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A Noval Approach of Array to Inverter Matching of Utility Scale Solar PV Plants

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***ABSTRACT*- The array to inverter matching of a utility scale solar PV plants are necessary for the PV plant design. In practical environment at low temperatures, the module voltage increases. If the inverter is switch off on a sunlit winter day, this can guide to the open-circuit voltage being moreover high when it is switch back on again. At high temperature during summer, modules on a roof can easily heat up to around 70°C. If the working voltage of the system drops lower than the minimum MPP voltage of the inverter, this would no longer feed the maximum possible power and, in the worst case, would even switch off itself. To solve this problem, in this paper the goals of array to inverter matching is proposed and the maximum and minimum number of modules in series per string and the number o f modules connected in parallel for the inverter is calculated using pv syst software, also the MATLAB/SIMULINK model for the PV array designed depending on the specifications of the module selected.**

In this paper we selected a site which has a Global Horizontal Irradiance of 5.65 kWh/m^2/day, and requires an area of 160582m^2 for developing a 25MW utility scale PV power plant having 50 inverters, for each inverter has 2000 modules, connected 20 in series and 100 in parallel and has an annual yield of 41,313 MWh.

***Key words*: photovoltaic (PV), utility scale solar PV plant, PV Syst software.**

I. INTRODUCTION

In the most recent time, fresh energy sources have been planned and urbanized due to the need and regular increase of expenses of vestige fuel. On additional hand, vestige fuels have a enormous pessimistic blow on the atmosphere. In this circumstance, the novel energy sources are basically non-conventional energies [1]. It is predictable that the electrical energy generation from non conventional energy sources will boost from 19% in 2010 to 32% in 2030 most important to a subsequent decline of CO2 emission [2]. The planetary PV systems have established that they can produce power to extremely minute electronic devices up to utility range PV power plant. The current power system is more and more attractive benefit of solar power systems incoming the marketplace. Solar PV power systems setting up in the region of the universal demonstrate a almost exponential boost.

Utility-scale PV plants are typically owned and operated by a third party and sells the electricity to a market or load serving entity through a Purchase Power Agreement (PPA). Utility scale systems that can reach tens of megawatts of power output under optimum conditions of solar irradiation [3]. These systems are usually ground mounted and span a large area for power harvesting [16]. Several components are needed to construct a grid coupled PV system to perform the power generation and conversion functions [4]. A PV array is used to transfer the light from the sun into DC current and voltage [3]. A three phase inverter is then attached to perform the power conversion of the array output power into AC power appropriate for injection into the grid [16] [15]. A harmonics filter is additional after the inverter to diminish the harmonics in the output current which result from the power conversion process [17]. An interfacing transformer is connected after the filter to step up the output AC voltage of the inverter to match the grid voltage level. The feat of a PV system is in general evaluate under the standard test condition (STC), where an regular planetary spectrum at AM1.5 is used, the irradiance is standardize to 1000W/m^2, and the cell hotness is defined as 25^{o}C [10] [11]. On the other hand, under actual working circumstances with changeable irradiance as well as major temperature changes in the ground most profitable modules do not automatically perform as in the condition given by the manufacturers [11]. The array to inverter matching of a utility scale solar PV plants are necessary for the PV plant design and the goals of array to inverter matching proposed in this paper. The major goal of matching an array to an inverter is to make sure that the inverter can capture a high proportion of the available energy that the array produces for the period of all of the environmental circumstances probable at the site. Frequently an inferior goal is to capitalize on the inverter ability so that the inverter will work at or near full power throughout high irradiance periods without power restrictive. It is important that power restrictive happen only for the period of excellent or temporary conditions not under ordinary working situation.

II. ARRAY TO INVERTER MATCHING

The overall power of the PV system can decides the number and power rating of inverters [19]. The solar array and inverter(s) have to be optimally coordinated to each other's yield values. The insignificant power of inverters can be ±20 per cent of the PV array yield power under STC depending in the lead the inverter and module expertise and the local surroundings such as local insolation and orientation of the modules. For sizing of PV plant the ratio between the PV array power and inverter power is 1:1 [19]. The level of the inverter's voltage is the addition of the voltages of the succession attached modules in a string. Since the voltage of the whole PV array depends upon the hotness, tremendous cases of wintry weather and summer. In order to make feasible inverters to be optimally coordinated to the solar array, it is important to take the modules hotness and irradiance in service parameters into description [18]. The working range of the inverter has to be matched with the *I-V* curve of the PV array. In order to make possible inverters to be optimally matched to the solar array following considerations are taking into account. Those are Maximum numeral of modules attached in series per string, Minimum numeral of modules attached in series per string, Maximum numeral of strings linked in parallel per inverter and Maximum array capacity.

A. Maximum number of modules in series per string.

The primary boundary is defined by a wintry weather temperature. At low temperatures the module voltage increases as shown in fig.2 [20]. The maximum voltage that can take place in a working circumstance is the open-circuit voltage at low temperatures [18]. If the inverter is switched off on a fair wintry weather day, this can guide to the open-circuit voltage being too high when it is switched on again. This voltage must be lower than the maximum DC input voltage at the inverter; otherwise the inverter can be broken. Thus, the maximum numeral of series-connected modules is consequential from the proportion of the maximum input voltage of the inverter and the open-circuit voltage of the module at low temperature [19]. The maximum figure of modules for string can be calculated by using the equation (1) to (3) mentioned below.

$$N_{max} \leq \frac{\text{inverter maximum dc input voltage}}{\text{maximum module voltage}(V_{oc-max})} \quad (1)$$

$$V_{oc\text{-}max} = V_{oc} + \{(\begin{matrix}\text{temperature}\\ \text{difference}\end{matrix}) \times (\begin{matrix}\text{temperature}\\ \text{co - efficient of } V_{oc}\end{matrix})\} \quad (2)$$

$$V_{oc\text{-}max} = V_{oc} + \{(T_{\_min} - T_{\_STC}) \times (\begin{matrix}\text{temperature}\\ \text{coefficient of } V_{oc}\end{matrix})\} \quad (3)$$

Where

N_{max} = Maximum number of modules in series per string.

V_{oc} =Open circuit voltage of the module.

$V_{oc\text{-}max}$ =Maximum module voltage.

$T\text{-}_{min}$ =Minimum temperature for the site.

$T\text{-}_{STC}$ =Temperature at Standard Test Conditions.

B. Minimum number of modules in series per string

During summer, modules on a roof can easily heat up to around 70°C. This temperature is generally used as a basis when determining the minimum number of modules in a string [18]. With open systems a maximum temperature of 60°C and full irradiance in summer a PV system has a lower voltage than at STC conditions due to the increased temperatures as shown in fig.2 [20]. If the operating voltage of the system drops below the minimum MPP voltage of the inverter, this would no longer feed the maximum possible power and in the worst case would even switch of itself. For this reason, the system should be sized such that the minimum numeral of series-connected modules in a string is derived from the minimum input voltage of the inverter at the MPP and the voltage of the module at the MPP at 70°C [19]. The following formulas from (4) to (6) provides the lower limit value for determining the number of modules in a series.

$$N_{min} \geq \frac{\text{minimum dc input voltage for the inverter}}{\text{maximum expected module maximum power voltage}(V_{mp\_min})} \quad (4)$$

$$V_{mp\_min} = V_{mp} + \{(\begin{matrix}\text{temperature}\\ \text{difference}\end{matrix}) \times (\begin{matrix}\text{temperature}\\ \text{coefficient of } V_{mp}\end{matrix})\} \quad (5)$$

$$V_{mp\_min} = V_{mp} + \{(T_{\_max} - T_{\_STC}) \times (\begin{matrix}\text{temperature}\\ \text{coefficient of } V_{mp}\end{matrix})\} \quad (6)$$

Where

N_{min} = Minimum number of Modules in Series

V_{mp} = Maximum power voltage

V_{mp_min} = Minimum expected module maximum power voltage

$T_{\_max}$ = Maximum temperature for the site

$T_{\_stc}$ = Temperature at Standard Test Conditions

C. Maximum number of strings in parallel per inverter

The highest figure of parallel strings that can be connected to the inverter without causing current limiting can generally firm by a simple calculation without the need for temperature adjustment. To calculate the maximum numeral of equivalent strings, divide the maximum inverter input current by either the module Maximum power current (Imp) or Short-circuit current (Isc) [19].

$$N \le \frac{\text{maximum inverter input current}}{\text{maximum power current at STC}} \quad (7)$$

Where N = Maximum number of Strings in Parallel

D. Maximum array capacity

The final step in formative the array to inverter match is to inspect the array maximum power. Some array configurations that do not go beyond the voltage or current constraints could still result in power levels that go beyond the inverter's output power capabilities. If this happens, precious solar-generated energy will be dissipate into the surroundings as waste heat or else vanished when the inverter is forced into power preventive [18].

Solitary method to match array input to inverter output power is to consider the array's PVUSA Photo Voltaic United States of America Test Condition rating. Power Test Condition (PTC) ratings better reflect real world performance. subsequent to matching an array's PTC rating to the inverter output power consider a factoring in the inverter's CEC (California Energy Commission) weighted efficiency. Inverter output power in this case should be less than or equal to the array PTC rating divided by the inverter's CEC weighted efficiency. Furthermore, the high irradiance conditions that could lead to inverter cutting or fleeting. The equation for manipulative the maximum number of modules in this manner is

$$\text{Inverter Power} \le N \times PTC \times \text{CEC weighted efficiency} \quad (8)$$

$$PTC = \text{fixed module power deratingfactor of } 0.90 \times P_{mp\_STC} \quad (9)$$

Where N = Maximum number of modules to the inverter

PTC = Power Test Condition

P_{mp_STC} = Maximum power at standard test condition.

Genuine full power inverter efficiency is somewhat lower than the weighted CEC efficiency. In adding together voltage fall, module inequality and array soiling could result in other system sufferers. A land based systems in an ideal world oriented to the sun for summer energy yield but high cell temperatures considerably derate peak power output. Wintry and comprehensible conditions at other times of the year are improbable to produce hypothetical high peak power outputs because the sun's incidence angle would not be idyllic. This is a case where oversizing the array in the proposed work may be acceptable. A further derating factor of 0.95 can be used to approximation the combined outcome of these supplementary factors.

$$\text{Inverter Power} \le N \times PTC \times \{\begin{matrix}\text{(CEC weighted efficiency)} \times \\ \text{(deratingfactor)}\end{matrix}\} \quad (10)$$

Where N = Maximum number of modules to the inverter

PTC = Power Test Condition

III. MODELING OF PHOTOVOLTAIC ARRAY

A Photovoltaic (PV) cells are used to convert the sunlight into direct current (DC). Due to the low voltages and current generate in a PV cell several PV cells are connected in series and then in parallel to form a PV module for desired output. The modules in a PV array are generally first connected in succession to obtain the desired voltages and individual strings are then connected in equivalent to allow the system to produce more current. The equivalent circuit of PV array is shown in fig.1 [6] [8] [9].

From the fig.1.

$$I_A = (I_{ph} N_P) - I_{sh} - I_d \quad (11)$$

The array output current is a function of I_{ph}, I_{sh} and I_d. The equations from (11) – (18) are the required to design a solar PV array.

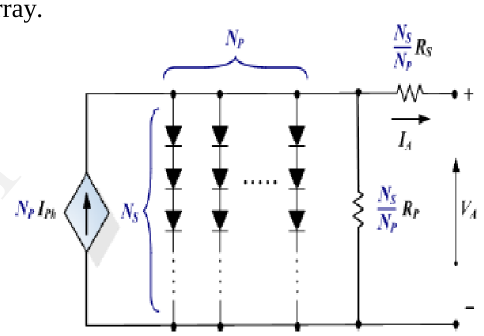

Fig.1.Equivalent circuit of a PV array.

$$I_{ph} = I_{rr}(I_{sc} + K_i(T_{op} - T_{ref})) \quad (12)$$

$$I_d = I_S N_P\{\{\exp \frac{[\frac{V + IR_S}{N_S}]}{n} \times V_T \times C\} - 1\} \quad (13)$$

$$V_T = \frac{KT_{OP}}{q} \quad (14)$$

$$I_S = I_{rs}[\frac{T_{OP}}{T_{ref}}]^3 (\exp \frac{q^2 E_g}{Kn} (\frac{1}{Tref} - \frac{1}{Top})) \quad (15)$$

$$I_{rs} = \frac{I_{sc}}{\exp(\frac{qV_{oc}}{KCT_{op} n})} - 1 \quad (16)$$

$$I_{Sh} = \frac{IR_S + V}{R_P} \quad (17)$$

$$V_T = \frac{KT_{OP}}{q} \quad (18)$$

Where

I_A PV array output current

I_{Ph} Solar cell photocurrent

I_{sh} Shunt current of PV array

I_d diode current of PV array

N_p number of modules in parallel

V_A array output voltage

R_s series resistance of the PV module

R_p parallel resistance of the PV module

I_{rr} cell reverse saturation current at temperature T_{ref}

I_{sc} short circuit current of the PV cell

K_i short circuit current temperature coefficient

T_{op} operating temperature of the PV cell in Kelvin's

T_{ref} reference temperature of the PV cell in Kelvin's

I_s Reverse saturation current equation at T_{op}

V_t terminal voltage of the pvcell

I_{rs} cell reverse saturation current at temperature T_{ref}

E_G band gap of the semiconductor used in the cell

K Boltzmann's constant, $1.380658e-23$ J / K

q Electron charge, $1.60217733e-19$ Cb

N_s number of modules in series

N_p number of modules in parallel

n p - n junction ideality factor

C total number of cells in a PV module

In this paper we are considering a typical CS6P-250P PV modules and SMA Solar Technology AG 500 XT inverter for designing a 25MW utility scale solar PV plant as given in table 1 and table 2 respectively [11] [12].

Table.1 Parameters of a CS6P 250P solar array under Standard test condition (STC).

Manufacturers	Canadiasolar inc250 P
Technology	Poly
Maximum Power (P_{max})	250W
Rated power @ PTC (W)	227.6W
Module efficiency (%)	15.54%
Power tolerance	+2%
Maximum Power Voltage (V_{mpp})	30.1 V
Maximum Power Current (I_{mpp})	8.30 A
Open Circuit Voltage (V_{oc})	37.2 V
Short Circuit Current (I_{sc})	8.87 A
Voltage/Temperaturecoefficient(Kv)	-0.0034 V/K
Current/Temperaturecoefficient (Ki)	0.00065 A/K
Series Connected cells (C)	60X1

Table.2 SMA Solar Technology AG SC 500CP XT.

Manufacturer	SMA Solar Technology AG
Maximum PV power (P_{dc}) kW	560
Maximum open circuit voltage (V_{dc})	1000
MPPT circuits	1
MPPT range(V_{dc})	430-850
Maximum DC input current (I_{dc})	1250
Maximum Output power(P_{ac}) KW	500
Nominal output voltage (V_{ac})	243-310
AC output wiring	3wire w/neut
Maximum Output current (I_{ac})	1176
Maximum efficiency (%)	98.6
CEC-weighted efficiency (%)	98.4

By using the equations (1) – (10) and the data available in the table.1 and table.2 the number of modules connected in per string are 20 and the number of strings per inverter are 100 so the total number of inverters required for generating the 25MW are 50 each of capacity 500kW total number of modules are 1, 00,000, and also we are using the PV syst software for analyzing the same with practically the results are shown in the fig.3 and fig.4.

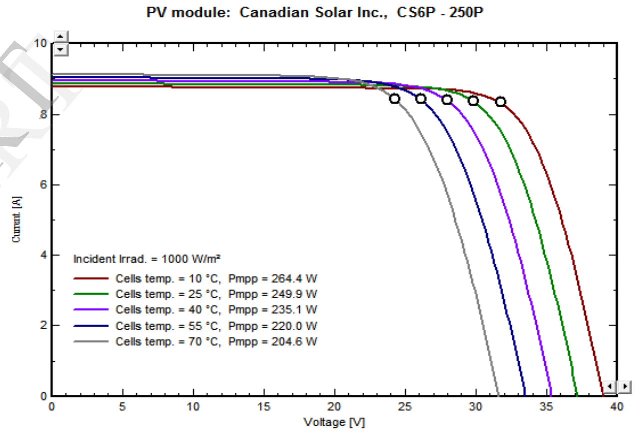

Fig.2 module behavior according to temperature [20]

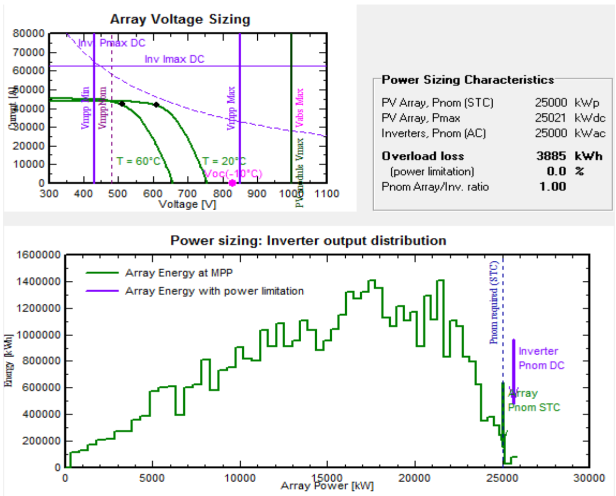

Fig.3. Power system sizing (solar PV modules and inverter)[20].

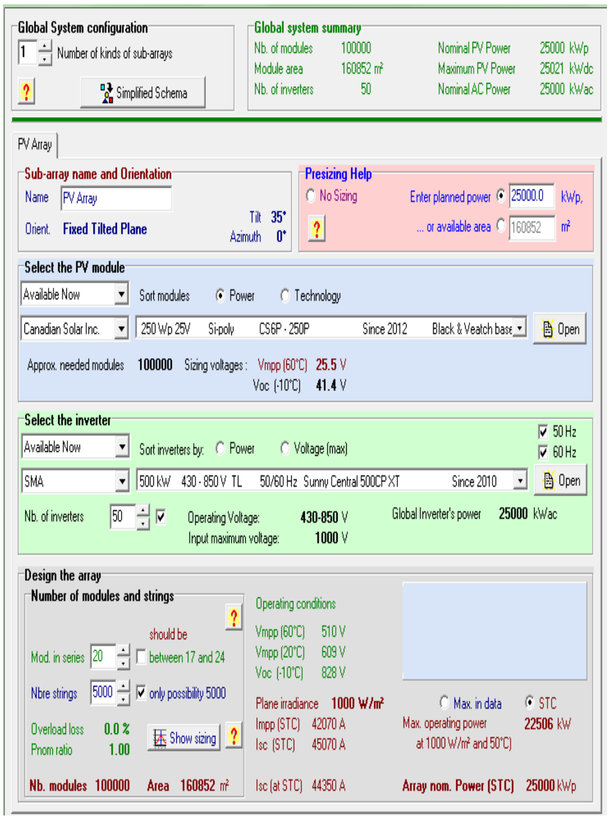

Fig.4. Solar PV power plant components sizing[20].

From the fig.3 the operating voltage of the inverter is in between 430 V to 850 V, operating current is 42,97A and the power generation is 22,506 kW. The total area required for generating 25MW is 1,60,852m^2; having tilt angle of 35˚ with south facing on ground based mounting structure [20].

IV. MATLAB/SIMULINK MODELING OF PV ARRAY PER INVERTER

By grouping the all the equations from (11) – (18) and the data available in the fig.3 the Simulink model for the PV array is shown in fig.5 [5] [7].

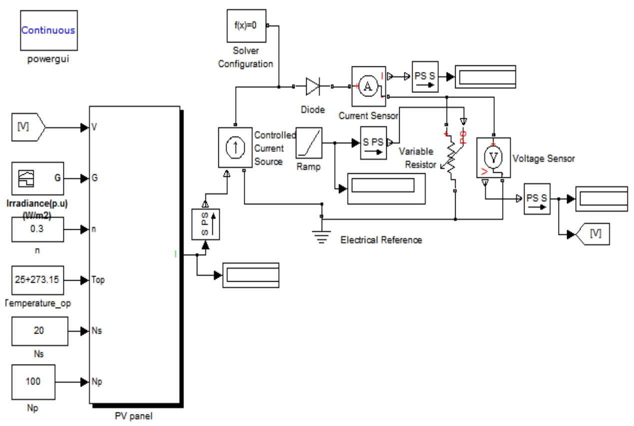

Fig.5.Simulink model of the PV array per inverter.

From fig.4 the number of modules per string is 20 and the number of string per inverter are 100. In this paper we are designing a 25 MW PV power plant that require 50 inverters each of capacity 500kW and the total number of modules are 1, 00,000 [20].

V. SIMULATION RESULTS AND DISCUSSIONS

The PV array voltage is powerfully dependent upon the temperature. The working range of the inverter must be coordinated with the *I-V* curve of the PV array [16]. The maximum occurring temperature is determined by the location of the system. This should be taken into account when determining the voltage change.

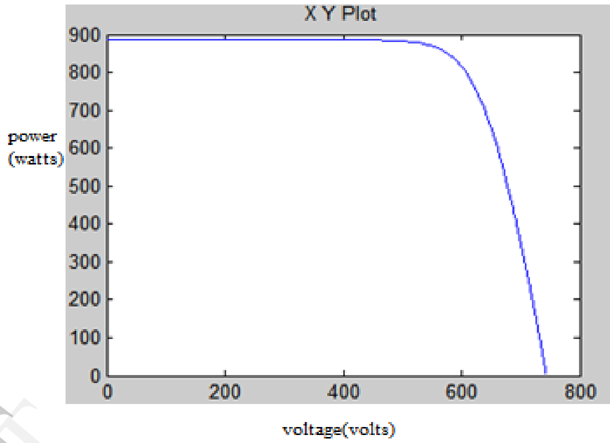

Fig.6 V-I Characteristics of PV array

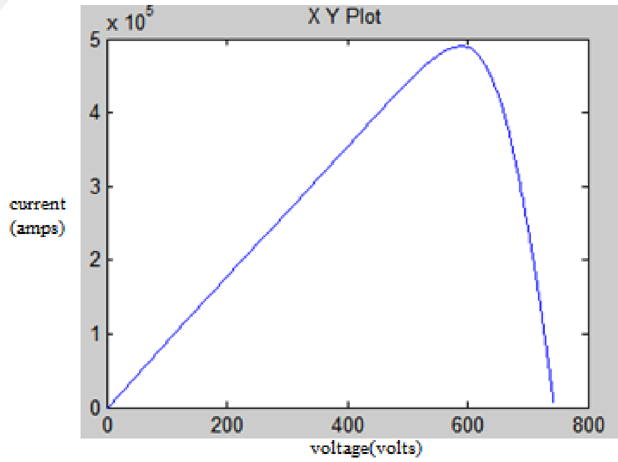

Fig.7 P-V characteristics of PV array

CONCLUSION

For developing a 25MW utility scale PV power plant in this paper a site which has a GHI of 5.65 kWh / m^2 / day is selected. It requires total area of 1, 60,582 m^2 and annual yield is 41,313 MWh. In this paper sizing of basics components of solar PV plant can be designed using the PV syst software and Simulink model for PV array per inverter is designed. The major goal of matching an array to an inverter is to make sure that the inverter can capture a high proportion of the available energy that the array produces for the period of all of the environmental circumstances probable at the site. Frequently an inferior

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goal is to capitalize on the inverter ability so that the inverter will work at or near full power throughout high irradiance periods without power restrictive. It is important that power restrictive happen only for the period of excellent or temporary conditions not under ordinary working situation.

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