A MAXIMUM POWER POINT TRACKING SYSTEM WITH PARALLEL CONNECTION

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***Abstract* – This paper presents the analysis, design and implementation of a parallel connected maximum power point tracking system (MPPT) for stand-alone photovoltaic power generation. The parallel connection of the MPPT system reduces the negative influence of the power converter losses in the overall efficiency because only a part of the generated power is processed by the MPPT system. A simple bi-directional power converter is proposed for the MPPT implementation and also presents the functions of battery charger and step-up converter. The operation characteristics of the proposed circuit in a practical application are analyzed with the implementation of a prototype and a data acquisition system.**

***Keywords* – Maximum power point tracking, photovoltaic systems, renewable energy sources.**

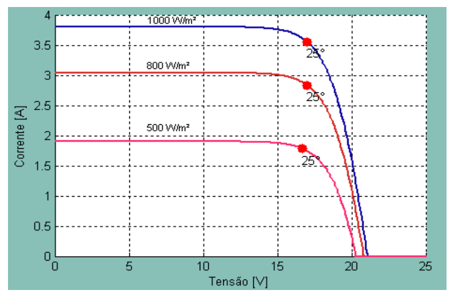
I. INTRODUCTION

The continuous growth of the energy demand and increased interest in environmental issues led to the exploration of the use of renewable energy sources, such as the photovoltaic technology. In the last decades, the photovoltaic energy received considerable attention, but the high cost and low efficiency difficult the use of this alternative in large scale. Therefore many researches are developed in order to improve these negative aspects [1-9]. This paper presents a system with parallel connection to extract the maximum power of the solar module called Maximum Power Point Tracking (MPPT). The classical implementation of the MPPT in stand-alone system is accomplished by the series connection of a DC-DC converter among the solar module and load or the energy storage element. With the series connection, the DC-DC converter always processes all generated power by the photovoltaic (PV) module. Thus the efficiency of the power converter is very important in the total efficiency of the solar system. With the parallel connection of the MPPT system presented in this paper, only part of the generated energy is processed by the DC-DC converter, increasing the total efficiency of the solar system. The operation principle, theoretical analysis, design and experimental results of a laboratory prototype of the parallel MPPT system are presented in the paper.

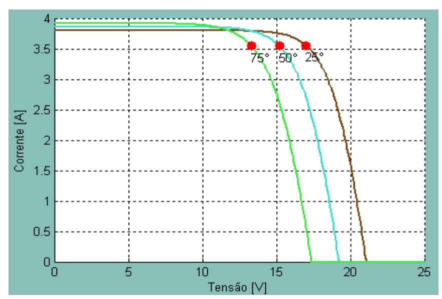
II. MPPT SYSTEM

A. Solar Cell Output Characteristic

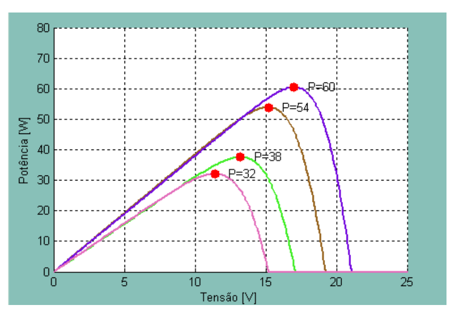
Figure 1 presents a typical output characteristic of a photovoltaic module. The generated current is very dependent of the solar irradiation, as shown in Fig. 1a. The temperature of the photovoltaic module presents influence in the output voltage as it can be observed in Fig. 1b. Therefore, the maximum power of the photovoltaic module changes with the climatic conditions and there is only one value of current (I_{mpp}) and voltage (V_{mpp}) that defines the maximum power point (MPP), as presented in Fig. 1c.



a) Output characteristic variation with the solar irradiation



b) Output characteristic variation with the temperature



c) Maximum power point variation

Fig. 1 – Output characteristic of a photovoltaic module

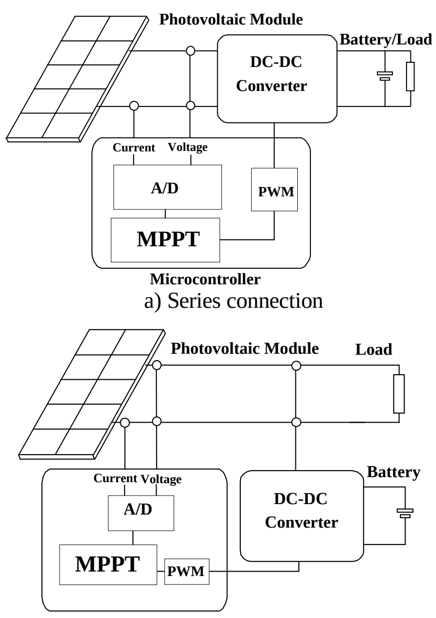
Therefore, a significant problem in photovoltaic systems is as to ensure the maximum energy generation with a dynamic variation of the source output characteristic and the connection of a variable load. A solution for this problem is the insertion among the source and load of a power converter that, with the use of a control algorithm, changes the impedance of the circuit. Thus, MPP operation is obtained for any operational condition of the system.

B. Series Connection of the MPPT

The classical implementation of the MPPT in stand-alone system is the connection of a DC-DC converter among the source and load, as shown in Fig. 2a. The usual topologies are the buck or boost converters. Also different control algorithms are studied in order to obtain a good performance in the dynamic tracking of the MPP [6-9]. The measurement of the voltage and current allows the knowledge of the power and different algorithms can be used in order to change de converter duty-cycle until to reach the maximum power. One problem of this configuration is that all generated power by the photovoltaic module is processed by the converter even if the load is close to the MPP. In order to overcome this limitation a parallel connection is analyzed.

C. Parallel Connection of the MPPT

The parallel connection of the MPPT, shown in Fig. 2b, was presented in [4, 5] in order to improve the total system efficiency. With the parallel configuration, the DC-DC converter processes only a part of the generated power. The best condition occurs when the value of the load current is equal to the value of the PV module maximum power point current (I_{mpp}), where the power processed by the DC-DC converter is zero. Thus, the influence of the power converter loss in the total system efficiency is lower.



a) Series connection

b) Parallel connection

Fig. 2 . Maximum power point tracking system.

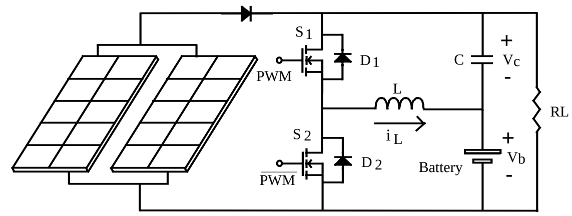


Fig. 3. MPPT system with bi-directional DC-DC converter.

III. PROPOSED MPPT

A. Power Circuit Operation

The power circuit of the MPPT is presented in Fig. 3 and is composed by the battery bank for to store energy, a capacitor (C), an inductor (L) and two power switches (S_1 and S_2) and diodes (D_1 and D_2). This structure is a bi-directional converter and operates as a buck converter in the battery charge and as a boost converter when the battery must supply the load (R_L) or to complement the energy of the photovoltaic module. The converter duty-cycle is defined by the same control algorithms that are used in the series connected MPPT. The transition among the operations as buck or boost mode is automatic by the duty-cycle variation.

1) Buck Operation

The battery voltage must be lower than the photovoltaic module voltage for the correct operation. When the generated energy is enough to supply the load, the exceeding energy is used to charge the battery. This is the buck operation and presents two topological stages as shown in Fig. 4. When the power switch S_1 is turned-on, the inductor L stores energy and also there is the energy transference from the photovoltaic module to the battery. When the power switch S_1 is turned-off, the diode D_2 conducts and the energy stored in the inductor L is transferred to the battery. As the switches command signals are complementary, the switch S_2 is turned-on during the conduction of the diode D_2.

2) Boost Operation

If the generated energy is not enough to supply the load, the power system operates as a boost converter transferring energy from the battery to the load. In this case, the switch S_2 is turned-on and the inductor L stores energy while the battery voltage is applied, as shown in Fig. 5. When the switch S_2 is turned-off the inductor energy is transferred to the load.

The transition of the buck or boost operation is automatic and depends of the photovoltaic module and battery voltages and also the duty-cycle. The inductor current waveform in the buck and boost operation is presented in Fig. 6.

The power circuit of Fig. 3 is a simple and low cost power converter, but presents multiple functions. This circuit operates as a battery charger when the generated energy is higher than the load consumption. The control algorithm ensures always the photovoltaic module operation at the maximum power point, implementing the MPPT function. The power circuit also operates as a step-up DC-DC converter, transferring energy from the battery to the load as a boost converter.

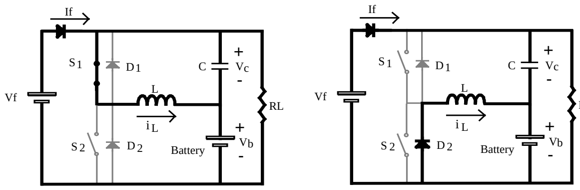


Fig. 4. Buck operation mode.

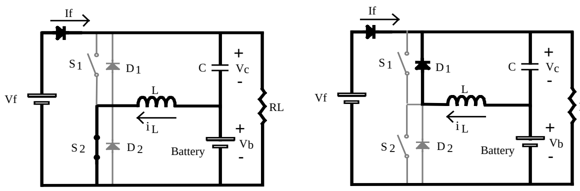


Fig. 5. Boost operation mode.

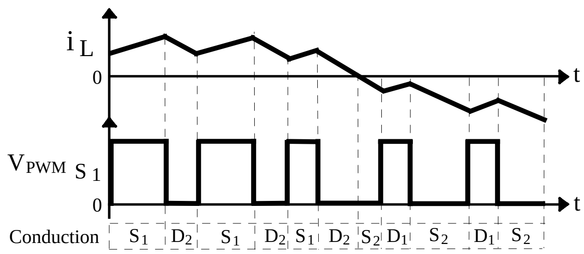


Fig. 6. Inductor current in the bi-directional operation.

B. System Operation Modes

The basic circuit of the parallel MPPT system can present five operation modes, depending of the load and climatic conditions. Figures 7 to 11 present the operation modes and for simplification, the PV module is represented by a current source (I_f).

1) Operation without load: I_c=0 (Fig. 7) - Mode 1

When the load is not connected, the battery is charged with the PV module current (I_f=I_b and I_c=0). The MPPT algorithm ensures that the converter current (I_b) is equal to the PV module maximum power point current (I_{mpp}). Also the sum of the battery voltage and the capacitor voltage (V_b+V_c) is equal to the PV module maximum power point voltage (V_{mpp}). The DC-DC converter operates as a buck converter charging the battery.

2) Operation with load current lower than the MPP current: I_c<I_{mpp} (Fig. 8) - Mode 2

If the load current value (I_c) is lower than the PV module maximum power point current (I_{mpp}), part of the generated energy by the PV module is used to supply the load and other part is used to charge the battery. The control algorithm maintains the sum of the load and converter current equal to the maximum power point current (I_f=I_{mpp}=I_c+I_b). The DC-DC converter operates as a buck converter charging the battery.

3) Operation with load current equal to the MPP current: I_c=I_{mpp} (Fig.9) - Mode 3

When the load current value (I_c) is equal to the PV module maximum power point current (I_{mpp}), the power processed by the DC-DC converter is zero. In this case, the efficiency of the system can be considered 100% because the maximum power of the PV module is obtained and transferred to the load and the power processed by the DC-DC converter is zero.

4) Operation with load current higher than the MPP current: I_c>I_{mpp} (Fig.10) – Mode 4

If the load current value (I_c) is higher than the PV module maximum power point current (I_{mpp}), all generated energy by the PV module is used to supply the load and the DC-DC converter complements the other part. The control algorithm maintains PV module current at the MPP (I_f=I_{mpp}=I_c-I_b). The battery is discharged during this operation mode and the DC-DC converter operates as a boost converter.

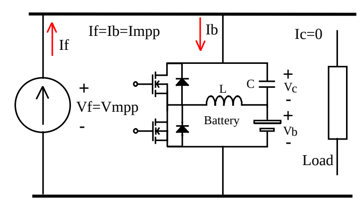


Fig. 7. Operation mode 1.

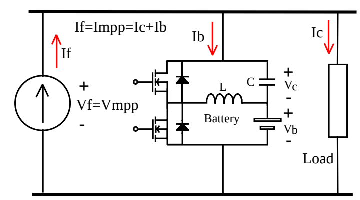


Fig. 8. Operation mode 2.

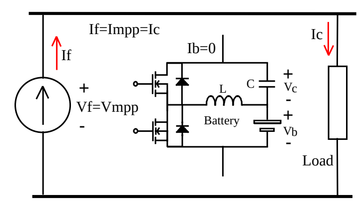


Fig. 9. Operation mode 3.

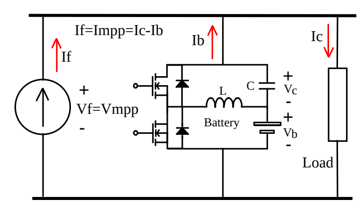


Fig. 10. Operation mode 4.

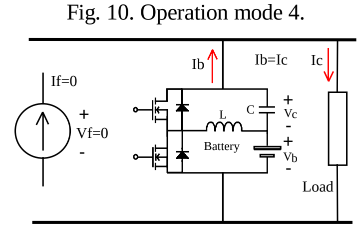


Fig. 11. Operation mode 5.

5) Operation without solar irradiation: (Fig.11) - Mode 5

The operation without solar irradiation, as at night, the DC-DC converter supplies the load. In this case, the MPPT algorithm is turned-off and a digital voltage control loop regulates the load voltage. The battery is discharged during this operation mode and the DC-DC converter operates as a boost converter, considering the battery as the input source.

C. Control Algorithm

The same control algorithm developed for the series connected MPPT can be used to control the proposed parallel system. There are many control algorithms presented in the literature and the method used in this implementation is the perturbation and observation [6-9]. This is a simple control method but presents an adequate performance. The microcontroller MSP430F149 was utilized in the practical control implementation. The PV module current and voltage are used to calculate the PV power. A small step variation in the converter duty-cycle is applied and the new power is compared with the previous value. With this comparison is defined if the duty-cycle must be increased or decreased in order to obtain the maximum power. A voltage control algorithm was implemented for the operation without the PV module (operation mode 5). In this case, the MPPT algorithm is not considered in the duty-cycle determination. Current and voltage sensors were utilized in order to verify the battery charge state. When the battery discharge or charge reaches the limit, the DC-DC converter is turned-off, avoiding a reduction of the battery lifetime. Overcurrent protections were also implemented. In order to verify all operations states and the management of the system, a state machine was developed. The input values of the PV module current and voltage and the battery current and voltage define the enabled routine that are the system start-up, MPPT algorithm, electrical problem, battery discharge or overcharge, low PV module voltage and voltage regulation.

D. Stand-Alone Systems

The parallel MPPT system presented in Fig. 3 can be integrated with a DC-AC converter in order to compose a complete stand-alone generation system, as shown in Fig. 12. The photovoltaic modules can be connected in series in order to obtain the DC voltage level necessary to generate the nominal AC voltage.

The series connection of a high number of photovoltaic modules presents the inconvenience of generation interruption if a problem occurs with one module or an important reduction of the generated energy if there is the interruption of the solar irradiation in one module. The generation of a high DC voltage and the problems of the series connection of the photovoltaic module can be solved with the configuration presented in Fig. 13. The parallel MPPT circuit is modular and two or more circuits can be connected in series, obtaining a high DC voltage. As each MPPT circuit is independent, if the generation interruption occurs in one module, the others circuits will operate at the maximum power point of the respective photovoltaic module and the generation is not interrupted.

III. DESIGN PARAMETERS

The maximum power point voltage (V_{mpp}) of the PV module utilized in the practical implementation is about 15V to 17V, depending of the climatic conditions and the battery voltage must be lower in order to allow the operation of the power circuit in the Buck and Boost operation modes. The battery utilized in the practical implementation presents a nominal voltage equal to 6V.

The continuous conduction mode operation is considered in the determination of the maim prototype components, based on the circuit presented in Fig. 3. The current level is higher in the boost operation without the photovoltaic module and the components are calculated in this operation mode, considering a switching frequency equal to 30 kHz.

1) Inductor

The average inductor current in the boost operation is defined by (1), considering an efficiency equal to η=90%.

$$I_L = \frac{P}{V_b \cdot \eta} = \frac{45}{6 \cdot 0.9} = 8.333\text{A} \qquad (1)$$

A current ripple equal to 20% was considered in the inductance determination.

$$\Delta I = 0.2 \cdot I_L = 0.2 \cdot 8.333 = 1.667\text{A} \qquad (2)$$

The operation point defined is a duty-cycle equal to D=0.67, in order to obtain a load voltage equal to 18V with a battery voltage equal to 6V. The inductance is calculated by (3).

$$L = \frac{V_{in} \cdot D}{f \cdot \Delta I} = \frac{6 \cdot 0.67}{30 \cdot 10^3 \cdot 1.667} = 80.4\mu\text{H} \qquad (3)$$

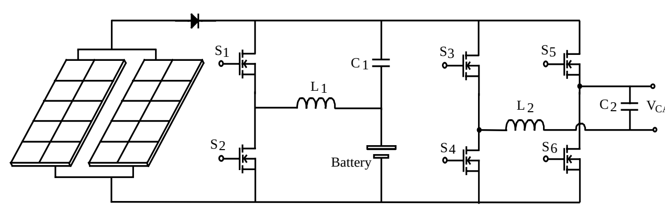


Fig. 12. Stand-Alone parallel MPPT system with single-phase inverter.

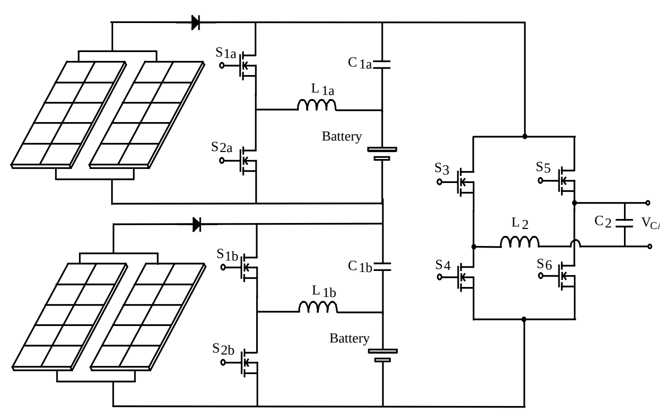


Fig. 13. Series connection of multiple parallel MPPT and single-phase inverter.

An inductance value equal to 90µH was utilized in the prototype.

2) Capacitor

A capacitor voltage ripple equal to 5% was adopted in the design of the filter capacitor.

$$\Delta V_C = V_o \cdot 0.05 = 18 \cdot 0.05 = 0.9V \tag{4}$$

The capacitance is calculated by (5).

$$C = \frac{I_{cap} \cdot D}{f \cdot \Delta V_C} \tag{5}$$

The capacitor current is defined by (6).

$$I_{cap} = I_c + \frac{\Delta I}{2} \qquad I_{cap} = \frac{45}{18} + \frac{1.667}{2} = 3.333A \tag{6}$$

Thus:

$$C = \frac{3.333 \cdot 0.667}{30 \cdot 10^3 \cdot 0.9} = 82.337\,\mu F \tag{7}$$

Three capacitors with 33µF/50V were connected in parallel for the output capacitor implementation, also considering the equivalent series resistance.

3) Power switches

The switch RMS current can be defined approximately by (8).

$$I_{Srms} = IL \cdot \sqrt{D} = 8.333 \cdot \sqrt{0.67} = 6.8A \tag{8}$$

The power switch utilized in the prototype implementation was the MOSFET IRFZ48N.

IV. EXPERIMENTAL RESULTS

The operation of the proposed system was tested with the implementation of a laboratory prototype. The PV module utilized in the practical test is the Kyocera Solar KC40T and the parameters are presented in Table I.

The data acquisition was obtained with the serial transmission from the microcontroller to a computer. The main control information as voltage, current, power and converter duty-cycle are stored during the MPPT operation. Figure 14 presents the interface of the software acquisition developed and the variables of the system during the MPPT operation.

The experimental results of the maximum power point tracking using the PV module KC40T are presented in Figs. 15, 16 and 17, considering a load resistance equal to 12Ω.

Table I – PV module KC40T parameters

Maximum power:	43W
MPP voltage (V_{mpp}):	17,4V
MPP current (I_{mpp}):	2,48A
Open circuit voltage (V_{oc}):	21,7V
Short-circuit current (I_{sc}):	2,65A
Operation temperature:	47°C

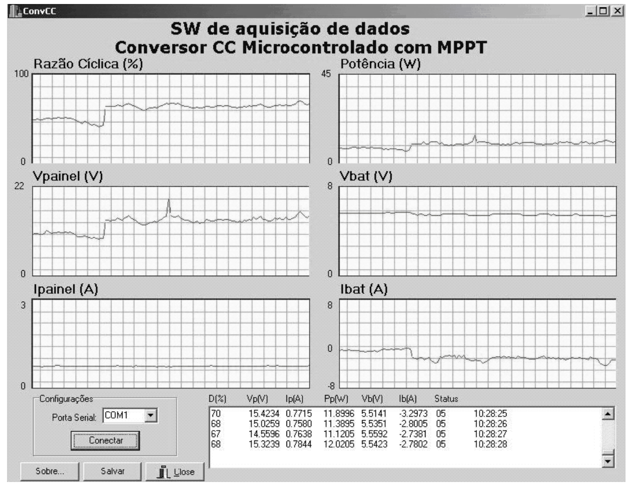


Fig. 14. Data acquisition software.

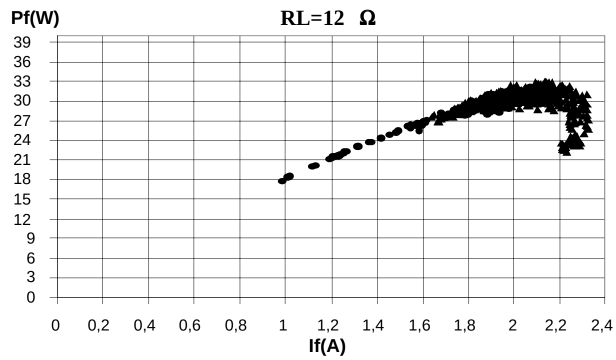


Fig. 15. Output power and current of the PV module.

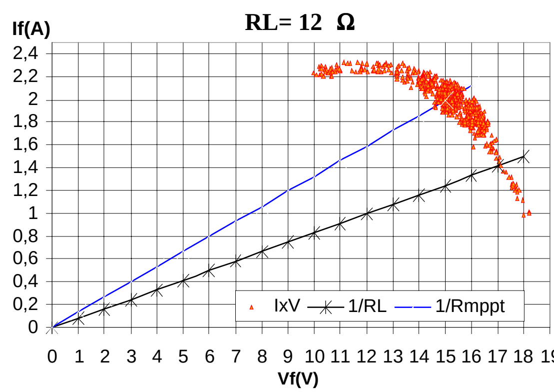


Fig. 16. Output current and voltage of the PV module.

Figure 15 presents the PV module power and current. The maximum power obtained for the climatic conditions was about 32W and the maximum power point current was equal to I_{mpp}=2.1A.

Figure 16 shows the PV module output voltage and current curve and also two load lines. The lower line represents the connection of the load resistance directly to the PV module, without the MPPT circuit. The power obtained in this case is equal to 24W. The upper line represents the equivalent load adjusted by the DC-DC converter and MPPT algorithm, obtaining a power equal to 32W. Thus the 25% of power gain obtained with the MPPT is used to store energy in the battery.

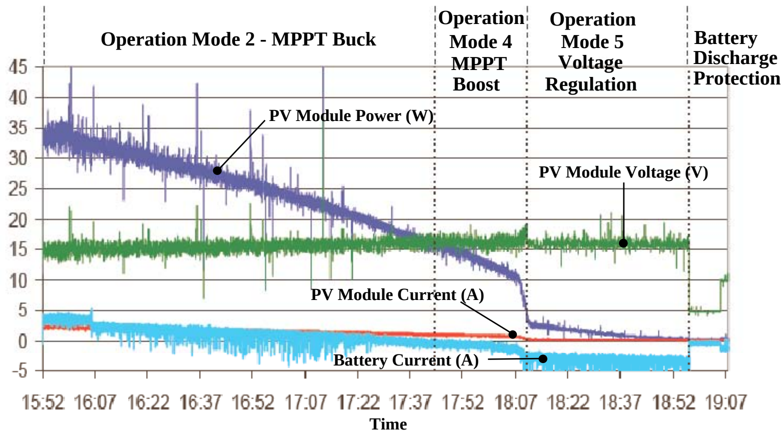


Fig. 17. Data acquisition of the parallel MPPT operation.

Figure 17 presents the data acquisition obtained with the MPPT operation during a period of 3 hours in a sunny day. This test shows the automatic transition between the different operation modes of the MPPT system. The test begins at 15:52hs and the generated energy by the PV module supplies the load and charge the battery, operating as a buck converter (operation mode 2). The battery current is positive during this operation mode. With the gradual reduction of the solar irradiation, the generated power decrease. When the generated power by the PV module is lower than 15W, the power circuit operates as a boost converter and the generated power is complemented with the battery energy (operation mode 4). The battery current is negative during this operation mode. At 18:07hs the solar irradiation is very low and the generated power is almost zero. Thus, a voltage control loop regulates the output voltage and only the battery energy supplies the load (operation mode 5).

A low capacity battery was used in order to show the discharge protection. One hour after the operation with the voltage regulation, the battery reaches the minimal charge level and the power converter was turned-off. As can be seen in Fig. 17, the load voltage variation is low and was maintained close to 15V for all operation modes. The temperature presents a most important influence in the maximum power point voltage (V_{mpp}) and therefore in the load voltage. The temperature coefficient for PV module KC40T is 82mV/°C and a temperature variation of 30°C represents a voltage variation of 13%. This variation is equivalent to the battery voltage reduction from the charge to discharge states of the series connected MPPT.

V. EFFICIENCY ANALYSIS OF THE PARALLEL MPPT

The efficiency of the parallel MPPT can be analyzed considering the different operation modes.

A. Efficiency for the operation mode 2

The operation mode 2, presented in Fig. 8, occurs when the load current (I_c) is lower than the photovoltaic module maximum power point current I_{mpp}. Thus, part of the generated energy is used to charge the battery. Therefore, the efficiency of the system is defined by (9), considering the input of energy the photovoltaic module and the outputs are the load and battery.

$$\eta(\%) = \frac{P_o}{P_{in}} = \frac{P_{Load} + P_{Battery}}{P_{Module}} = \frac{V_f \cdot I_c + V_{Bat} \cdot I_{Bat}}{V_f \cdot I_f} \quad (9)$$

B. Efficiency for the operation mode 4

The operation mode 4, presented in Fig. 10, occurs when the load current (I_c) is higher than the photovoltaic module maximum power point current I_{mpp}. Thus, part of the energy used by the load is supplied by the battery. Therefore, the efficiency of the system is defined by (10), considering the input of energy the photovoltaic module and the battery and the output is the load.

$$\eta(\%) = \frac{P_o}{P_{in}} = \frac{P_{Load}}{P_{Module} + P_{Battery}} = \frac{V_f \cdot I_C}{V_f \cdot I_f + V_{Bat} \cdot I_{Bat}} \quad (10)$$

C. Efficiency for the operation mode 3

When the load current (I_c) is equal to the maximum power point current (I_{mpp}), corresponding to the operation mode 3, the battery current (I_{Bat}) is zero. As shown in Fig. 9, the load current (I_c) is the same of the photovoltaic module current (I_f) when I_b is zero. Thus, substituting I_f=I_c and I_{Bat}=0 in (9) or (10), the efficiency is equal to 100%. In this case all generated energy is used by the load without losses, considering ideal cables and connections.

D. Efficiency for the operation mode 5

When photovoltaic module is out of the system, the battery supplies the load as a classical boost converter. Thus the efficiency is defined by (11). But in this equation V_f is the load voltage regulated by the control algorithm of the boost converter operation.

$$\eta(\%) = \frac{P_o}{P_{in}} = \frac{P_{Load}}{P_{Battery}} = \frac{V_f \cdot I_C}{V_{Bat} \cdot I_{Bat}} \quad (11)$$

E. Efficiency Experimental Results

Figure 18 presents the parallel MPPT system efficiency curve obtained experimentally with the photovoltaic module KC40T. The maximum power point for the climatic conditions is equal to 32W, as can be seen in Fig. 15. Thus, when the load power is equal to 32W, the maximum efficiency is obtained because all generated energy is transferred to the load (operation mode 3) and the power processed by the DC-DC converter is zero. The operation mode 2 occurs when the load power is lower than 32W and the operation mode 4 occurs for a load power higher than 32W.

Figure 19 presents the parallel MPPT system efficiency for the operation mode 5, with the disconnection of the photovoltaic module. The bi-directional converter operates as a classical boost. As the battery voltage of the prototype is only 6V, the conduction loss is significant and increase proportionally with the load power. The efficiency result in this operation mode must be improved in a practical application using a photovoltaic module and battery with higher voltage and also with the optimization of the power converter.

However, it is important to note that the efficiency of the parallel MPPT system is always higher than the efficiency of the power converter, while the efficiency of the series MPPT system is equal to the power converter efficiency and the power stage process the total power. In some situations, the energy increment obtained with the series MPPT system can be canceled by the converter losses. Therefore the parallel structure allows an efficiency optimization.

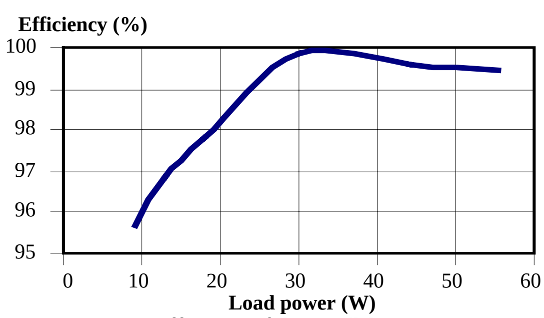


Fig. 18. Efficiency of the parallel MPPT system for the operation modes 2, 3 and 4.

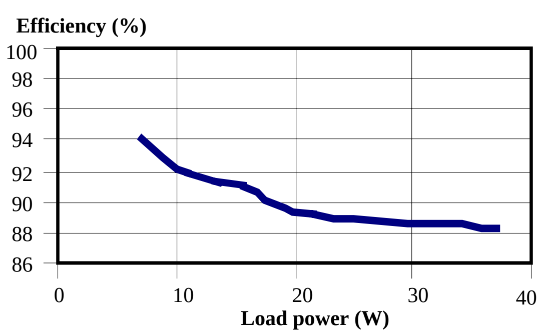


Fig. 19. Efficiency of the parallel MPPT system for the operation mode 5.

VI. CONCLUSION

A maximum power point tracking circuit with parallel connection is presented in this paper. The parallel connection of the MPPT system reduces the negative influence of the power converter losses in the overall efficiency. The control algorithm ensures the operation at the MPP as the classical system, but only a part of the generated power is processed by the DC-DC converter. The main operational aspects of the parallel MPPT were verified with the implementation of a prototype. The transitions of the different operational modes where tested and occurs without discontinuity of the system operation.

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