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Açıklama: Bu çalışmada, güneş pilleri ile doğrudan beslenen elektrik makinelerindeki geçici rejim analizi yapılmıştır. Deneysel çalışmalarda kurulan 500W'lık PV panele doğrudan bağlanan Asenkron motor, Transformatör ve Seri, Şönt, Kompunt D.C. motorların ilk kalkınma anındaki akım değerleri kaydedilmiş ve bu veriler MATLAB Wavelet ile harmonik analizi için kullanılmıştır.

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Experimental Wavelet Packet Transient-State Analysis of Electrical Machines Directly Fed by Photovoltaic Cells

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Experimental Wavelet Packet Transient-State Analysis of Electrical Machines Directly Fed by Photovoltaic Cells

N. Onat[1], İ. Kıyak[2], G. Gökmen[2]

Abstract – *This work describes an experimental wavelet packet transient state analysis for educational purposes. The study particularly deals with electrical machines directly fed by photovoltaic cells. In a PV system design, the selection and proper installation of appropriately-sized components directly affects system reliability, lifetime and initial cost. In any installation, one must keep in mind that trade-offs are necessary in system design and component selection. In this study, the startup and nominal operating behaviors of electrical machines directly connected to a photovoltaic system (not having any storage or control system) were empirically examined. The power values obtained (in p.u.) were decomposed to sub-frequency components by means of the discrete wavelet packet transformation then they were compared to each other.* ***Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords**:** *Photovoltaic Cells, Transient State, Electrical Machines, Wavelet Filter Bank, Wavelet Packet Transform*

Nomenclature

I_g	Load current [A]
V_g	Terminal voltage of PV cell [V]
N_s	Number of cells in series connected
N_p	Number of cells in cells in parallel connected
I_{ph}	Photocurrent of cell [A]
I_0	Cell reverse saturation current [A]
R_s	Cell series resistance [Ω]
q	Electron charge, $q = 1.6x10^{-19}$ [C]
k	Boltzmann's constant, $k = 1.38x10^{-23}$ [j/K]
T	Absolute temperature [K]
I_{SC}	Short circuit current of cell [A]
V_{OC}	Open circuit voltage of cell [V]
G	Irradiance [kW/m^2]
P_{max}	Maximum power of cell [W]
I_m	Cell current at maximum power [A]
V_m	Cell voltage at maximum power [V]
FF	PV cell fill factor
n	Sample number
$s(n)$	Discrete signal of length n
$h(n)$	Impulse response of high pass filter
$g(n)$	Impulse response of low pass filter
$\psi_{j,k}(n)$	Wavelet function
$\phi_{j,k}(n)$	Scaling function
i, j, k	Positive integers
$2n-k$	Downsampling by two
$s_m^i(n)$	-m- number signal sequence at stage i
$s_{m0}^{i+1}(n)$	Low pass filter output of $s_m^i(n)$ at stage $i+1$
$s_{m1}^{i+1}(n)$	High pass filter output of $s_m^i(n)$ at stage $i+1$
$db4$	Daubechies 4 wavelet family
f_{max}	Maximum frequency of the signal [Hz]

I. Introduction

As conventional fossil fuels are depleting at a rapid rate while the cost of electrical energy is increasing due to growing consumer demand, photovoltaic energy becomes a promising renewable alternative source. The emerging renewable energy from solar and wind generators are expected to play a major role and supply at least 5-10% of total electrical energy demand worldwide. Over 2 billion people in the developing world have no access to electricity. For these people, photovoltaic (PV) is probably the most economical and abundant power source available today. It is anticipated that within the next 10 years, PV solar arrays will become cost competitive with traditional power sources in countries with extensive electrical infrastructure (like the U.S. and Europe). They have the advantages of requiring less maintenance and are free of air pollution, but their installation cost is relatively high and in most cases they need a power conditioner (DC/DC or DC/AC) for interfacing to any motorized load due to the load non-linearity (V-I) relationship [1].

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II. Structure of Photovoltaic

PV modules still have relatively low conversion efficiency; so significant price reductions can be achieved by using a high efficiency power conditioner designed to extract the maximum power from the PV module. The performance of a PV array depends on the operating conditions as well as the solar cell and array design quality. The output voltage, current and power of a PV array vary as function of solar irradiation level, temperature and load current. So the combined effect of all these parameters must be considered when designing the PV array. The least expensive method of converting solar energy into mechanical energy is direct interfacing of DC motors with photovoltaic generators without using storage batteries. One of the most suitable systems for utilizing solar energy is with a PV–DC motor to drive a water pump for storing water for subsequent use in various forms [1], [2].

The solar cell is a semiconductor device that converts the solar insolation directly to electrical energy. The cell is a non-linear device and can be represented by a set of $I-V$ terminal characteristics, or by an approximate electrical equivalent circuit as shown in Fig. 1.

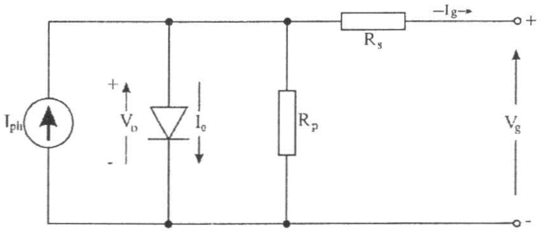


Fig. 1. Photovoltaic cell equivalent circuit

The cells are connected in series and in parallel combinations in order to form an array of the desired voltage and power levels. The I_g-V_g equation of the solar cell generator is given by [3]:

$$V_g = I_g R_s \frac{N_s}{N_p} ln\left(1+\frac{N_p I_{ph}-I_g}{N_p I_0}\right) \tag{1}$$

$$I_g = I_{ph} - I_0\left(e^{\frac{qV_g}{kT}}-1\right) \tag{2}$$

To determine the short circuit current of a PV cell, simply set $V_g = 0$ in the exponent. This leads to $I_{SC} = I_{ph}$. To a very good approximation, the cell current is directly proportional to the cell irradiance. Thus, if the cell current is known under standard test conditions, $G = 1\text{kW/m}^2$ at A.M.1.5, then the cell current at any other irradiance is given by:

$$I_{ph}(G) = \frac{G}{G_0} I_{ph}(G_0) \tag{3}$$

To determine the open circuit voltage of the cell, the cell current is set to zero and Eq. (2) is solved for V_{OC}, yielding the result:

$$V_{OC} = \frac{kT}{q} ln\frac{I_{ph}+I_0}{I_0} \cong \frac{kT}{q} ln\frac{I_{ph}}{I_0} \tag{4}$$

Since normally $I_{ph} >> I_0$. For example if the ratio of photocurrent to reverse saturation current is 10^{10}, using a thermal voltage (kT/q) of 26mV yields $V_{OC} = 0.6\text{V}$. Note that the open circuit voltage is only logarithmically dependent on the cell illumination, while the short circuit current is directly proportional to the cell illumination.

The maximum power point may also be determined by differentiating the cell power equation and setting the result equal to zero. After finding that the cell power equation is satisfied, and checking to verify that this voltage represents a maximum, the maximum power point is known. The maximum power point is also readily found by simply plotting cell power versus cell voltage and the cell maximum power can be expressed as:

$$P_{max} = I_m \cdot V_m = FF \cdot I_{SC} \cdot V_{OC} \tag{5}$$

The fill factor is a measure of the quality of the cell. Cells with large internal resistance will have smaller fill factors, while the ideal cell will have a fill factor of unity. Note that a unity fill factor suggests a rectangular $I-V$ characteristic. Although a real cell does not have a rectangular characteristic, it is clear that it has a region where its operation approximates to that of an ideal voltage source and another region where its operation approximates that of an ideal current source [4]-[6].

III. Feeding of Electrical Machines from Photovoltaics

It is possible to encounter some studies in the literature, which have been carried out on photovoltaic systems feeding electrical machines. Arrouf has worked on various control systems related to the feeding of one and three-phase asynchronous (induction) motors from photovoltaics [7], [8]. Singer has examined the startup characteristics of various DC machines fed from photovoltaics and made some suggestions aimed at improving performance [9]. Since DC motors are particularly used in transportation systems, they should be taken into account in designing transportation vehicles fed from photovoltaics. To achieve maximum performance from DC motors to be used in such vehicles, various parameters should be taken into account [10], [11]. The startup and nominal operating behaviors of electrical machines directly connected to photovoltaic systems (without any storage or control system) are empirically examined in this study.

IV. Discrete Wavelet Packet Transform

One of the transient analysis methods is the wavelet packet transform. The wavelet transform is a recently developed mathematical tool for signal analysis. It has become a very important tool for research in the fields of mathematics, physics and engineering [12].

The wavelet packet transform is a time varying representation of a digital signal using digital filtering techniques. The resolution of the signal, which is a measure of the amount of detail information in the signal, is changed by the filtering operations, and the scale is changed by the down sampling operations. The output of the cascaded filter banks associated with the selected mother wavelet and the number of levels of resolution produce details and approximations of the original signal, which are related to high frequency and low frequency components, respectively. The procedure starts with passing the discrete signal through a high pass filter and then through a low pass filters [13], [14]. The outputs of the high-pass and low-pass filters constitute one level of decomposition of the discrete signal. They can be mathematically expressed as [15]:

$$s_0^1(n) = \sum_k s(k)h(2n-k) \tag{6}$$

Similarly:

$$s_1^1(n) = \sum_k s(k)g(2n-k) \tag{7}$$

The $\phi_{j,k}(n)$ and $\psi_{j,k}(n)$ do not appear in these expressions. This is an advantage for simulation with a digital bank structure in a computer environment [16]. The sequences $s_0^1(n)$ and $s_1^1(n)$ are then decomposed further in the second stage of the wavelet packet decomposition tree:

$$\begin{aligned} s_{00}^2(n) &= \sum_k s_0^1(k)h(2n-k) \\ s_{01}^2(n) &= \sum_k s_0^1(k)g(2n-k) \\ s_{10}^2(n) &= \sum_k s_1^1(k)h(2n-k) \\ s_{11}^2(n) &= \sum_k s_1^1(k)g(2n-k) \end{aligned} \tag{8}$$

The decompositions from $s_m^i(n)$ into the sequences $s_{m0}^{i+1}(n)$ and $s_{m1}^{i+1}(n)$ using the two decomposition quadrature filters are given by flowing equations [15]:

$$\begin{aligned} s_{m0}^{i+1}(n) &= \sum_k s_m^i(k)h(2n-k) \\ s_{m1}^{i+1}(n) &= \sum_k s_m^i(k)g(2n-k) \end{aligned} \tag{9}$$

The three stage discrete wavelet packet transform tree is shown in Fig. 2 [15].

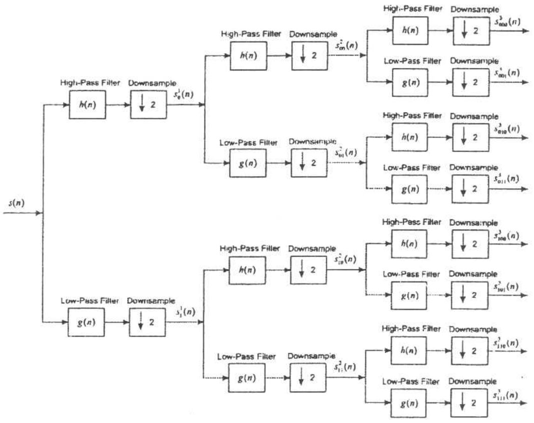


Fig. 2. Discrete wavelet packet decomposition tree

This decomposition is equivalent to first passing the input sequence through the two decomposition quadrature filters and then down-sampling the outputs by two [15]. The three stage discrete wavelet packet transform has eight decompositions and the input signal is decomposed into eight uniform frequency bands (Fig. 3) [16], [17].

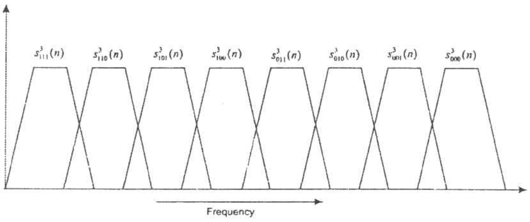


Fig. 3. The frequency coverage of the third stage discrete wavelet packet transform

V. System Description

The proposed small scale PV energy system has the following parts:

- PV array string of series/parallel modules
- DC/AC Inverter
- AC/DC Rectifier for DC motor loads
- Measurement and recording system (Multiplexer and computer)
- AC loads : Transformer and 1 phase induction motor
- DC loads : Separate shunt, series and compound excited direct current motors

The experiment was set up as a 24 V DC system. Four 12V, 125W PV modules were made up as an array by connecting two sets of two series-connected panels in parallel. A DC–AC inverter of 500 W was used to link the PV cells to the loads. For DC motors, an AC-DC rectifier was used. The electrical wiring connections in the system used 2.5 mm^2 copper cables.

VI. Experimental Applications

Two separate experimental sets have been designed to examine the transient operation of the PV cells feeding electrical machines. The system established for alternating current machines is shown in Fig. 4. As the alternating current machine, a single-phase induction motor and transformer were separately connected to the system and measurements were made.

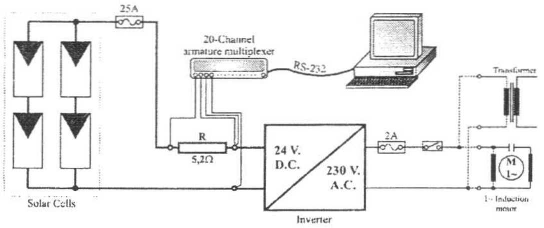


Fig. 4. Experimental setup for induction motor and transformer loads

The experimental system shown in Fig. 5 has been established to examine the effects of the transient regimes of direct current machines. Measurements were made for four basic DC machines: serial, shunt, compound and separately excited DC motors.

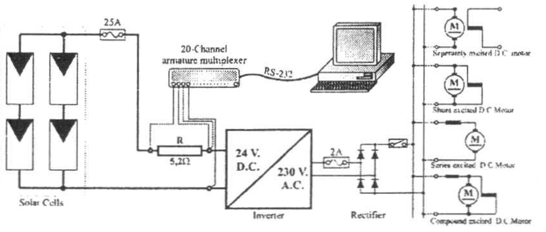
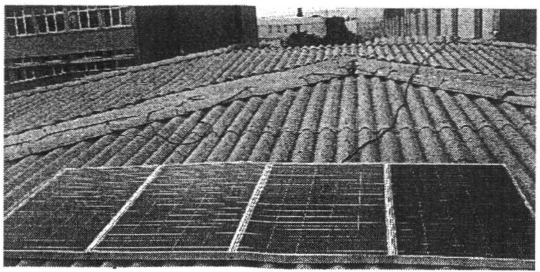
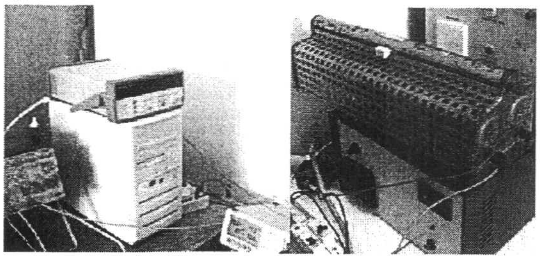


Fig. 5. Experimental setup for DC motor loads

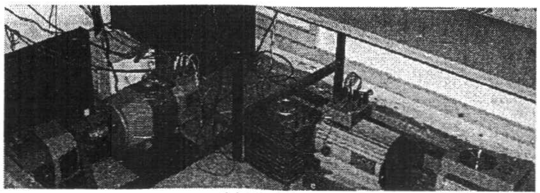
Measurements for both experimental systems were made with a multiplexer device connected to a computer through an RS-232 communication system. Multiplexer devices can take measurements at 0.1 sec intervals and transfer the measurement values to the computer. The values of the current and voltage drawn by each electrical motor from the PV batteries were measured and recorded at 0.1 sec intervals. Measurements were continued until the startup step was completed and steady-state operation was achieved (nearly 10 s). At the end of the measurements, the current values were multiplied by the voltage values to find the power drawn from the cells. By making appropriate unit conversions, curves showing the power changes as a function of time were prepared. Some photographs of experimental set are given in Figs. 6.



(a) Photovoltaic cells



(b) Measurement systems and inverter



(c) Machines

Figs. 6. Experimental setup photographs

At the end of the experimental tests, curves of the changes observed as a function of time of the power drawn at startup by alternating and direct current electrical machines from PV batteries and their wavelet decompositions are shown in Figs. 7, Figs. 8 and Figs. 9 respectively.

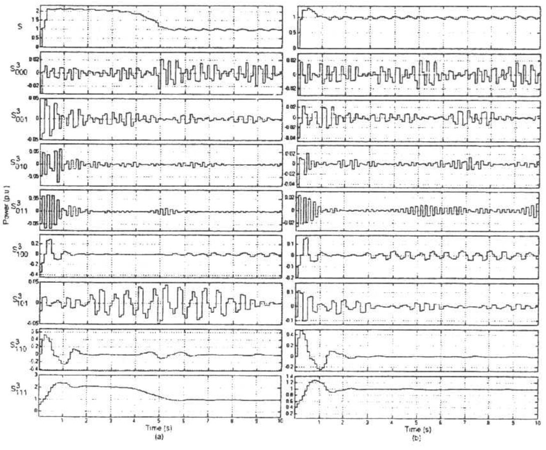
Wavelets can be used as an aid to the detection of features in transient states. Because of the nature of wavelet packet transforms, high and low frequency components of the input signals can be obtained. In general, the first level of the wavelet filter bank decomposes the input signal into two uniform frequency bands ($f_{max}/2$). The second decomposes the input signal into four frequency bands ($f_{max}/4$) and the third level decomposes the input signal into eight frequency bands ($f_{max}/8$). The sequence of frequency decomposition is due to the downsampling before each filtering operation. This shifting in the frequency domain is known as frequency translation [18], [19].

The measured input signal has a low frequency, namely 10 Hz. For all the electrical machines a third level decomposition was carried out using db4. The wavelet decompositions and their frequency ranges are given in Table I.

TABLE I
WAVELET PACKET DECOMPOSITION AND FREQUENCY RANGE

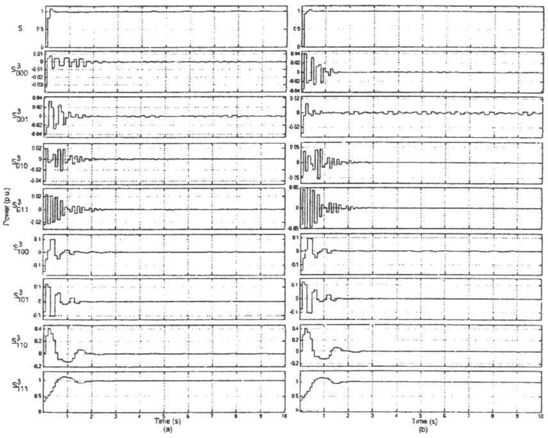
Decomposition	Frequency Range (Hz)
$s_{000}^3(n)$	4.375 ~ 5
$s_{001}^3(n)$	3.75 ~ 4.375
$s_{010}^3(n)$	3.125 ~ 3.75
$s_{011}^3(n)$	2.5 ~ 3.125
$s_{100}^3(n)$	1.875 ~ 2.5
$s_{101}^3(n)$	1.25 ~ 1.875
$s_{110}^3(n)$	0.625 ~ 1.25
$s_{111}^3(n)$	0 ~ 0.625

When Table I is examined, it can be seen that $s_{111}^3(n)$ is the lowest frequency component and $s_{000}^3(n)$ is the highest frequency component. The increase in frequency is constant (0.625 Hz) so at the end of the decomposition eight uniform frequency sub-bands are obtained.



Figs. 7. Decomposition signals a) Induction Motor b) Transformer

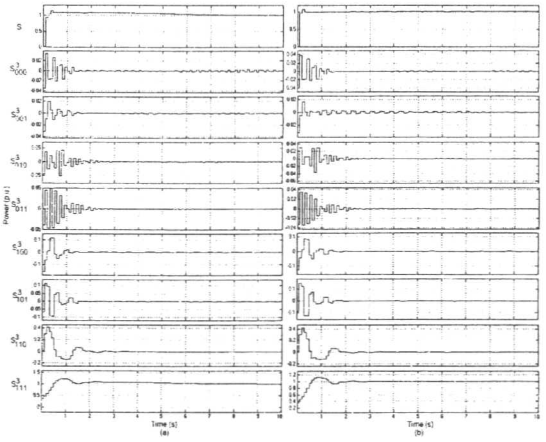
In Figs. 7 the input and decomposition signals of an induction motor and transformer are shown. It is clear that the induction motor has been the most forced electrical machine for PV systems. When we consider the input signals of the induction motor and transformer, we conclude that the startup power of this motor is 2.14 times higher than its nominal power value. On the other hand, the startup power of transformers is shown to be 1.3 times higher than the nominal value. The transient powers of induction motors, except for $s_{101}^3(n)$, are bigger than that of transformers. Even though the transient state had finished there are still continuous ripples at higher frequencies. These ripples originate from the inverter and AC machine characteristics and therefore the low frequency decompositions should be evaluated to examine these transients over time. The transient time of $s_{110}^3(n)$ and $s_{111}^3(n)$ decompositions lasted nearly at 6.5 seconds for the induction motor and 3.5 seconds for the transformer.



Figs. 8. Decomposition signals a) Serial Excited b) Shunt Excited

DC motors have also produced similar characteristics in terms of startup power and transient times. When we consider input signals from DC motors (Figs. 8 and Figs. 9), we conclude that the shunt motor has demanded a startup power that is 1.05 times higher than the nominal value. This value has been calculated as 1.1 times higher for the serial motor, 1.07 times higher for the compound motor and 1.15 times higher for an external excitation motor. When the decomposition signals of DC motors (Figs. 8 and Figs. 9) are examined, it can be seen that the input signals and their decompositions are very similar. For all DC machines, low frequency decompositions ($s_{100}^3(n), s_{101}^3(n), s_{110}^3(n)$, $s_{111}^3(n)$) are very close to each other but there are differences between high and middle frequency decompositions ($s_{000}^3(n)$, $s_{001}^3(n)$, $s_{010}^3(n)$, $s_{011}^3(n)$). The magnitude order of $s_{000}^3(n)$ decompositions is; shunt > compound > serial > separately excited motor. The magnitude order of $s_{001}^3(n)$ decompositions is; serial > separately excited > compound > shunt motor. The magnitude order for $s_{010}^3(n)$ and $s_{011}^3(n)$ decompositions are the same; shunt and separately excited have equal magnitude > compound > serial motor.

High frequency decomposition transient times are different from low frequency decompositions times. There are some continuous ripples in the high frequency decompositions (especially in shunt and compound motors). When the longest transient time of the decomposition signals are examined, the transient periods were calculated as 2.6 s for the shunt motor, 2.9 s for the serial motor, 3.2 s for the compound motor and 3.6 s for the external excitation motor. It has been noted that the transient time of a separately excited machine was longer than that of other DC motors. In addition, the demanded startup power was rather higher than that of the others as well. Such a situation results from the fact that the nominal excitation current is applied to the windings before the motor starts. Thus, the motor starts operating exposed to the nominal magnetic field. This, in turn, brings a higher magnetic friction and power loss at startup. Such a situation is not the case for other motors.



Figs. 9. Decomposition signals a) Separately Excited b) Compound Excited

VII. Conclusion

Photovoltaic systems are designed based on the nominal load of the receiver they will feed. Due to their structural features, the level of the startup current does not have any significant effect on the photovoltaics in the short term. However, if the startup current is not taken into consideration, particularly for systems that are frequently connected and disconnected, the high power drawn may result in over-heating of the modules and decrease of the efficiency of the photovoltaic system. Moreover, power demands that are too high and that last too long may not be met, particularly for PV systems feeding alternating current machines. In this case, the startup performance of the machine will be quite negatively affected. As well as the decrease in the machine efficiency, the efficiency of the photovoltaic batteries will decrease more than expected in the long run and their life cycle will be shortened. Therefore, it is of great importance to consider the power quality as well as the power load when designing photovoltaic systems. For systems that feed alternating current machines, the load should be calculated on the basis of a specific value above the nominal operating value and the system should be designed accordingly.

As shown in this study, using the wavelet packet transform technique for transient analysis is useful for comparisons of the transient power of electrical machines and identification of certain transient times for research and educational purposes

Appendix

TABLE A.1
ELECTRICAL SPECIFICATIONS OF PV MODULES

Rated output (P_{mpp})	Rating values
Output tolerance (DP_{mpp})	125 W
Guaranteed minimum output ($P_{mpp\ min}$)	5% / -0%
Nominal voltage (U_{mpp})	18.8 V
Nominal current (I_{mpp})	6.65 A
Open circuit voltage (U_{OC})	24.0 V
Short circuit current (I_{SC})	7.27 A
Module efficiency	12.5%
Temperature coefficient a (P_{mpp})	-0.491%/°C
Temperature coefficient b (I_{SC})	+4.7%/°C
Temperature coefficient c (U_{OC})	-87.4%/°C
Temperature coefficient d (I_{mpp})	+0.3%/°C
Temperature coefficient e (U_{mpp})	-91.9%/°C
Normal operating cell temperature (NOCT)	46.6°C
Normal permissible system voltage	600 V
Maximum permissible system voltage	1000 V

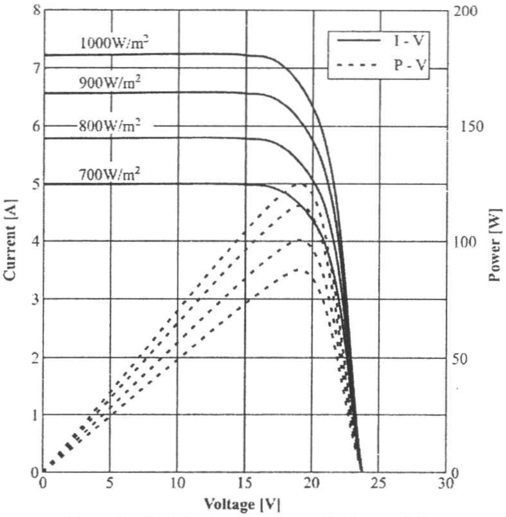


Fig. A.1. Electrical performance of solar modules

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