaktadır. Fakat, FV sistemler düşük verimlilik, yüksek kurulum maliyeti ve değişken atmosferik koşullardan negatif olarak etkilenmektedirler. Son zamanlarda çalışmalar kullanılan hammaddeleri modifiye ederek FV panellerin yapısal verimliliğini artırmak ve enerji verimliliği çözümleri sağlamak amacıyla genişletilmiştir. Bu yazıda FV hücre teknolojisi üzerine kullanılan hammadeler baz alınarak verimlilik, fiyat ve teknik özellikler açısından inceleme yapılması amaçlanmıştır. Öte yandan panel karakteristiği çıkarımı ve güç sistemlerinin benzetiminde kullanmak için PSCAD/EMTDC programı kullanılarak FV panel modeli sunulmuştur. Bu panel modeli hem şebeke bağlantılı FV sistemlerin hemde şebekeden bağımsız sistemlerin güç sistem dinamiği ve geçici durum analizi çıkarımı için uygundur. Ayrıca Türkiye için şebekeye bağlantı şartları ve baz alınan şartnamelerin detaylı incelenmesi.

Keywords: Fotovoltaik teknolojisi, Şebeke kodları, Fotovoltaik hücre modellemesi, FV şebeke bağlantısı

1. INTRODUCTION

Energy is the basic constituent of life and its supply effects directly on the social and economic development of nations. In modern societies, development level and economic growth are directly measured by energy consumption and generation. It can be clearly said that our prosperity is fundamentally dependent on a continuous, abundant, and economic energy supply [1-3]. Moreover, the tremendous advancement in industry is another reason that raises the energy issue to the foreground. Hence, there is a growing demand to increase the energy generation capacity due to rising of the global energy consumption in all over the world as shown in Figure 1. According to the United States Energy Information Administration (EIA), total world consumption of commercial energy is predicted to increase by 49% from 2007 to 2035 in International Energy Outlook 2010 reference case [4]. While there is so much need of energy, fossil fuels are running out, oil prices are getting higher and more importantly environmental issues of customary energy resources such as global warming and impact of carbon emissions are forced people to find different energy sources. Therefore, in the last decades there has been an increasing interest in the field of production and saving of energy. Saving of energy can be one of the cost effective solution but it is not enough to prevent energy crisis and global warming. Furthermore, energy efficiency and energy incentives remain consistently relevant and renewable energies are becoming increasingly important in all over the world [5].

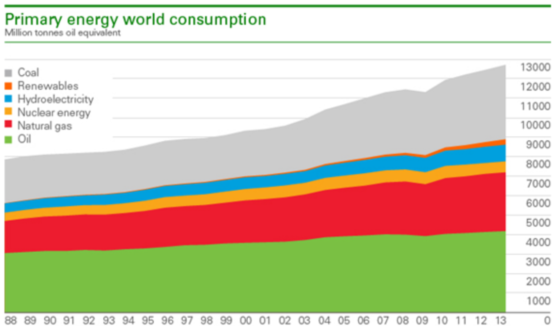


Figure 1. Primary energy world consumption [6]

In recent years, renewable energy attracts great interest because of being sustainable, abundant inexhaustible and environmentally friendly. The sources of the renewable energy are inherently renewed on its own accord such as biomass, wind, hydropower, geothermal and solar. Their application areas can be investigated under four main headings, electricity generation, solar heating/solar cooling, rural (off-grid) application and vehicle fuels. So the share of the renewable energy in global energy production and consumption increasing day by day as demonstrated in Figure 2 and renewable contributed 19% to our energy consumption and 22% to our electricity generation in 2012 and 2013, respectively [7]. Although renewable energy has many advantages compared to conventional fossil fuel based energy, it has some drawbacks such as high initial cost of material purchasing, installing and maintenance. These drawbacks create some prejudices against the renewable energy. When depreciation period is considered, they suffer from long term fulfilling. It is one of the most important parameters for companies However, technical studies in this area for reducing initial installing costs continue.

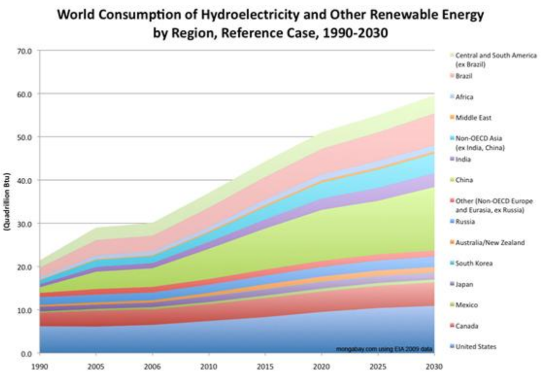


Figure 2. Renewable energy world usage [6]

In all over the world energy demand has been increasing steadily during the past five decades, and it is believed that this trend will continue to rise [8]. Also it is estimated that global energy consumption in 2055 will increase up to 3 times compared to in 1998. Parallel to this, growing energy demand becomes one of Turkey's most important development precedence. Thus, effective utilization of renewable energy sources has a vital importance for Turkey for reducing the dependence on expensive foreign energy supplies. Turkey has a various energy resources, including hard coal, lignite, oil, hydropower, natural gas, geothermal, bioenergy and renewable energy [9].

Despite being very rich in terms of renewable energy sources, in our country these sources are not utilized effectively. When Figure 3 is investigated, the distributions of the resources in terms of installed power are not in desired level. To eliminate this situation, The Law of Utilization of Renewable Energy Resources in Electricity Generation is constituted in 2005. Main goals of the law can be summarized as; to expand the utilization of renewable sources for generating electrical energy, to benefit from these resources in secure, economic and qualified manner, to increase the diversification of energy resources [10]. In addition, for identify the country's energy source potentials, preparing sample application projects and feasibility studies, preparing regulations in the areas of renewable energy and energy efficiency, following development in relevant areas/sector, defining goals and priorities in energy sector and creating specific incentives General Directorate of Renewable Energy was founded in 2011. It is the fundamental governmental body in the areas of renewable energy and energy efficiency. In Turkey, electricity energy consumption that was 230 billion kWh by the year 2011 is predicted to reach to 450 billion kWh at the beginning of 2023. Turkey's energy policy targets to increase the installed capacity of renewable energy in solar plants to 600 MW, in wind energy plants to 20.000 MW, in geothermal energy plants to 600 MW and in hydraulic power plants to 36.000 MW until 2023. Hence, it is aimed to increase the share of renewable energy in the electricity supply above 30% [10]. The current installed capacity of Turkey is 71,429 MW [11].

2. SOLAR PHOTOVOLTAIC TECHNOLOGIES

Solar energy is one of the most important renewable sources. The sun emits huge amounts of irradiation, which can be used as direct source of energy, onto the earth surface everyday [12]. PV is a technology with the inclusion of the direct conversion of solar radiation into electricity by using solar cells. Some materials demonstrate photoelectric effect, which causes them to absorb photons and snatch electrons from p-n junction. These free electrons are forced to fill the holes on a path and an electric current occurs that can be used as electricity. Photovoltaic history starts in 1839, Edmund Becquerel discovered that electrical currents occur from certain light induced chemical reactions, and then in 1883 Charles Fritts created the first solid state photovoltaic cell by layering the semiconductor selenium with a thin layer of gold to form the junctions [13]. The first practical PV cell was exhibited at Bell laboratories, but it was too expensive to obtain common usage. Up to now, intensive studies have carried out on materials and structure development to expand and improve this energy collector, because minimum depreciation period is desired by maximum power generation [13, 14].

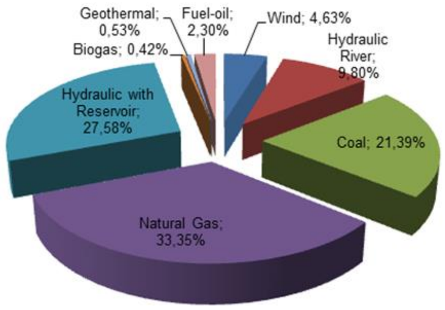


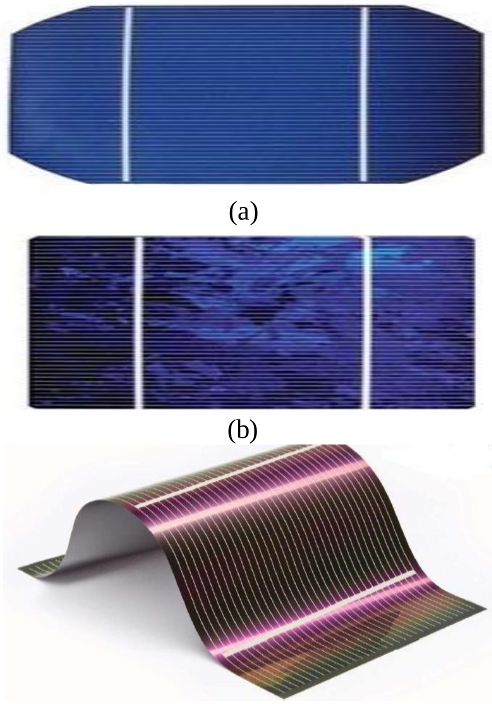
Figure 3. Total installed power according to source usage in Turkey [11]

The rapid growth of the PV market began in the 1980s due to the application of multi-megawatt PV plants for power generation. As a result of studies, cost reduction and market development have become possible [15]. Traditional PV cells are made from semiconductor material especially silicon, are usually flat-plate, and generally are the most efficient. Second-generation PV cells are called thin-film solar cells because they are made from amorphous silicon or non-silicon materials such as cadmium telluride. Third-generation PV cells are being made from a variety of new materials besides silicon, including solar inks using conventional printing press technologies, solar dyes, and conductive plastics [16]. These leading types of PV cells have merits and demerits relative to each other in terms of efficiency, raw material usage, reasonable cost and technical properties.

2.1. Crystalline Silicone

2.1.1. Monocrystalline Photovoltaic Modules

It is quite easy to recognize these types of PV modules; PV cells look perfectly rectangular with no rounded edges, in other words the crystalline framework is homogenous. This type of PV panel has many advantages compared to other types. Because of being space-efficient, these PV panels generate much more power than other panels [17]. Also, in regions dominated by high temperature, monocrystalline PV modules suffer from temperature but demonstrate higher energy yield compared to other types. However, partially covered with shade, dirt or snow seriously decreases energy harvesting and it comes to halt. In addition, they are weak against physical impacts; when a fracture starting at any point, it affects the entire of the panel [4, 16, 18].



(a)

(b)

(c)

Figure 4. (a) Monocrystalline PV cell
(b) Polycrystalline PV cell
(c) Thin-film PV Cell

2.1.2. Polycrystalline Photovoltaic Modules

Production process is differently performed from monocrystalline, raw silicon is melted and poured into a square mold, which is cooled and cut into square wafers. It is quite distinguishable from monocrystalline because of the appearance [17]. These types of PV modules were first launched in

1981. Due to the less amount of wasted raw material, these type PV modules have simpler and inexpensive manufacturing process. Polycrystalline PV panels are not as efficient as monocrystalline PV panels. Series resistance of the connection points can be shown one of the reason of being less efficient. In addition they are not quite as good as monocrystalline in terms of heat tolerance and being space-efficient [18, 19].

2.2. Thin-Film Photovoltaic Modules

Amorphous silicon (a-Si) was the first thin-film technology used in PV technology. There are three main types of thin film solar panels are commercially available; Amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIS/CIGS) [18]. Ease of production process, low cost, raw material savings, lower construction cost and their specific electricity production values (kWp/kWh) make them popular over the PV technologies. However, their square per meter generation (kWh/m^2) is low and consequently installation costs go up due to the need for more panels [4, 16].

2.2.1. Amorphous Silicon

Amorphous silicon solar cells are made from a layer of silicon deposited as thin film on a plastic sheet. The silicon atoms are irregular and do not form perfect crystals, and have a comparatively low efficiency. The first thin film solar cells are based on amorphous silicon [20]. The technology is most commonly used in devices that require very little power as calculator or because of low efficiency rates [17].

2.2.2. Copper Indium Gallium Sellenide (CIS)

CIGs cells are made with a thin layer of copper indium gallium diselenide Cu (In, Ga) Se2 (CIGS). CIGS cells have up to 10% efficiency with similar strength as silicon solar cells. Since they are a thin film technology they can be less costly than Si cells [20].

2.2.3. Cadmium Telluride (CdTe)

Cadmium telluride is the only thin-film solar panel technology that has surpassed the cost-efficiency of crystalline silicon solar panels in a significant portion of the market (multi-kilowatt systems). According to the other thin-film technologies, CdTe solar cells are one step ahead in terms of efficiency [17]. Efficiency of various solar cell types is provided in Table 1.

3. PHOTOVOLTAIC CELL AND MODULE CHARACTERISTIC

A PV system directly converts sunlight into electricity. The basic component of a PV module is the PV cell. This is fundamentally a semiconductor diode that can generate electricity when its p-n junction exposed to sun light [22]. A PV cell's physical cross-sectional view is demonstrated in Figure 5.

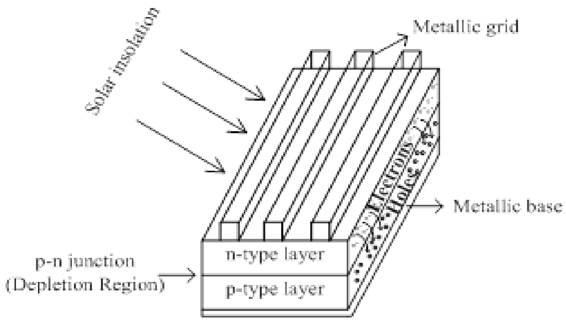


Figure 5. PV cell's physical demonstration [22]

To form a PV panel a set of cell is connected in series or parallel, these connection types can exhibit different variations according to the desired output voltage and current. It is very important to understand and estimate the PV characteristics in order to use a PV plant effectively, regardless of external factors. Therefore effect of atmospheric conditions especially irradiation and temperature should be deeply investigated [23].

3.1. Effect of Irradiance and Temperature

PV array's output characteristic curves, current-voltage and power-voltage reflect PV array's dependence on atmospheric conditions such as temperature and radiation. The current and voltage dependence on radiation and temperature is given in Figure 6.

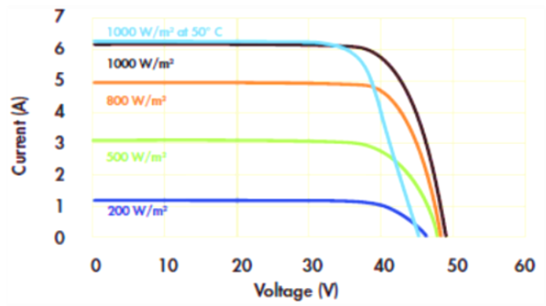


Figure 6. Current/voltage characteristics with dependence on irradiance and temperature (Sunpower 19\240 solar panel)

It can be clearly seen that the cell output voltage related with the temperature and the cell output current is affected by irradiation level. Due to these characteristic dependencies, extraction of maximum power from PV modules mainly changed by the temperature and irradiance level [22, 24]. Furthermore, for specifying rating of power electronics equipment, these variations should be taken into consideration. Open circuit voltage (V_{oc}) is primarily affected by temperature and the relationship between them is inversely proportional whereas the current is only slightly dependent [25, 26]. This relationship can be extracted by using Equation (1).

$$V_{oc} = V_{oc-STC} - \gamma * (T - T_{STC}) \qquad (1)$$

"γ" is a constant which can be obtained from datasheet of a PV module. It is a negative value and shows change of open circuit voltage by increasing or decreasing ambient temperature for 1 ºC. Short circuit current (I_{sc}) is mostly affected by irradiation level and the relationship between them is directly proportional as shown in Equation (2)

$$I_{sc} = I_{sc-STC} * \left(1 + \alpha * (T - T_{STC})\right) * \frac{G}{G_{STC}} \qquad (2)$$

3.2. Equivalent Circuit and Mathematical Model

Modeling of photovoltaic cell is an essential research area for implementing performance analysis, sizing, performance estimation and optimization of PV energy systems [27]. Because PV panel manufacturers do not supply sufficient information over a large operating conditions except for some electrical quantities and this makes designers to develop a realistic alternative simulations. PV models are generally built up by using four parameter and five parameter model [28, 29]. The five parameters model includes light-generated current, diode reverse saturation-current, series resistance, shunt resistance and diode ideality factor. The four parameters model neglects the shunt resistance and assumes it as infinity [27]. Moreover, there are one diode and two diode models are available in the literature. One of the models proposed in literature is the double exponential model depicted in Figure 7 [24]. The models comprising two or more diode are more sophisticated and constructed for obtaining better accuracy.

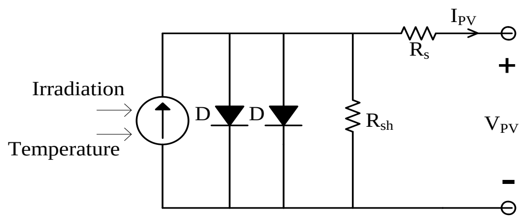


Figure 7. The equivalent circuit of a two diode PV cell [24]

However, single diode model has many advantages for designers such as being simpler, easy adjustment of parameters and effective model for the simulations [22, 23, 30]. In this paper a well-known one diode model consists of a series and a parallel resistance is implemented. This model expresses a good balance between simplicity and accuracy. The circuit diagram of the model is given in Figure 8.

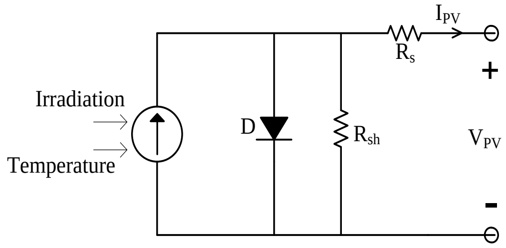


Figure 8. The equivalent circuit of a single diode PV cell

The general current-voltage characteristic of a PV panel based on the single diode model is [31]:

$$I_{pv} = I_{ph} - I_o * \left(e^{\frac{V+I_{pv}}{n_s V_t}} - 1\right) - \frac{V+IR_s}{R_{sh}} \quad (3)$$

$$V_t = \frac{AkT_{STC}}{q} \quad (4)$$

The five parameters of the model are given below:

- "I_{ph}" is the photo generated current in STC
- "I_o" is the dark saturation current in STC
- "R_s" is the series resistance of the PV module
- "R_{sh}" is the shunt resistance of the PV module
- "A" is the diode quality factor
- "V_t" is the junction thermal voltage
-

$$I_{ph} = \frac{G}{G_{STC}}(I_{SC-STC} + \alpha * (T - T_{STC})) \quad (5)$$

$$I_o = \frac{(I_{SC-STC}+\alpha*(T-T_{STC}))}{e^{(\frac{V_{OC-STC}+\gamma(T-T_{STC})}{AV_t})}-1} \quad (6)$$

Other unknowns in the equations are; "k" is the Boltzmann's constant, "q" is the charge of electrons, "n_s" is the number of cells connected in series, "I_{SC-STC}" is the short circuit current value at STC, "V_{OC-STC}" is the open circuit voltage at STC, "G" (W/m2) is the radiation on the PV surface, "G_{STC}" is the radiation at STC and "T_{STC}" is the temperature at STC in Kelvin. The following equations summarize how a single-cell model can be extended to represent a PV panel [32]:

$$I_{pv-tot} = N_p I_{pv} \quad (7)$$

$$I_{o-tot} = N_p I_o \quad (8)$$

$$R_{s-tot} = \frac{N_s}{N_p} R_s \quad (9)$$

$$R_{sh-tot} = \frac{N_s}{N_p} R_{sh} \quad (10)$$

$$A_{tot} = N_s A \quad (11)$$

where "N_p" is the number of parallel cells and "N_s" is the number of series cells.

When the effect of temperature variations are investigated for the single diode model, the deficiency of the model can be clearly seen. At low irradiation levels, the single diode model exhibits different I/V characteristic curve from the curve provided by manufacturer. This insufficiency is notably improved by usage of series and parallel resistance. Furthermore, these drawbacks are highly eliminated in two diode model but this model is required complex calculation due to number of parameters [33]. In Table 2 power rate and fill factor of a PV panel model for single and two diode model are provided and compared with each other to show accuracy of the models.

3.3. Photovoltaic Module Verification

In order to study the embedded power system applications, generalized PV module and array model are quite essential. In this paper, a generalized five parameters model of a PV panel is reviewed by employing an equivalent single diode model and performed with PSCAD/EMTDC software environment by employing a number of pre-defined constants with FORTRAN coding. The simulated model only uses the data provided by the manufacturer with equations given in previous section to extract the cell I–V characteristics curve for any operating condition. Sun Power E19\240 solar panel output characteristics have been simulated and examined by taking into account the effect of operating temperature and irradiance on the I/V and P/V curves. Furthermore, a model is constructed to study the effect of partial shading on the PV array.

To approve the validity of the model, the presented experimental results under STC in datasheet, which is demonstrated in Figure 6, is compared with the simulation results. The used mathematical model has more favorable features than the physical model, since it is easy to control diode quality factor, band gap energy and temperature coefficient by varying those [30]. The considered model can be used to extract a cell characteristic or a module characteristic.

Table 2. Comparison of one and two diode PV panel models with datasheet values in terms of power and fill factor [34]

		Power Rate (at MPP)		Fill Factor		
Irradiance (W/m^2)	Measurements	One Diode Model	Two Diode Model	Measurements	One Diode Model	Two Diode Model
600	25,1194	25,1201	25,0915	0,6424	0,6427	0,6434
520	22,4528	22,4681	22,3444	0,6513	0,6509	0,6498
780	31,0414	31,0373	31,1237	0,6566	0,6582	0,6607

Also the given model is applicable to different modules by changing the electrical data provided by the manufacturer such as open circuit voltage, short circuit current, voltage and current at maximum power point, number of parallel and series cells and reference temperature. The most important point to obtain the closest simulated model of a real system, values of serial and parallel resistance must be accurately defined. The definition method consisting of serial and parallel resistance is fundamentally based on trial and error. The error rate is obtained by comparing the simulation results and experimental results provided by the datasheet of the PV module. The power circuit used to extract I/V and P/V characteristics is given in Figure 9. The waveforms of open circuit voltage and short circuit current of the PV panel under different atmospheric conditions are given in Figure 10, Figure 11, Figure 12, and Figure 13, respectively.

I/V characteristics of the modeled PV panel at 1000 W/m^2 irradiance and at 800 W/m^2 irradiance are demonstrated in Figure 14 and Figure 15, respectively.

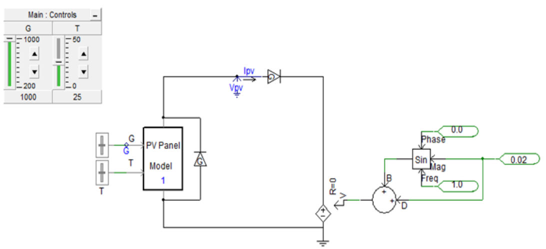


Figure 9. The power circuit used for characterization of modeled PV panel

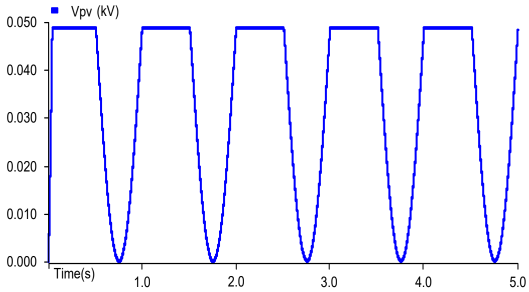


Figure 10. Open circuit voltage of the modeled PV panel at 1000 W/m^2 irradiance

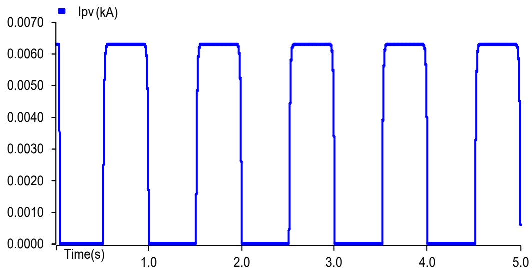


Figure 11. Short circuit current of the modeled PV panel at 1000 W/m^2 irradiance

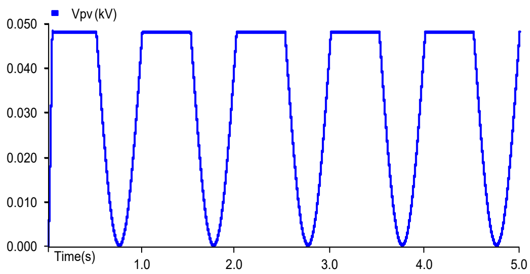


Figure 12. Open circuit voltage of the modeled PV panel at 800 W/m^2 irradiance

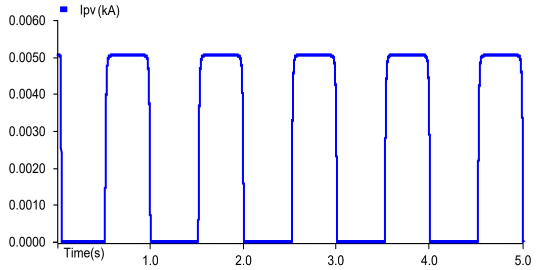


Figure 13. Short circuit current of the modeled PV panel at 800 W/m^2 irradiance

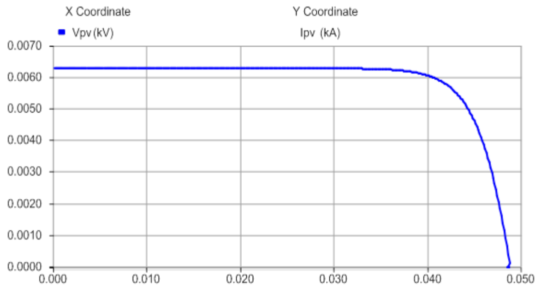


Figure 14. I/V characteristic of the modeled PV panel at 1000 W/m^2 irradiance

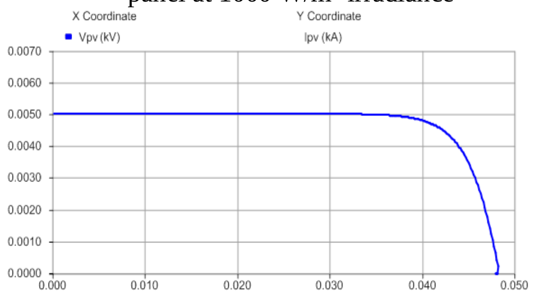


Figure 15. I/V characteristic of the modeled PV panel at 800 W/m^2 irradiance

The extracted panel characteristics results are presented for 1000 W/m^2 and 800 W/m^2 irradiance values. With the experimental results provided in datasheet, it is easy to compare the results for validation of the developed model. Finally, the I/V and P/V characteristics of the constructed PV array, which includes 6 PV panel in parallel and 9 in series, is provided in Figure 16. Moreover, characteristics of the constructed PV strings are demonstrated in Table 3.

Table 3. Characteristics of the constructed PV strings

Number of series connected panels in a string	9
Number of parallel connected panels in a string	6
Output voltage rating at MPP under STC	364.5V
Output current rating at MPP under STC	35.58A
Maximum power output under STC	13.1kW

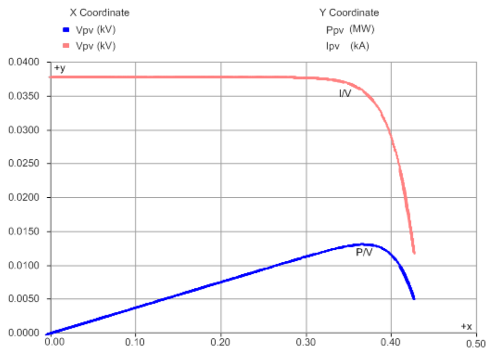


Figure 16. I/V and P/V curves of the constructed PV array

4. PHOTOVOLTAIC SYSTEM CONNECTION FORMS

There are mainly three types of PV system connection forms: stand-alone PV system, grid-tied PV system and hybrid systems [30].

4.1. Stand-alone Photovoltaic Systems

For places that are particularly remote from a conventional power generation system, stand-alone PV systems have been considered a visible alternative as shown in Figure 17 [35].

This system can be used for both domestic and non-domestic areas and completely independent from the grid. Non-Domestic applications can be illustrated by solar water pump system, traffic lights and space satellites. Also, building integrated PV systems are generally given as an example of domestic applications. The possible installation power range can be extended for both domestic and non-domestic applications from 100W to 15 kW [36]. This power range information is experienced from commercial companies that deal with this area. Stand-alone PV systems can only include load and PV module or may additionally comprise the battery for providing continuous energy. Stand-alone systems fundamentally contain PV panel, charge controller, batteries, and inverter [37].

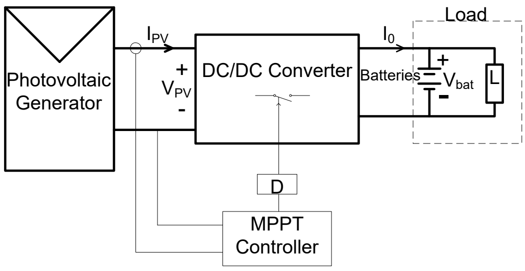


Figure 17. General block diagram of a stand-alone PV system with MPPT [35]

4.2. Grid Connected Photovoltaic Systems

Recently, the grid-connected PV systems are getting more popular over traditional stand-alone PV systems [38]. A grid connected PV system's output is conducted directly to the grid. The produced DC power converted to AC power through a high quality inverter for feeding the grid. These types of PV systems contain either a single or a two stage power conditioning system, this affects the control strategies in order to achieve grid-code appliance [39]. In other words having DC-DC converter changes the control diagram, because without DC-DC converter MPPT controller must be integrated to inverter's controller. Grid connected PV systems, which demonstrated in Figure 18, are generally designed to generate huge amount of power, therefore reliable and efficient operation is the most important issue. Hence, power electronic inverter, converter, controller of them, protection and grid-code compatibility gaining more and more importance.

4.3. Hybrid Photovoltaic System

Hybrid PV systems comprise of both stand-alone and grid-tied PV systems. These systems are also described as stand-alone PV system with utility interface. The main advantage of this system is providing uninterruptible power without the need for any power source [4, 17].

5. GRID CONNECTION STANDARDS and CODES

Before making a network connection of a PV system, it should be evaluated to show how it affects the network. To be synchronized with the network is a crucial problem. To design a power electronic inverter for grid-tied PV system, an overview of rules and regulations should be investigated in order to be allowed to connect to the grid. With these regulations a common point is created and reliable, safe and steady operation of the system is aimed [40]. There are various grid codes, standards and related documents are available. By using them technical requirements for connection of National Electricity Transmission System is specified. These rules will however not be the same for all countries; they demonstrate small variations in the degree of limitations and in the definitions. The standards from two of the major international standardization organizations listed below, an overlook of the most important demands and limitations can be found [40].

- Institute of Electrical and Electronics Engineers – IEEE
- International Electrotechnical Commission – IEC

In Turkey these regulations are demonstrated in Electricity Market Grid Regulation (EMGR) which published in Official Gazette of the Republic of Turkey no. 25001 on 22/01/2003. Due to the connection of Turkey to the interconnected electrical system, given specifications in this regulation are mostly same with the European

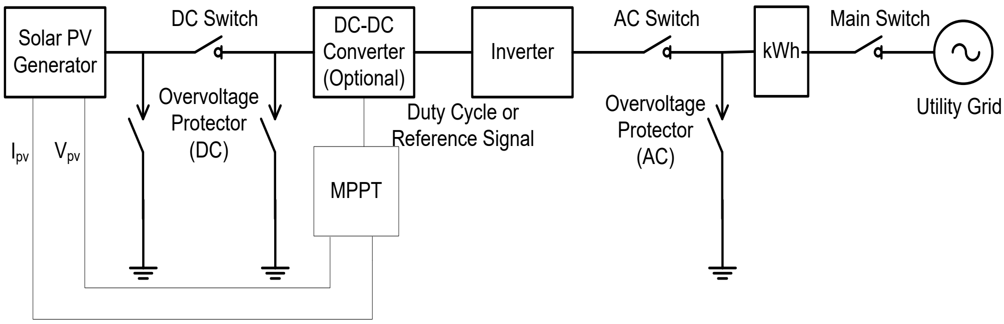


Figure 18. General block diagram of a grid connected PV system with MPPT

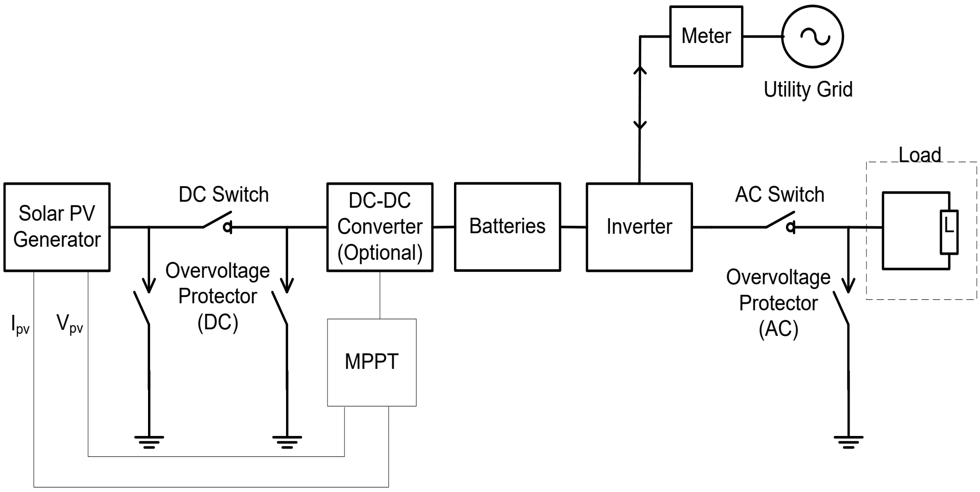


Figure 19. General block diagram of a hybrid PV system with MPPT

regulations. Technical criteria regarding transmission system performance, plant and equipment parameters are [41]

- Frequency: Rated frequency of the system is controlled by TEİAŞ around 50 Hertz (Hz) between 49.8-50.2 Hz range. The system must be disconnected in 0.2 sec. for low voltage connections and 0.5 sec. for high voltage connections when the operating frequency becomes less than 47 Hz or exceeds 51 Hz.
- Voltage fluctuations: Instantaneous changes of the voltage not allowed exceeding 1% of the operating voltage level. Larger voltage changes can be permitted up to 3% by TEİAŞ in extraordinary cases without affecting the transmission system or other consumers. In Table 4, the voltage distortion limit values are presented.

In Table 5, the current distortion limits for general distribution systems are shown.

- Voltage and Current distortion limits: In Table 4, the voltage distortion limit values are presented. In Table 5, the current distortion limits for general distribution systems are demonstrated.
- Harmonic distortion: Harmonic distortion cannot exceed 5% for both the current and voltage as noted in IEC-61000-4-7.
- Vector shift: Relay trip setting must be adjusted to 6°…9° and the system must be disconnected in 0,2 sec. for both low voltage and high voltage applications.

Table 4. Voltage distortion limits [42]

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3,0	5
69 kV through 161 kV	1,5	2,5
161 kV and above	1	1,5
Note: High voltage systems can have up to 2.0 % THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.		

Table 5. Current distortion limits for general distribution systems [42]

Individual Harmonic Order (Odd Harmonics), h						
I_{sc}/I_L	Max. Harmonic Current Distortion for h					TDD
	h<11	11≤h<17	17≤h<23	23≤h<35	35≤h	
Below 20	,0	2	1,5	0,6	0,3	5,0
Between 20-50	,0	3,5	2,5	1,0	0,5	8,0
Between 50-100	0,0	4,5	4,0	1,5	0,7	12,0
Between 100-1000	2,0	5,5	5,0	2,0	1,0	15,0
Above 1000	5,0	7,0	6,0	2,5	1,4	20,0
Even harmonics are limited to 25% of the odd harmonics limit above						
Current distortions that result in dc offset, e.g., half wave converters, are not allowed						
All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L						
I_{sc}= Maximum short circuit current at PCC, I_L= Maximum demand load current (fundamental frequency component) at PCC.						

- Injected DC current: The value of the injected DC current must be limited 0,5% of the rated current.

6. CONCLUSIONS

In this paper, the solar PV technologies, PV cell and module characteristics and PV system connection forms are reviewed. It is discussed how the employed material effect the efficiency of the panel. The material dependent efficiency of the PV panel is provided in a table.

In addition, mathematical model of PV cell is provided and it is modeled in a simulation program to make an evaluation for effects of atmospheric conditions on PV modules. The results of this study indicate that the presented model can accurately extract the characteristic of a PV panel by using the electrical data given in datasheet.

This model can be used for power system analyze, a robust simulation model can be derived to see the merits and demerits of the system. The on-grid, off-grid and hybrid PV systems are also discussed and their components are focused. Finally, grid connection standards and codes for Turkey is examined and provided.

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