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# Simulation and implementation of Perturb and Observe Maximum Power Point Tracking System (MPPT) With Parallel Connection for PV Stand-Alone Application

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***Abstract*—This paper presents the analysis, design, and implementation of a parallel connected maximum power point tracking (MPPT) system for stand-alone photovoltaic power generation.Maximum power point tracking (MPPT) plays an important role in photovoltaic systems because it maximize the power output from a PV system for a given set of conditions, and therefore maximize the array efficiency and minimize the overall system cost. Since the maximum power point (MPP) varies, based on the irradiation and cell temperature, appropriate algorithms must be utilized to track the (MPP) and maintain the operation of the system in it. Mat lab/Simulink is used to establish a model of photovoltaic system with (MPPT) function. The parallel connection of the MPPT system reduces the negative influence of power converter losses in the overall efficiency because only a part of the generated power is processed by the MPPT system. Furthermore, all control algorithms used in the classical series-connected MPPT can be applied to the parallel system. A simple bidirectional dc–dc power converter is proposed for the MPPT implementation and presents the functions of battery charger and step-up converter. The operation characteristics of the proposed circuit are analysed with the implementation of a prototype in a practical application.***

**Keywords—DC–DC power conversion, photovoltaic (PV) power systems, solar energy.**

## I. INTRODUCTION

THE CONTINUOUS growth of the global energy demand associated with society's increasing awareness of environmental impacts from the widespread utilization of fossil fuels has led to the exploration of renewable energy sources, such as photovoltaic (PV) technology. Therefore, several studies are being developed in order to minimize these drawbacks. In order to extract the maximum power of the PV array, the classical implementation of the maximum power point tracking (MPPT) in stand-alone systems is generally accomplished by the series connection of a dc–dc converter between the PV array and the load or the energy storage element. Considering that in the series connection, the dc–dc converter always processes all power generated, the total efficiency of thePV system greatly depends on the efficiency of this series dc–dcconverter. As an alternative to this configuration, this paperpresents an MPPT system based on the parallel connection of a dc–dc converter. With this configuration, only part of the energy generated is processed by the dc–dc converter, making it possible to obtainan increase in the total efficiency of the PV system as compared with the series configuration. Methodology and experimental results of a laboratory prototype of the parallel MPPT system are presented in this paper.

## II. MPPT IN STAND-ALONE PV SYSTEMS

### *A. Solar Cell Output Characteristic*

The maximum power of the PV module changes with climatic conditions, and there is only one value for the current (*I*mpp) and the voltage (*V*mpp), which defines the maximum power point (MPP), as shown in Fig. 1. The PV current changes with the solar irradiation level, whereas the PV output Voltage changes with the temperature of the PV module. Therefore, an important challenge in a PV system is to ensure the maximum energy generation from the PV array with a dynamic variation of its output characteristic and with the connection of a variable load. A solution for this problem is the insertion of a power converter between the PV array and load, which could dynamically change the impedance of the circuit by using a control algorithm. Thus, MPP operation can be obtained under any operational condition.

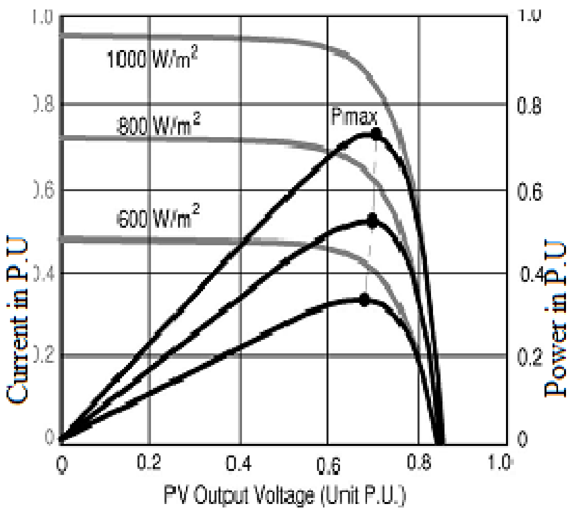


Fig. 1 Output characteristic of a PV module

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### *B. Simulink Model of Solar PV Module*

Solar cell is basically a p-n junction fabricated in a thin wafer or layer of semiconductor. The electromagnetic radiation of solar energy can be directly converted to electricity through photovoltaic effect. Being exposed to the sunlight, photons with energy greater than the band-gap energy of the semiconductor are absorbed and create some electron-hole pairs proportional to the incident irradiation. Under the influence of the internal electric fields of the p-n junction, these carriers are swept apart and create a photocurrent which is directly proportional to solar insolation. PV system naturally exhibits a nonlinear I-V and P-V characteristics which vary with the radiant intensity and cell temperature. Fig. 2 shows the equivalent circuit models of cell and Fig.3 shows the simulation circuit in mat lab.

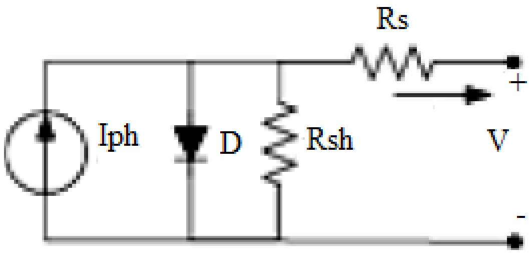


Fig.2Equivalent circuit model of pv cell

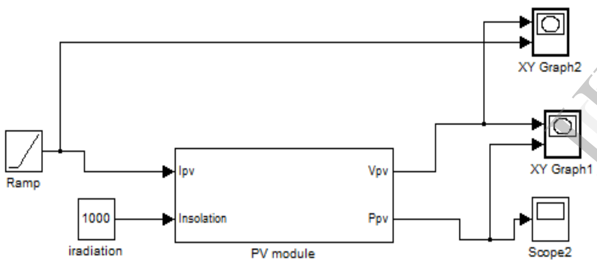


Fig.3 Simulation circuit of the PV module

Since a typical PV cell produces less than 2W at 0.5V approximately, the cells must be connected in series configuration on a module to produce enough high power. A PV array is a group of several PV modules which are electrically connected in series and parallel circuits to generate the required current and voltage. The equivalent circuit for the solar module arranged in NP parallel and NS series is shown in Fig. 2. The terminal equation for the current and voltage of the array becomes as follows.

I=NpIph-NpIs[exp(q(V/Ns+IRs/Np)/KTcA)-1]-[NpV/Ns+IRs]/Rsh……………………1

where, IPH is a light-generated current or photocurrent, I the cell saturation of dark current, q electron charge, k is a Boltzmann's constant, TC is the cell's working temperature, A is an ideal factor, RSH is a shunt resistance, and RS is a series resistance.

The photocurrent mainly depends on the solar insolation and cell's working temperature, which is described as

Iph=[Isc+K1(Tc-Tref)] □…………………………………2

where ISC is the cell's short-circuit current at a 25 1kW/m2, KI is the cell's short-circuit current temperature coefficient, TRef is the cell's reference temperature, and □ the solar insolation in kW/m2.

### *C. Parallel Connection of the MPPT*

Fig. 4 shows an alternative proposal to implement standalone PV power generation based on a parallel MPPT system. The parallel connection of the MPPT circuit was introduced in Fig.4, and the main advantage of this configuration is that the dc–dc converter processes only a part of the generated power, allowing for higher efficiency as compared with the series configuration. In line with this concept, an integrated power circuit is proposed in this paper with the following multiple functions: battery charge, battery regulator, and step up converter. The best operation condition occurs when the load current value is equal to the PV module MPP current value (*I*mpp), where the dc–dc converter does not process power.

Depending on the dc load voltage level, the dc loads can be connected in parallel with the PV module ("DC Load-1") and/or in parallel with the battery bank ("DC Load-2"). However, the voltage level of the PV module is higher than the battery voltage. If the system must also supply the ac loads, a dc–ac converter can be connected in parallel with the PV modules, as shown in Fig. 4. In this case, an output transformer can be used to generate the nominal ac voltage, or additional PV modules can be added in a series connection in order to obtain the dc voltage level that is necessary to generate the nominal ac voltage. As can be seen, two conversion stages between the PV modules and the output inverter are eliminated in the proposed parallel stand-alone system when compared with the series stand-alone system.

This may represent a significant increase in the overall efficiency and reliability of the system, which is besides enabling a reduction in the cost of the electronic system utilized. On the other hand, the series connection of a higher number of PV modules would present a significant reduction in the energy generated and could make it difficult to obtain the MPP in cases of shading/defect of one or more PV modules.

The output characteristic of two PV modules under two different sunlight conditions is shown in Fig. 5. The black curve represents the output characteristic of the module operating with total solar irradiation, and the graycurve represents the output characteristic of a shaded module operating with partial solar irradiation. Fig.6 shows the equivalent output characteristic of PV modules connected in series, where one module operates with partial solar irradiation.

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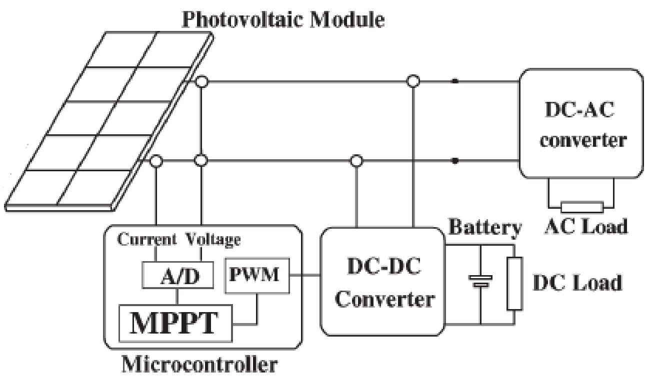


Fig. 4 MPPT System with parallel connection

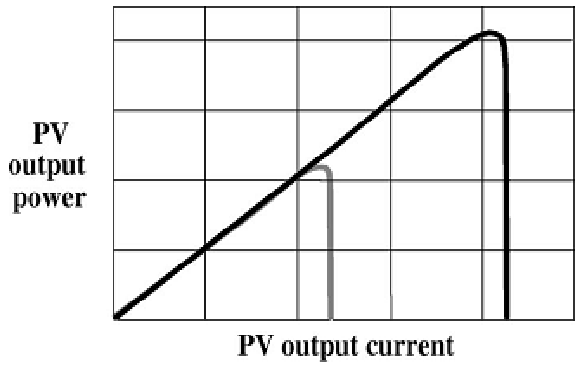


Fig. 5 Output curve of (gray line) shaded and (black line) unshaded PV modules.

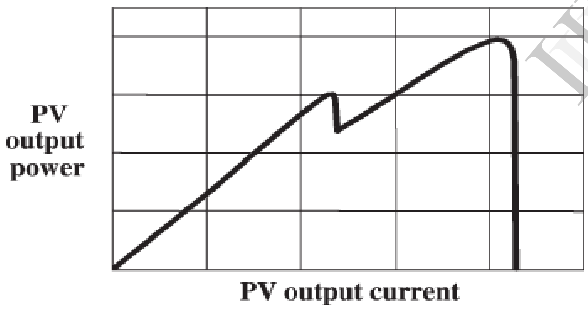


Fig. 5 Output curve of (gray line) shaded and (black line) unshaded PV modules.

## III. PROPOSED MPPT CONTROLLER

### *A. Power Circuit Operation*

In order to verify the operation characteristics of the proposed parallel MPPT system shown in Fig. 7, only a dc load connected in parallel with the PV module was considered . It was composed of a battery bank storage energy, (C) a capacitor, (L) an inductor, and a power semiconductor leg (S1−D1 and S2−D2). The bidirectional converter operates as a buck converter in the battery charge modeand as a boost converter when the battery must supply the load (RL) or when the load energy demand is higher than the energy generated.

The converter duty cycle is generated by the same control algorithms that are used in the series-connected MPPT.

The operation analysis of the proposed converter is presented for use with hard-switching pulse width modulation. However, it must be highlighted that the power circuit efficiency can be improved by using soft-switching techniques.

*1)* Buck Operation Mode:Fig. 8 shows the two topological stages that occur during the buck operation mode. The battery bank voltage must be lower than the PV module voltage for correct operation. When the energy generated is enough to supply the load, the exceeding energy is used to charge the battery. When the power switch S1 is turned on, the inductor L stores energy, and the energy flows from the PV module to the battery bank. When the power switch S1 is turned off, the diode D2 conducts, and the energy stored in the inductor L is transferred to the battery. The switches' command signals are complementary, and therefore, the switch S2 is turned on during the conduction of the diode D2.

*2)* Boost Operation Mode:If the energy generated at theMPP is not enough to supply the load, the power systemoperates as a boost converter, transferring energy from thebattery to the load. Inthiscase, while the switch S2 is turnedon, the inductor L stores energy from the battery, as shown inFig. 9. When the switch S2 is turned off, the energy storedin the inductor is transferred to the load. Fig. 10 shows thecommand signal of the power switches S1(*V*CS1) and S2(VCS2)and the inductor current waveform (*I*L) in the buck and boostoperations.

The greatest advantage of the proposed parallel MPPT systemwith a bidirectional power circuit, which is as shown inFig. 7, is the integration of multiple functions in a single costeffectiveconverter, which combines simplicity, reliability, andlow cost. The multiple functions of the proposed system areas follows: battery bank charger, which is when the energygenerated by the PV array is higher than the load consumption;MPPT controller, which is in order to extract the maximumenergy from the PV array; and step-up dc–dc converter, whichis when the energy of the PV array is not enough to supplythe load. The control algorithm ensures the operation of the PVmodule at the MPP, implementing the MPPT function.

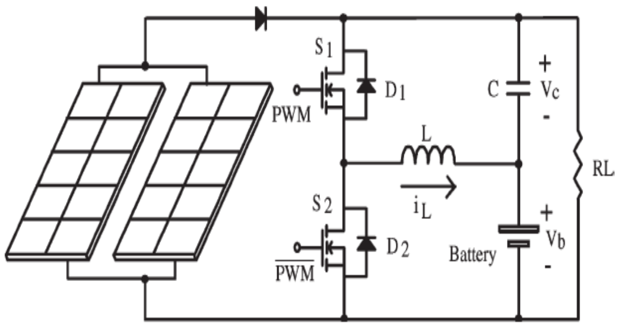


Fig. 7 MPPT System with bidirectional dc–dc converter.

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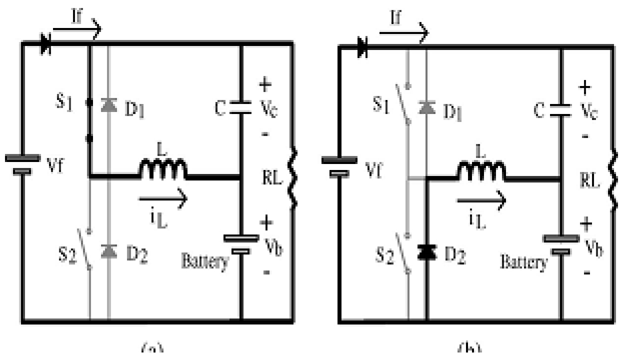


Fig. 8. Buck operation mode. (a) S1 turned on. (b) S1 turned off.

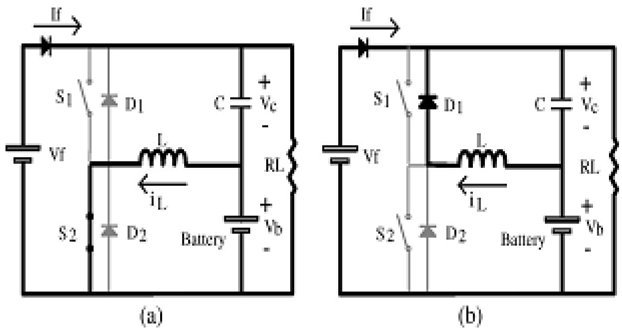


Fig. 9. Boost operation mode. (a) S2 turned on. (b) S2 turned off

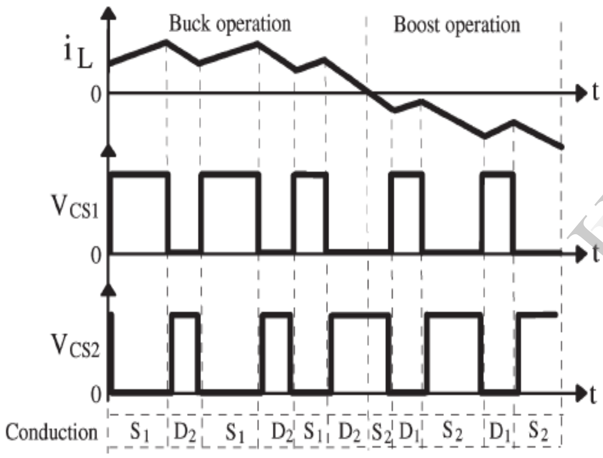


Fig. 10 Bidirectional Operation of the inductor current.

### *B. Control Algorithms*

*1)*Perturb And Observe MPPT Algorithm*:*

The PV voltage and current are monitored, and the PV power can be controlled as in the series connected system. There are many studies that analyse the energy efficiency of different MPPT algorithms, the transition between the different operations modes must occur without discontinuity of the load in the parallel-connected MPPT system. The convergence time of the MPPT algorithm is, normally, not important for the series connected system because the climatic transitions occur with a high constant time and because the load is connected to the battery bank. However, the utilization of afast convergence MPPT algorithm is important for the parallel system in order to minimize the transient in the output voltage with the load variation. As the analysis of the MPPT algorithm was not the focus of this paper, the perturbation and observation method was utilized, and the control algorithm is shown in Fig. 11.The algorithm reads the value of current and voltage from the solar PV module. Power is calculated from the measured voltage and current. The value of voltage and power at kth instant are stored. Then next values at (k+1)th instant are measured again and power is calculated from the measured values. The power and voltage at (k+1)th instant are subtracted with the values from kth instant. If we observe the power voltage curve of the solar pv module we see that in the right hand side curve where the voltage is almost constant the slope of power voltage is negative (dP/dV<0) where as in the left hand side the slope is positive.(dP/dV>0). The right side curve is for the lower duty cycle (nearer to zero) where as the left side curve is for the higher duty cycle (nearer to unity). Depending on the sign of dP (P(k+1) - P(k)) and dV (V(k+1) -V(k)) after subtraction the algorithm decides whether to increase the duty cycle or to reduce it.

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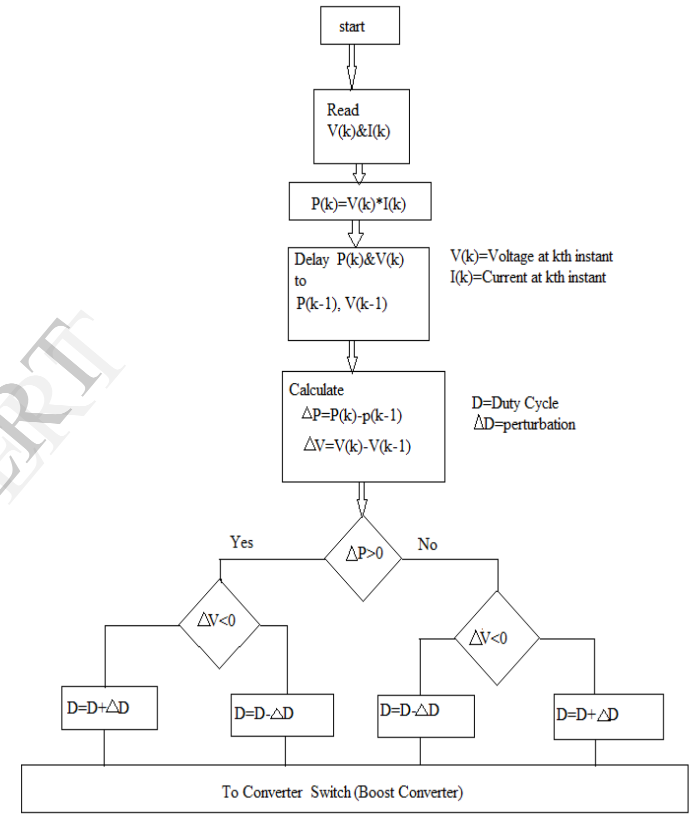


Fig.11 Perturb Observe MPPT Algorithm

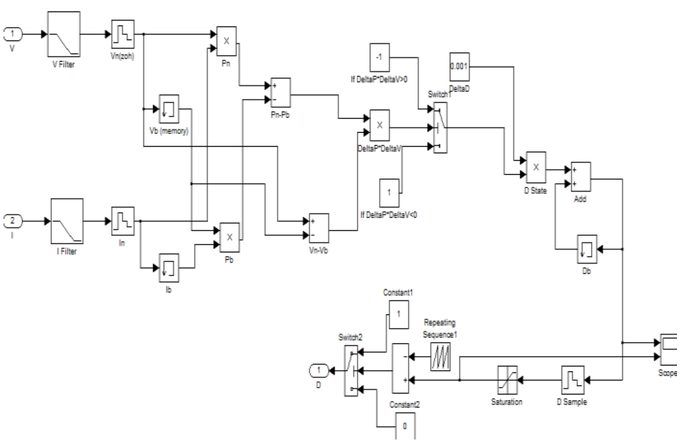

Fig.12Simulation Circuit Of Perturb and Observe MPPT Algorithm.

*2)* Battery Charge Control*:* While the PV module generatesenergy, the MPPT algorithm is active and maintains the PVmodule operating with maximum power. If the PV currentis higher than the load current, the battery bank is chargedwith the difference between these currents. The PV modulepresents a current source output characteristic at the maximum
Current value, as shown in Fig. 1. Therefore, if the maximumPV current is considered in the design of the battery bank, acurrent control loop is not necessary to limit the maximum batterycharge current. The highest battery charge current occurswhen the system operates with maximum solar irradiation andwithout load. When PV-generated energy is lower than the loaddemand, the necessary additional energy is supplied by thebattery bank. Thus, the charge or discharge battery current iscontrolled by the MPPT algorithm. During the operation of theMPPT algorithm, the battery state of charge is verified, andwhen the state of charge reaches its lowest level, the batterydischarge function is disabled, and the system is turned off. Inaddition, when the battery state of charge reaches its highestlimit level, the MPPT algorithm is disabled, and the outputvoltage control loop is enabled (operation mode 5). In thiscase, the reference voltage adopted for the constant voltagecontrol loop must define an output voltage that is close to thePV MPP voltage but higher in order to allow for the batterydischarge. After a small partial battery discharge, the MPPTalgorithm returns to operation and a cyclic transition betweenthe MPPT and voltage regulation algorithm occurs while thebattery is fully charged and the energy generated is higherthan the load energy demand. The control algorithm developedfor the parallel MPPT operates only with the battery bankconnected to the system.

*3)* Voltage Control Loop*:* The voltage control loop is also activated when the energy from the PV module is very low or null. In this case, the MPPT algorithm is disabled, the dc–dc power circuit operates as a boost converter, and the battery bank supplies the load with a constant voltage. In this situation, the reference voltage defined in the control algorithm is compared with the output voltage, and the error signal is applied to the digital voltage compensator. The control action defines the converter duty cycle in order to regulate the output voltage. The voltage reference considered is equal to 15 V, which is the intermediate value of the MPP voltage of the PV module utilized in the practical implementation. As occurs with the MPPT algorithm during the voltage control loop operation, the battery state of charge is verified, and the system is turned off when the battery reaches its lowest level.

## IV. EXPERIMENTAL RESULTS

The operation of the proposed system was tested with theimplementation of a laboratory prototype, which is shown. The PV module utilized in the practical test was theKyocera Solar KC40T with maximum power equal to 45 W.

### *A. MPPT Operation*

The practical implementation of the control algorithms wasaccomplished with the microcontroller MSP430F149. The data acquisition was obtained through serial transmission from the microcontroller to a computer. The main control information,such as voltage, current, power, and converter duty cycle, isstored during MPPT operation.

The experimental results of the MPPT system using the PVmodule KC40T are shown in Figs. 13-15, considering a loadresistance that is equal to 12 Ω. Fig. 13 shows the PV modulepower and current.

The maximum power obtained for the climatic conditionswas about 32 W, and the MPP current was equal to *I*mpp =2.1 A. Fig. 13 shows the PV module output current and voltagecurve, as well as two load lines. The lower line represents the connection of the load resistance directly to the PV modulewithout the MPPT circuit.

The power obtained in this case was equal to 24 W. Theupper line represents the equivalent load adjusted by the dc–dcconverter and MPPT algorithm, obtaining a power that is equal to 32 W. Thus, the 25% gain in power obtained with the MPPTwas used to store energy in the battery.

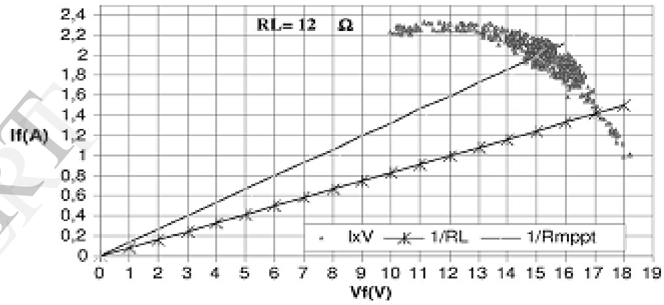


Fig. 13 Output Current and voltage of the PV module.

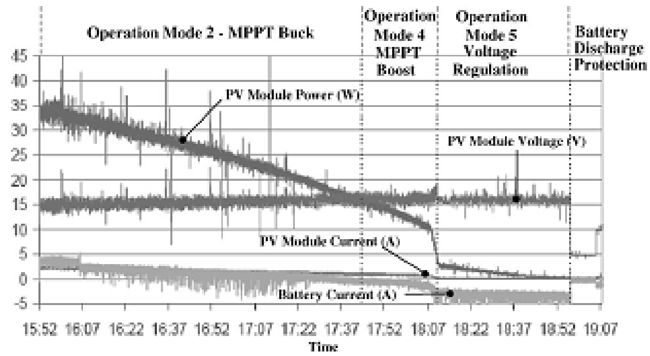


Fig. 14 Data Acquisition of the parallel MPPT operation.

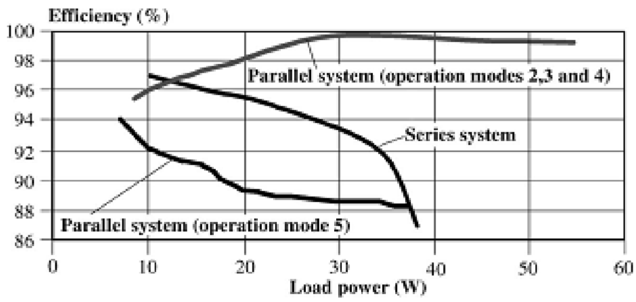


Fig. 15 Series and parallel MPPT systems efficiency.

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## V. CONCLUSION

In this paper a standalone PV system has been simulated by Mat lab/Simulink. Perturb and observe algorithm has been used for maximum power point tracking. Simulation results show that the system operates in the maximum power point for the different irradiances values. An MPPT circuit with parallel connection is presented in this paper. The parallel connection of the MPPT system reduces the negative influence of power converter losses in the overall efficiency during PV power generation. The control algorithm ensures operation at the MPP as in the classical system; however, only a part of the power generated is processed by the dc–dc converter. The power converter implemented is multifunctional, operating as an MPPT circuit, battery charge, battery regulator, and step-up converter. A stand-alone generation system, with a reduced number of energy-processing stages, is proposed, allowing for the implementation of a high-efficiency PV system. The main operational aspects of the parallel MPPT were verified with the implementation of a prototype. The transitions of the different operational modes were tested and occurred without any discontinuity of the system's operation.

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