

Design and Implementation of a Hybrid MPPT technique based on the Scan of the Power vs Voltage input characteristic of the inverter

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Abstract- The adoption of a Hybrid MPPT (HMPPT) technique is mandatory in PV applications operating under mismatching conditions. It is called Hybrid because it is neither only Distributed (on the PV modules) nor only Centralized (on the inverter). In this paper it is shown how to properly optimize an HMPPT technique based on the periodic scan of the Power vs. Voltage characteristic at the input of the inverter in order to locate the optimal operating value, from the energetic efficiency point of view, of the bulk inverter voltage. Therefore, numerical simulations and experimental measurements on a reduced scale laboratory prototype are carried out to confirm the validity of the theoretical predictions.

I. Introduction

In case of mismatch (due to clouds, shadows, dirtiness, manufacturing tolerances, aging, different orientation of parts of the PV field, thermal gradients etc.), the Power versus Voltage (P-V) characteristic of a PhotoVoltaic (PV) field may exhibit more than one peak, because of the presence of bypass diodes, and therefore Centralized Maximum Power Point Tracking (CMPPT) algorithms can fail. Moreover, the maximum power of a string of PV modules operating in mismatching conditions is lower than the sum of the powers which could be extracted by the PV modules if, each one of them, could operate in its Maximum Power Point (MPP) [1]. Distributed Maximum Power Point Tracking (DMPPT) architectures allow to overcome the drawbacks associated to mismatching phenomena. They are based on the use of module dedicated DC/DC converters (microconverters) realizing the MPPT for each module and central inverters [2-5]. The most frequently used architecture is the one adopting the series connection of the output ports of the microconverters. A not exhaustive list of commercial devices, developed with reference to such a DMPPT architecture, includes the following devices: SolarMagic Power Optimizers by National Semiconductors [6], SPV1020 produced by STMicroelectronics [7], etc. In the following, a system composed by a PV module with a dedicated DC/DC converter will be called Self Controlled PV Module (SCPVM). As for the topology of DC/DC converters adopted in DMPPT PV systems, from the aforementioned list, it is evident that SCPVMs based on the buck or on the boost or on the buck-boost topology are available on the market. In [3] advantages and drawbacks of such basic topologies are discussed, and the conclusion is that a practical compromise solution for series-connected DC/DC converters installed on all the PV modules of the string is generally represented just by the boost converter. Therefore, in the following we will refer to such a basic converter. Usually, 10-20 boost based SCPVMs are connected in series in order to achieve the desired value of the inverter's DC input voltage. Because of the series connection of the output ports of the SCPVMs, the output voltage V_{outk} of the kth SCPVM is given by [3]:

$$V_{outk} = \frac{P_{pank}}{i_{outk}} = \frac{V_b}{\sum_{k=1}^N P_{pank}} P_{pank} \quad (1)$$

where P_{pank} is the power extracted from the kth PV module and i_{outk} is the output current of the kth SCPVM. On the basis of eq. (1) the output voltage of the SCPVMs providing higher powers can become very large thus causing potentially dangerous voltage stresses. To prevent the output voltage of one or more SCPVMs from exceeding a given maximum value $V_{ds\ max}$, an output voltage limitation technique must be adopted [3]. In [8-10] it has been shown that, in order to get full profit from DMPPT, it is necessary that the bulk inverter voltage belongs to an optimal range whose position and amplitude are functions of the following factors: the number of PV modules and dedicated DC/DC converters in a string, the atmospheric operating conditions characterizing each PV module (irradiance and temperature values), the voltage and current ratings of the physical devices the DC/DC converters are made of, and the adopted DC/DC converter topology. Therefore the optimal range for the inverter input voltage continuously changes in time. In conclusion, the joint adoption of both a DMPPT technique, acting on the voltages of the PV modules, and a CMPPT technique, acting on the input voltage of the inverter, is mandatory. That is, a Hybrid MPPT (HMPPT) technique is needed. It is called Hybrid because it is neither only distributed (since it involves also the DC input inverter voltage v_b) nor only centralized (since it involves also all the PV module voltages). It is worth noting that the DMPPT technique and the CMPPT technique must be properly chosen and optimized. In fact, most inverter manufacturers adopt standard CMPPT techniques (e.g. the Perturb and Observe technique (P&O) [11]) that, because of the multimodal shape exhibited,

under mismatching operating conditions, by the P-V characteristic at the output of a string of SCPVMs may fail. In this paper a Modified P&O (MP&O) technique has been used as DMPPT technique while the adopted CMPPT technique is based on the periodic scan of the P-V characteristic and will be identified with the acronym CMPPTS. As concerns the MP&O technique, it allows to limit the output voltage of the SCPVMs. In particular, when v_{outk} exceeds a guard level $V_{out\ lim}$ ($v_{outk} > V_{out\ lim}$), thus approaching the voltage rating $V_{ds\ max}$ of power devices, it drives the k th SCPVM in the direction of decreasing output power, instead, when $v_{outk} < V_{out\ lim}$, it drives the k th SCPVM in the direction of increasing output power. It is desirable to adopt a value of $V_{out\ lim}$ which is as high as possible in order to profitably exploit the whole voltage rating ($V_{ds\ max}$) of SCPVMs' components. As general rule, the lower $V_{out\ lim}$ the lower the maximum power which can be extracted from the DMPPT PV systems. In particular, it can be shown that the value adopted by $V_{out\ lim}$ must fulfill the following inequality [8]:

$$V_{out\ lim} \leq \frac{V_{ds\ max} \left(1 - \frac{\Delta P_{pan}}{P_{pan}} \right)}{\left(1 + \frac{V_{ds\ max} \cdot \Delta P_{tot}}{N \cdot V_{oc} \cdot P_{pan}} \right)} \quad (2)$$

where N is the number of SCPVMs in the string, V_{oc} is the open circuit voltage of the PV module, ΔP_{pan} is the power variation of the PV module characterized by the highest value of the irradiance level in correspondence of a variation of amplitude equal to Δv_{pan_ref} of the reference voltage for the PV voltage, ΔP_{tot} is the total power variation of all the modules in correspondence of synchronous variations of amplitudes equal to Δv_{pan_ref} of the reference voltages for the PV voltages, P_{pan} is the maximum power which can be extracted by the PV module characterized by the highest value of the irradiance level. It is worth noting that, if there is no prior knowledge of the irradiance levels, the worst case value of ΔP_{pan} , ΔP_{tot} and P_{pan} must be adopted. Instead, if the irradiance levels of all the modules of the string are known, then ΔP_{pan} , ΔP_{tot} and P_{pan} can be easily and directly evaluated [11]. As for the CMPPTS technique, the scan of the P-V characteristic of the string of SCPVMs is used in order to locate the optimal operating value, from the energetic efficiency point of view, of the bulk inverter voltage v_b . Even if at a first glance, the application of such a CMPPT technique could seem trivial, indeed, it will be shown that much care is needed in order to avoid errors due to the peculiar shape assumed, under mismatching operating conditions, by the P-V characteristic of a string of SCPVMs. Such a curve is characterised by the possible presence of multiple peaks and/or flat regions and/or abrupt nearly vertical portions which may easily lead to the error of the CMPPTS technique, and, consequently, to a more or less consistent waste of the potentially available energy.

II. CMPPT Technique based on the SCAN of the P-V inverter input characteristic

The CMPPTS technique proposed in this paper is based on the periodic scan of the whole P-V characteristic of the string of SCPVMs in order to locate the operating value V_{b_opt} of v_b in correspondence of which the power P provided by the string of SCPVMs is maximum. The scan is carried out by means of the CMPPT controller (Fig. 1) which provides a staircase reference voltage signal v_{b_ref} which must be followed by v_b (Fig. 2). The amplitude of the steps of v_{b_ref} is equal to Δv_{b_ref} and the duration of each step is equal to T_b . The initial value V_{b_min} and the final value V_{b_max} of v_{b_ref} must of course belong to the allowed inverter input voltage operating range. v_{b_ref} assumes n different values: $V_{b_min}, V_{b_min} + \Delta v_{b_ref}, \dots, V_{b_max}$. It is:

$$n = 1 + (V_{b_max} - V_{b_min}) / \Delta v_{b_ref} \quad (3)$$

The n steady-state values of the total power which is extracted in correspondence of the n values assumed by v_{b_ref} are recorded, and, after the scan, the CMPPT controller sets the reference voltage for v_b to V_{b_opt} . The while scan needs a total time T_{tot} equal to $n \cdot T_b$.

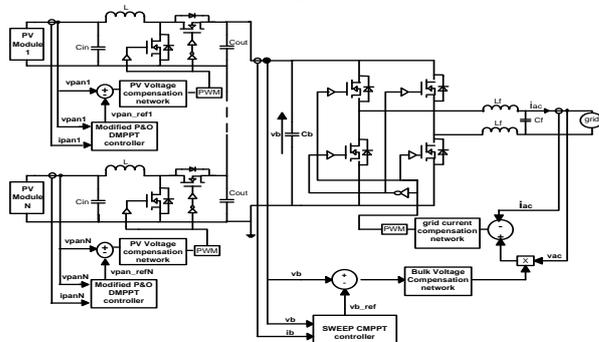


Figure 1: Grid-connected PV system adopting boost based SCPVMs with the output ports connected in series.

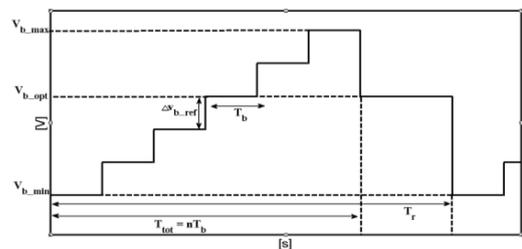


Figure 2: staircase signal v_{b_ref} .

As concerns the choice of Δv_{b_ref} it is worth noting that it must be carried out on the basis of two contrasting requirements. The first requirement can be explained on the basis of the following considerations. It is well-known that the voltage v_b across the energy-storage bulk capacitor placed at the interface between the array of SCPVMs and the inverter (Fig. 1) exhibits an oscillation with a frequency equal to the second harmonic of the grid frequency f_{line} and with a peak to peak amplitude Δv_{b_fline} equal to ([12]):

$$\Delta v_{b_fline} = \frac{P}{C_b 2\pi f_{line} V_{RMS}} \quad (4)$$

where V_{RMS} is the rms value of the input inverter voltage and P is the DC power injected into the grid. The worst-case (highest) value of Δv_{b_fline} is obtained by assuming $V_{RMS} = N \cdot V_{MPP}$ and $P = N \cdot V_{MPP} \cdot I_{MPP}$. Of course such an oscillation can lead the CMPPTS technique to the error due to the fact that, at the steady state, when v_{b_ref} is fixed, the total power extracted from the SCPVMs is instead time varying because of the unwanted additional local scan of the P-V characteristic in a voltage region around v_{b_ref} caused by the above oscillation. Therefore, in order to avoid that the CMPPTS controller is confused and therefore the efficiency of the system is severely compromised, it is necessary to adopt enough large values of Δv_{b_ref} :

$$\Delta v_{b_ref} \geq \Delta v_{b_fline} \quad (5)$$

The second requirement is explained in the following. It must be ensured that the increase Δv_{b_ref} of v_{b_ref} , taking place at the generic i th sampling instant $i \cdot T_b$, does not cause that the output voltage of one or more SCPVMs exceeds V_{ds_max} . For simplicity, as shown in Fig. 1, a unit gain of the sensor of voltage v_b has been assumed. Therefore, due to the zero steady-state error ensured by the inverter outer voltage feedback control circuitry, it can be assumed that $\Delta v_b = \Delta v_{b_ref}$. As a worst case, it will be assumed that the steady-state variations Δv_b of v_b and the corresponding variations Δv_{outk} ($k=1,2,\dots,N$), occurring as a consequence of the variations of v_{b_ref} , take place almost instantaneously and not after a suitable settling time after each sampling instant (as indeed instead it happens). When the operating conditions of the SCPVMs are uniform, then the variation $\Delta v_b = \Delta v_{b_ref}$ is equally shared among all the N output voltages of the string of SCPVMs. In such a case the increase Δv_{outk} of v_{outk} ($k=1,\dots,N$) is equal to $\Delta v_{b_ref}/N$. Unfortunately, in mismatching operating conditions, the variation $\Delta v_b = \Delta v_{b_ref}$ is unequally shared among the N output voltages. On the basis of eq. (1), it can be stated that the SCPVMs which are characterised by very low irradiance levels are forced to operate with very low output voltages which, in extreme mismatching conditions, can become nearly equal to 0. That is, the low irradiated SCPVMs may operate with their output ports in nearly short circuit conditions while, at the same time, carrying the whole string current i_{out} . The bypass function is automatically ensured in according with [12]. Therefore, as concerns the distribution of Δv_b among the N output voltages, the worst case takes place when the maximum possible number M of SCPVMs is working in short circuit conditions because, of course, in such a case Δv_b must be shared only among the remaining $(N-M)$ SCPVMs which are instead working at the maximum allowed output voltage (V_{out_lim}). That is, in the worst case, it is $v_{outk} = V_{out_lim}$ ($k=1,\dots,N-M$) while $v_{outk} = 0$ ($k=N-M+1,\dots,N$). It is:

$$M = N \cdot \frac{V_{b_min}}{V_{out_lim}} \quad (6)$$

Since it is desired that:

$$v_{outk} + \Delta v_{outk} \approx V_{out_lim} + \Delta v_{outk} \approx V_{out_lim} + \frac{\Delta v_b}{N-M} \leq V_{ds_max} \quad (k=1, 2, \dots, N-M) \quad (7)$$

it must be:

$$\Delta v_{b_ref} = \Delta v_b \leq (V_{ds_max} - V_{out_lim}) \frac{V_{b_min}}{V_{out_lim}} \quad (8)$$

As for the choice of T_b , the effect of the possible presence of nearly vertical portions in the P-V characteristic of the string of SCPVMs must be considered. In general, in correspondence of a given arbitrary value v_{bl} assumed by v_b during the scan, N_{lim} SCPVMs are working with an output voltage nearly equal to V_{out_lim} , N_r SCPVMs are working with an output voltage comprised between 0 and V_{out_lim} and, finally, N_{sc} SCPVMs are working with an output voltage nearly equal to 0. This means that, by remembering that the higher the index of a given SCPVM the lower the corresponding value of the irradiance level, at $v_b = v_{bl}$ it is: $v_{outk} \approx V_{out_lim}$ for $1 \leq k \leq N_{lim}$, $0 < v_{outk} < V_{out_lim}$ for $N_{lim}+1 \leq k \leq N_{lim}+N_r$, $v_{outk} \approx 0$ for $N_{lim}+N_r+1 \leq k \leq N$. Of course, it is $N_{lim}+N_r+N_{sc}=N$. Moreover N_{lim} and/or N_r and/or N_{sc} can be equal to zero. Let's assume that a certain vertical portion in the P-V characteristic of a string of SCPVMs is located in correspondence of a voltage value $v_b = v_{bd}$ such that $v_{bl} < v_{bd} < v_{bl} + \Delta v_b$. During the scan, when v_b changes from v_{bl} to $v_{bl} + \Delta v_b$, moving from the left to the right of v_{bd} , a more or less consistent decrease of the total output power must take place and therefore one or more SCPVMs (among those ones with index k such that $1 \leq k \leq N_{lim}+N_r$) must reduce their output power and therefore their output voltage. Such a reduction may also allow in turn one or more SCPVMs (among those ones with index k such that $N_{lim}+N_r+1 \leq k \leq N$), which were working in short circuit conditions at $v_b = v_{bl}$, to begin to provide power and therefore to

increase their output voltage. Such a process cannot happen instantaneously but it needs, in the worst case, the time T_1 necessary to one or more SCPVMs (among those ones with index k such that $1 \leq k \leq N_{lim} + N_r$) to move their input operating voltage from V_{MPP} to zero in order to decrease their output power, plus the time T_2 necessary to one or more SCPVMs (among those ones with index k such that $N_{lim} + N_r + 1 \leq k \leq N$) to move their input operating voltage from zero to V_{MPP} in order to increase their output power. Of course, times T_1 and T_2 represent the worst-case (longest) times needed by the SCPVMs to reach the new steady-state condition (at $v_b = v_{bl} + \Delta v_b$) which are characterised by numbers N_{lim} , N_r and N_{sc} which are different from the corresponding ones at $v_b = v_{bl}$. Moreover, due to its own dynamics, the inverter itself needs a time T_3 in order to regulate its input voltage v_b from v_{bl} to $v_{bl} + \Delta v_b$. In conclusion, the whole process associated to the scan of the P-V characteristic needs, in the worst-case, a time T equal to:

$$T = T_1 + T_2 + T_3 \quad (9) \quad T_1 = T_2 = \frac{V_{MPP}}{\Delta v_{pan_ref}} T_a \quad (10)$$

Instead T_3 can be numerically evaluated as the settling time of the step response of the closed-loop transfer function $W(s)$ between v_b and v_{b_ref} , as in (11), where $T_{cv}(s)$ is the loop gain of the inverter outer voltage feedback loop [10]. Then the value of T_b must be as in (12).

$$W(s) = \frac{\hat{v}_b(s)}{\hat{v}_{b_ref}(s)} = \frac{T_{cv}(s)}{1 + T_{cv}(s)} \quad (11) \quad T_b \geq T \quad (12)$$

If properly designed as discussed above, the CMPPTS technique is able to avoid errors. Of course, the period T_r between two consecutive scans must be greater than T .

III. Numerical Analysis

The reduced scale system of Fig. 1 has been simulated by using PSIM (simulation software for power conversion and control). The PV array is composed by a string of $N=2$ PV modules. The electrical characteristics of such modules in STC are the following ones: Open circuit voltage $V_{OC} = 10$ V, Short circuit current $I_{SC} = 5$ A, $V_{MPP} = 8.05$ V, $P_{MPP} = 37.43$ W. The values of the parameters appearing in the previous sections are: $V_{ds_max} = 60$ V; $P_{pan1} = 37.4385$ W, $\Delta P_{pan1} = 8.4216$ W, $\Delta P_{tot} = 0$ W (at $S_{max} = 1000$ W/m²); $\Delta v_{pan_ref} = 0.15$ V, $T_a = 20$ ms. By applying (2) the value of V_{out_lim} can be evaluated as in (13). By applying (8), the value of Δv_{b_ref} can be calculated as in (14):

$$V_{out_lim} \leq 46.50 \text{ V} \quad (13) \quad \Delta v_{b_ref} \leq 15 \text{ V} \quad (14)$$

The switching frequency f_s of the boost converters has been chosen equal to 30 kHz. Moreover $L = 100$ μ H, $C_{in} = 6$ μ F, $C_{out} = 10$ μ F.

The reported simulation refers to the following set of parameters: $V_{out_lim} = 30$ V, $\Delta v_{b_ref} = 10$ V, $T_b = 1$ s, $S = [1000 \ 200]$ W/m², $V_{b_min} = 20$ V, $V_{b_max} = 80$ V. It is worth noting that the values of V_{out_lim} , Δv_{b_ref} respectively fulfill inequalities (13) and (14); therefore a correct behavior of the CMPPTS technique is expected. The P-V characteristic is shown in Fig. 3; the n ($n=6$) steady-state operating points associated to the scan are marked by means of circle symbols. The corresponding waveform of the power P extracted during the scan is reported in Fig. 4. The values of P reported in Fig. 4 are in very good agreement with the theoretical predictions of Fig. 3. In the considered case, the operating voltage where the recorded value of P is maximum is $v_b = 40$ V, which corresponds to the third point of the scan (Figs. 3 and 4); therefore, at the end of the scan, the CMPPTS controller correctly sets $v_b = 40$ V.

IV. Hardware implementation

Every SCPVM [13-23] and the central inverter need a dedicated control electronic device (CED) which has to implement the control techniques briefly described before. In particular, the CED of a SCPVM has to implement the DMPPT technique, while the CED of the central inverter has to implement the CMPPTS technique. The CED of SCPVM, in order to implement the DMPPT, has to measure input voltage and current and output voltage of the DC/DC module; the CED of the inverter has to measure input current and voltage and output voltage of the inverter. In order to prove the effectiveness of the proposed technique, a laboratory test system has been implemented. For sake of simplicity, it is composed by only two SCPVMs and a central inverter. In order to make the experimentation independent from solar irradiance, the PV module has been emulated with a numerically controlled power source. It is the Kepco BOP 36-12M, a 400 W four-quadrants power supply. This power supply digitally communicates over an IEEE 488 digital bus, through which it can be programmed to reproduce the static and dynamic characteristics of a PV panel. As DC/DC converter, a step up regulator has been used. As CEDs the microcontrollers STM32F407VGT6 from ST Microelectronics have been used. The input port of the inverter has been emulated by means of a Chroma 63802 AC/DC Electronic Load.

V. Experimental Results

In order to experimentally validate the realized embedded measurement system which implement the HMPPT_F technique, a measurement station has been set up (Error! Reference source not found.,

Error! Reference source not found.-Error! Reference source not found.). Its block scheme is represented in Figure 5. It is composed of two emulated PV modules, two Boost converters, a load for the SCPVM array, a Personal Computer (PC), a data acquisition (DAQ) board, voltage and current transducers. The SCPVMs, the load and the PC are connected together through IEEE 488 bus; the DAQ board communicates with PC through USB bus. The voltage and current transducers are, respectively, LEM CV3-1000 and CT-10. The measurement software has been developed in LabView environment. A photo of the measurement setup is shown in Figure 6. In the experimental test, the emulated PV modules, are exposed to two different irradiance levels: 1 sun, 0.2 sun, where 1 sun is equal to $1000 \frac{W}{m^2}$. Figures 7-8 show the simulated and the emulated P-V characteristics of, the emulated PV modules exposed, respectively, to 1 sun and to 0.2 sun. A good agreement among simulated and emulated curve can be appreciated. Moreover, Figure 9 shows the output voltages and Figure 10 the total output power of the two emulated PV modules: their mean values correspond to those found in simulations.

VI. Conclusions

The adoption of a Hybrid MPPT (HMPPT) technique is mandatory in PV applications operating under mismatching conditions. It is called Hybrid because it is neither only Distributed (on the PV modules) nor only Centralized (on the inverter). In this paper it is shown how to properly optimize an HMPPT technique based on the periodic scan of the Power vs. Voltage characteristic at the input of the inverter in order to locate the optimal operating value, from the energetic efficiency point of view, of the bulk inverter voltage. Therefore, numerical simulations and experimental measurements on a reduced scale laboratory prototype are carried out and they confirm the validity of the theoretical predictions.

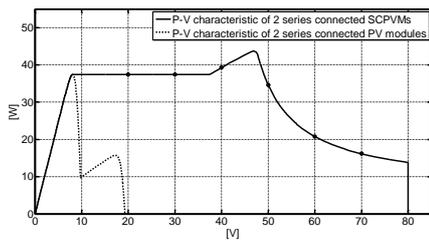


Figure 3: P-V characteristics

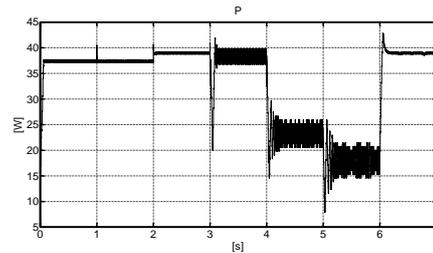


Figure 4: power P extracted during the scan

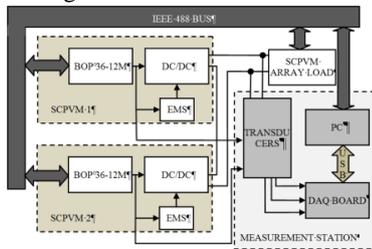


Figure 5: Block scheme of the measurement station



Figure 6: A photo of the measurement station

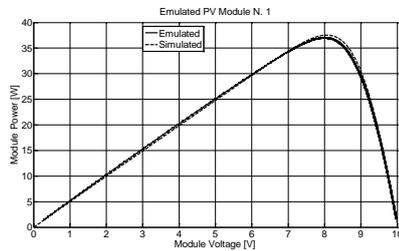


Figure 7: P-V characteristic of Emulated PV module n.1

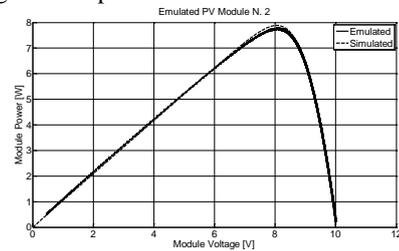


Figure 8: P-V characteristic of Emulated PV module n.2

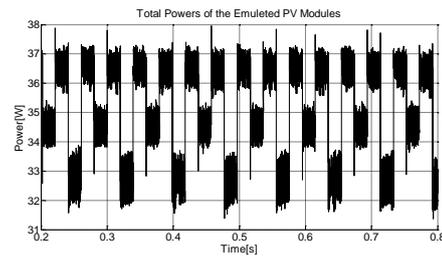
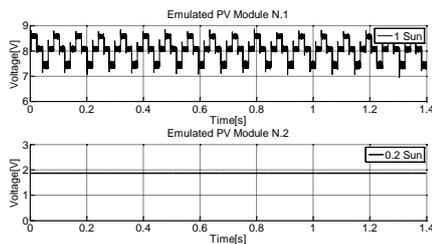


Figure 9: Output voltages of the Emulated PV modules Figure 10: Output Power of the Emulated PV modules

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