Determination of Optimal Modules Number in Photovoltaic Strings for Inverter Power Maximization

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Abstract – **In this paper is presented a way for determination the optimal number of photovoltaic (PV) modules connected in a string. The aim for optimal number of modules determination is to obtain the optimal working voltage on inverter DC side and activate the device for Maximal Power Point Tracker – MPPT. The calculations are performed according the PV module and inverter data for Standard Test Conditions and defined specific working scenarios. After that, a way for determination of optimal number of strings connected to the inverter is shown. The calculations are performed under condition to gain the maximum active power from the inverter in all possible working scenarios (working states of the inverter with activated MPPT device). To avoid the inverter damage, during the calculations the inverter limiting working performances are taken into account. The proposed methodology in this paper is practically applied on PV modules from Yingli Solar Company of China and inverter from the SMA Company of Germany.**

Keywords – **Photovoltaic modules, DC/AC inverter, maximum active power, photovoltaic power plants.**

I. INTRODUCTION

The total energy from the solar radiation which yearly reaches the Earth is about 10^{18} kWh/year. This energy is 60.000 times greater then the yearly consumed electricity and 25 times greater from the all fossil energy potentials on the Earth. Because of the energy losses in the atmosphere (absorption and reflection) the average daily energy reaches the Earth surface is about 5,52 kWh/m^2 [1]. For the specific location on the Earth the exact value of solar radiation will depend of a latitude, longitude and elevation of the location, season (position of the Sun over horizon), temperature, presence of: fog, clouds, pollution, wind etc. Consequently, it is obvious that the Sun is the biggest and main source of renewable energy. The geographical position and a climate in the Republic of Macedonia offer very good perspective for solar energy utilization. The average daily radiation per year is between 3,4 kWh/m^2 in the north part of the country (Skopje) and 4,2 kWh/m^2 in the south-west part (Bitola). Total solar radiation per year varies from minimum 1250 kWh/m^2 in the north to maximum 1530 kWh/m^2 in the south-west part of the country. Therefore, the yearly average solar radiation is 1390 kWh/m^{2}year [2]. In the Study for renewable sources of energy in the Republic of Macedonia [2] and Strategy for energy sector development in the Republic of Macedonia in the period 2008-2020 [3] (published by the Macedonian Academy of Sciences and Arts) is predicted construction of 10 to 30 MWp photovoltaic power plants (PVP). These PVP will produce electricity from 14 to 60 GWh/year.

Solar energy transformation in the electricity is directly performed in the photovoltaic (PV) solar cells grouped in solar modules. For more electrical power, the modules are connecting in serial and form a string. More strings can be connected in parallel. The electricity produced in PV modules is on direct current (DC). The electricity conversion from DC to alternative current (AC) is performing in the inverters. With the set of PV modules (connected in strings) and inverter(s) altogether connected in proper way, the PVP are constructed. The purpose of PVP is production of electricity directly with solar energy transformation. The produced electricity can be used individually from separated consumers (Off-Grid) or be injected into a power distribution system (On-Grid).

During the PVP design and construction it is necessary to take into account a way for strings forming and their connection to the inverter(s). These procedures are required because the aim is to get maximum produced electricity from the solar radiated energy on the PV modules surface in combination with inverter(s) optimal working performances.

In this paper from theoretical and practical aspect on the real case of applied PV modules and inverter a way for determination of optimal photovoltaic modules number in a string and optimal strings number connected into inverter for active power maximization is presented.

In the section II the main characteristics for photovoltaic modules and inverters necessary for proposed calculations are given. The calculations for certain types of PV module and inverter are shown in section III. The conclusions are drawn in the section IV.

II. PHOTOVOLTAIC MODULE AND INVERTER CHARACTERISTICS

The determination of the optimal PV modules number in a string depends of the module characteristics and optimal working performances of the inverter in which the string(s) is/are connected. The theoretical calculations are practically applied on the PV module Yingli Solar type YL235P-29b with power output of 235 Wp [4].

The current-voltage (*I-V*) diagram of this type of PV modules is given on Fig. 1. On this figure can be seen that for different intensity of solar radiation exists only one point on the *I-V* diagram for which the product *V·I* has maximal value. More exactly, for each curve exists only one working point (named Maximal Power Point – MPP) in which the PV

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module voltage is V_{MPP} and flows current I_{MPP} with production of maximal power $P_{MPP} = V_{MPP} \cdot I_{MPP}$.

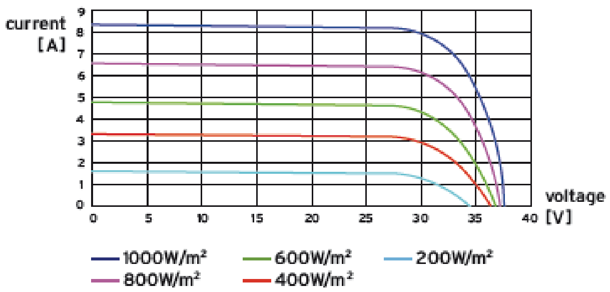

Fig. 1. *I-V* diagram for PV module type YL235P-29b.

In case for Standard Test Conditions – STC (radiation 1000 W/m^2, air mass coefficient AM=1,5 and temperature T=25^{0}C) applied on PV module YL235P-29b, the *I-V* and $P = f(I,V)$ diagrams are shown on Fig. 2. The function $P = f(I,V)$ shows how PV module output power depends from module voltage and current. Open circuit voltage, signed as V_{OC} is a voltage on not connected plugs of the radiated PV module on STC. A short circuit current, signed as I_{SC} is current through the PV module output when the plugs are short connected.

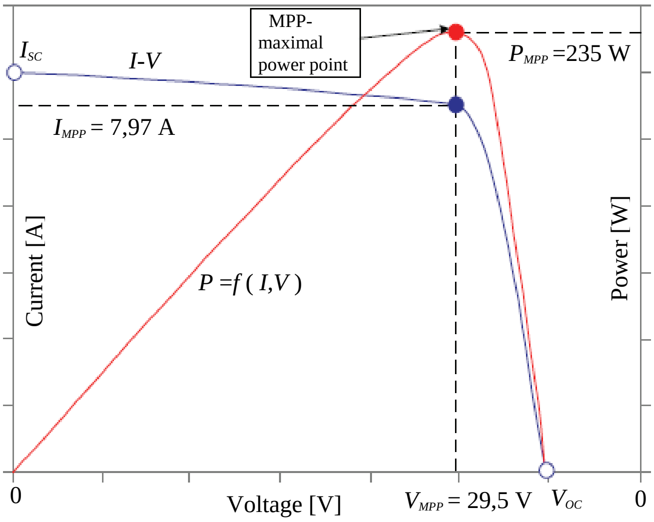

Fig. 2. *I-V* and *P =f (I,V)* diagrams for module YL235P-29b.

The main aim for calculation of optimal PV modules number in a string is to gain maximal active power from the string. In other words, obtained string voltage should be in such interval that with application of Maximum Power Point Tracker (MPPT) device built in the inverter provides inverter working voltage $U_{MPPT} = V_{MPP}$ and current through inverter I_{MPP} . The other electrical and thermal characteristics for the PV module type YL235P-29b for STC conditions are given in Table I.

The electricity produced by a string or group of strings connected in parallel is on DC voltage. It is necessary to convert the electricity from DC to AC voltage if PVP will be connected on a grid. For that purpose group of strings is connected on DC/AC inverter(s).

TABLE I
ELECTRICAL AND THERMAL PV MODULE CHARACTERISTICS [4].

PV module type		**YL235P-29b**
Power output	[W]	235,0
Power output tolerance	[%]	± 3
Module efficiency	[%]	14,4
Voltage at P_{max}, V_{MPP}	[V]	29,5
Current at P_{max}, I_{MPP}	[A]	7,97
Open circuit voltage V_{OC}	[V]	37,0
Short circuit current I_{SC}	[A]	8,54
Nominal operation Cell Temp. NOCT	[^{0}C]	46 ±2
Temperature coefficient ΔI_{SC}	[1/^{0}C]	+ 0,0006
Temperature coefficient ΔV_{OC}	[1/^{0}C]	– 0,0037
Temperature coefficient ΔV_{MPP}	[1/^{0}C]	– 0,0045

This type of inverter converts the electricity from DC voltage on AC voltage with minimal losses of electricity. If in the inverter has built in the MPPT device in certain intensity of solar radiation the group of strings will delivered maximum DC power to the inverter. For practical analysis in this paper, inverter type SMA SMC 11000TL [5] is taken in consideration. This inverter is from German producer SMA Solar Technology AG and has very good characteristics. The efficiency curves [5], for different AC powers P_{AC} (on the output) and different DC voltages V_{DC} (on the DC input) are shown on Fig 3.

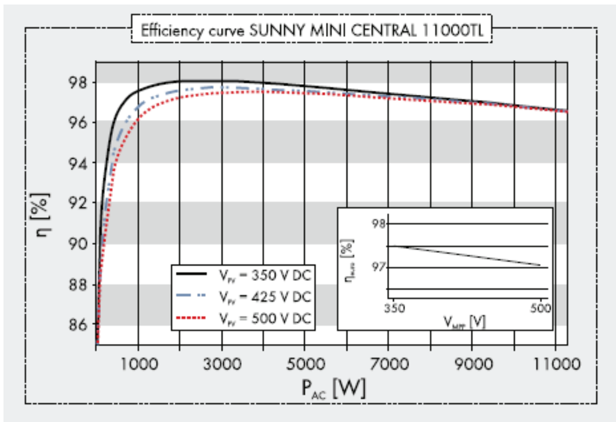

Fig. 3. SMC 11000TL inverter efficiency η[%] curves [5].

All technical data for the inverter necessary for determination of optimal PV modules number in a string and optimal number of strings connected into inverter DC input are given in Table II. It should be taken into account that practically only 5 strings can be connected to the inverter DC input with one MPPT device.

TABLE II
TECHNICAL DATA FOR INVERTER TYPE SMC 11000TL [5].

Input (DC)		
Maximum DC power	[W]	11.400
Maximum DC voltage	[V]	700
MPP voltage range	[V]	333 − 500
DC nominal voltage	[V]	350
Minimum DC voltage / start voltage	[V]	333/400
Maximum input current / per string	[A]	34/34
Number of MPPT / strings per MPPT	No	1/5
Output (AC)		
AC nominal power (230 V, 50 Hz)	[W]	11.000
Nominal AC voltage range	[V]	180 − 260
AC grid frequency range	[Hz]	50 - 60±4,5
Maximum output current	[A]	48
Power factor (cosφ)	[p.u.]	1
Efficiency / Euro-eta	[%]	98,0 / 97,5

III. DETERMINATION OF OPTIMAL NUMBER OF PV MODULES IN A STRING AND STRINGS IN INVERTER

For certain intensity of solar radiation the string or group of strings (PV generator) will delivered maximum DC power to the inverter if it's MPPT device is activated. According to the technical data of the inverter SMA SMC 11000TL (Table II), the MPPT device will be active if inverter input DC voltage U_{PV} is between 333 and 500 V, or:

$$U_{MPPT,\min} = 333\,V \le U_{PV} \le 500\,V = U_{MPPT,\max}\,. \qquad (1)$$

This voltage range should be achieved during the long time of PV generator operation. According to the recommendations of inverter producer it is necessary to check the PV generator voltage in the Maximal Power Point V_{MPP} for PV cells temperature of 15 ^{0}C and 70 ^{0}C. The V_{MPP} for a PV module on temperature T can be calculated by Eq. (2), [6]:

$$V_{MPP,T} = V_{MPP,STC}\left[1 + \frac{\Delta V_{MPP}}{100}(T-25)\right], \qquad (2)$$

where ΔV_{MPP} is temperature coefficient for voltage changing in MPP and $V_{MPP,STC}$ is PV module voltage in MPP for STC. These values for PV module type YL235P-29b are: $\Delta V_{MPP} = -0{,}45\,\%/^0\mathrm{C}$ and $V_{MPP,STC} = 29{,}5$ V. Applying the Eq. (2) for the proposed PV module obtained values are: for cells temperature T=15 ^{0}C the MPP voltage is $V_{MPP,15} = 30{,}8$ V and for T=70 ^{0}C $V_{MPP,70} = 23{,}5$ V.

Taking into account recommendations and also parameters of inverter and PV module the permitted number of PV modules in a string can take values from $n_{\min}$ to $n_{\max}$. For the proposed inverter and PV module these numbers are obtained through Eqs. (3) and (4) taken from [6]:

$$n_{\min} = \frac{U_{MPPT,\min}}{V_{MPP,70}} = \frac{333}{23{,}5} = 14{,}17 \Rightarrow n_{\min} = 15 \text{ modules/string} \qquad (3)$$

$$n_{\max} = \frac{U_{MPPT,\max}}{V_{MPP,15}} = \frac{500}{30{,}8} = 16{,}23 \Rightarrow n_{\max} = 16 \text{ modules/string.} \qquad (4)$$

Inverter producers proposed maximal value for input DC voltage. For inverter SMC 11000TL this voltage is 700 V. During the calculation process for PV module number in a string it is necessary to check if string voltage exceeds maximal input DC voltage. For this check the cells temperature should be T=–10 ^{0}C. The worst case for voltage increasing is when the PV string (or PV generator) is working in open circuit. If the cells temperature is different than that in STC, the open circuit voltage can be calculated with Eq. (5), [6]:

$$V_{OC,T} = V_{OC,STC}\left[1 + \frac{\Delta V_{OC}}{100}(T-25)\right]. \qquad (5)$$

Temperature coefficient for open circuit voltage changing for PV module YL235P-29b is $\Delta V_{OC} = -0{,}37\,\%/^0\mathrm{C}$. According to this data and Eq. (5) for cells temperature T=–10 ^{0}C, $\Delta V_{OC,-10} = 41{,}8$ V.

For 15 serial connected PV modules input DC voltage to the inverter will be $U_{PV,15} = 15 \times 41{,}8 = 627{,}0$ V whereas for 16 PV modules will be $U_{PV,16} = 16 \times 41{,}8 = 668{,}8$ V. It is obvious that in both cases the input DC voltage to the inverter don't exceed 700 V.

According to the technical data for the inverter SMA SMC 11000TL maximal power on the DC input (from PV generator side) is 11400 W. In real working conditions PV module maximum (peak) power cannot be greater than power on STC. For the proposed PV module YL235P-29b this power is 235 Wp. In case for 15 PV modules, the peak power of a string is $15 \times 235 = 3525$ Wp whereas in case for 16 PV modules $16 \times 235 = 3760$ Wp. Technically it is possible to connect 5 strings to the proposed inverter. However, taking into account before explained voltage and maximal DC input power limits for the chosen type of PV modules, the optimal number of strings that can be connected to the inverter is 3. Therefore, the PV generator should be constructed with 3 strings connected in parallel with same number of PV modules per string.

In case for 15 PV modules per string the peak power to the inverter DC input will be $3 \times 3525 = 10575$ Wp whereas in case for 16 PV modules per string $3 \times 3760 = 11280$ Wp. The main purpose in PVP designing is to obtain the maximum active power from the inverter as it is possible. According the above conducted considerations the optimal number of PV modules per string is 16 (Fig. 4 a)) and optimal number of parallel strings connected on inverter DC input is 3 (Fig. 4 b)).

Finally, it is necessary to check if the current of calculated number and configuration of modules and strings doesn't exceed limited maximal current of the inverter. According to the technical data in Table II, for the proposed inverter value of this current is $I_{PV,\max} = 34$ A. Maximal current which can flow through a string is short current of PV modules.

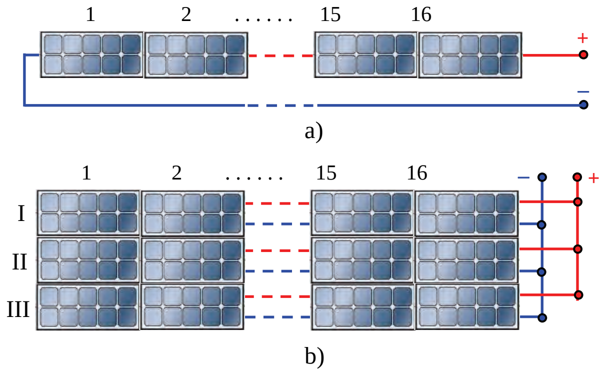

Fig. 4. a) String with 16 PV modules b) PV generator with 3 strings.

During the calculations it can be taken into account that the value of this current rises when the cells temperature rise. For the proposed PV module the short current is $I_{SC,STC} = 8{,}54$ A on STC and temperature coefficient is $\Delta I_{SC} = 0{,}06\ \%/{}^{0}\mathrm{C}$. Short current value for cells temperature T=70 ^{0}C can be calculated according Eq. (6), [6]:

$$I_{SC,T} = I_{SC,STC}\left[1 + \frac{\Delta I_{SC}}{100}(T - 25)\right]. \qquad (6)$$

With the above adequate quantities and applying Eq. (6) the PV module short current (which is the same as a string short current) $I_{SC,70} = 8{,}77$ A is calculated.

Because the PV generator is consist of 3 parallel connected strings maximum current in the inverter DC input can be short current of the PV generator or $3 \times 8{,}77 = 26{,}31$ A. Therefore, the inverter maximum DC input current of 34 A (Table II) will not be exceed. Taking into account all considerations it can be conclude that 3 parallel connected strings with 16 PV modules per string is optimal combination from the aspect of maximum gained active power for certain solar radiation intensity. This combination of PV modules and strings totally satisfy all limitations and recommendations for accepted PV modules YL235P-29 and inverter SMA SMC 11000TL.

IV. Conclusion

During the designing and construction of PVP it is necessary to gain maximum power from the chosen equipment for certain solar radiation intensity. Beside selection the quality equipment, it is required to match optimal PV generator parameters with the inverter parameters. In this paper is presented a way for determination of optimal photovoltaic modules number in a string and optimal strings number connected into inverter for active power maximization. All limiting factors of the inverter as: MPPT device working voltages, maximal permitted voltage and current are taken into account. On a real case of chosen types of PV module and inverter are performed calculations. Step by step is explained way of calculations applying technical data of PV module and inverter. The obtained results are analyzed and commented.

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