Integrated Photovoltaic Maximum Power Point Tracking Converter

Johan H. R. Enslin, *Senior Member, IEEE*, Mario S. Wolf, Daniël B. Snyman, and Wernher Swiegers

***Abstract*— A low-power low-cost highly efficient maximum power point tracker (MPPT) to be integrated into a photovoltaic (PV) panel is proposed. This can result in a 25% energy enhancement compared to a standard photovoltaic panel, while performing functions like battery voltage regulation and matching of the PV array with the load. Instead of using an externally connected MPPT, it is proposed to use an integrated MPPT converter as part of the PV panel. It is proposed that this integrated MPPT uses a simple controller in order to be cost effective. Furthermore, the converter has to be very efficient, in order to transfer more energy to the load than a directly coupled system. This is achieved by using a simple soft-switched topology. A much higher conversion efficiency at lower cost will then result, making the MPPT an affordable solution for small PV energy systems.**

***Index Terms*—Maximum power point tracking, remote electrification, solar energy, solar power generation.**

I. Introduction to MPPT's in PV Panels

The costliest per-watt expenditure in a photovoltaic (PV) system arises in generation [3]. The current–voltage and power–voltage characteristics of a solar panel change with the meteorological conditions the panel is exposed to. The *V–I* output characteristics of a PV panel show peak power points with solar insolation and cell temperature as parameters, as shown in Figs. 1 and 2 [7].

Fig. 3 presents the contributing components to the total capital cost of installed PV remote area power systems (RAPS) [7]. This analysis shows that, in a PV system, the PV array contributes to 57% of the total cost, with the battery storage the second major contributor, at 30%. Other components in the systems, i.e., inverters and regulators/maximum power point tracker (MPPT) contribute to a smaller portion, at 7% [3]. The cabling and installation costs can also form another 6% of the total capital cost. Fig. 4 shows the block diagram of a typical large PV energy generation system [7] and the low total system efficiency η_t. The system efficiency is determined from Fig. 4 as follows:

$$E_{\text{sol}} \cdot \eta_s \cdot \eta_k \cdot \eta_{\text{MPPT}} = E_s + E_m \tag{1}$$

$$E_{\text{out}} = E_s \cdot \eta_b \cdot \eta_I + E_m \cdot \eta_I. \tag{2}$$

E_{sol} is the energy delivered by the sun and E_{out} is the energy delivered to the load over the same period of time. On

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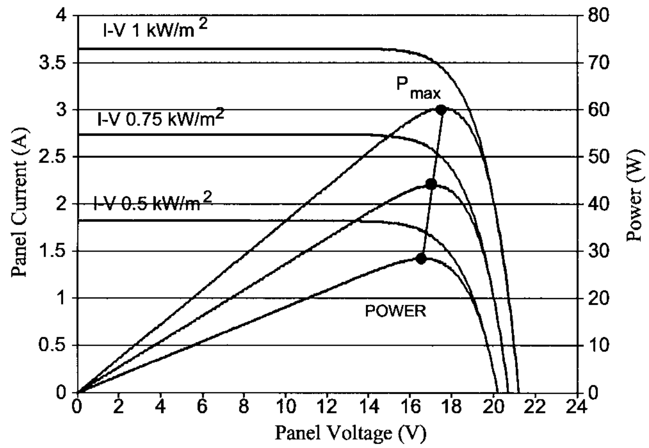

Fig. 1. PV panel insolation characteristics.

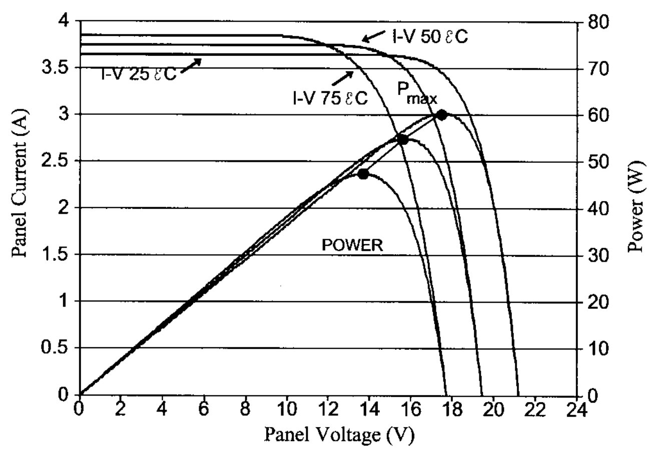

Fig. 2. PV panel temperature characteristics.

rearranging (1) and substituting (1) into (2), the total system efficiency $\eta_t = E_{\text{out}}/E_{\text{sol}}$ is found to be as shown in Fig. 4.

It makes good economic sense to use very-high-efficiency low-power MPPT's in order to scale down the PV array and batteries, thus resulting in a lower cost system. This will result in a total PV system that is much more economically viable [4] and, therefore, suitable to be utilized on a wider application base for remote electrification.

The approach described in Section II was used to develop the proposed integrated MPPT converter system. In high-performance MPPT regulators, dc–dc converters with self-adaptive control algorithms should be used to utilize the input power source to its fullest capability. Several MPPT systems

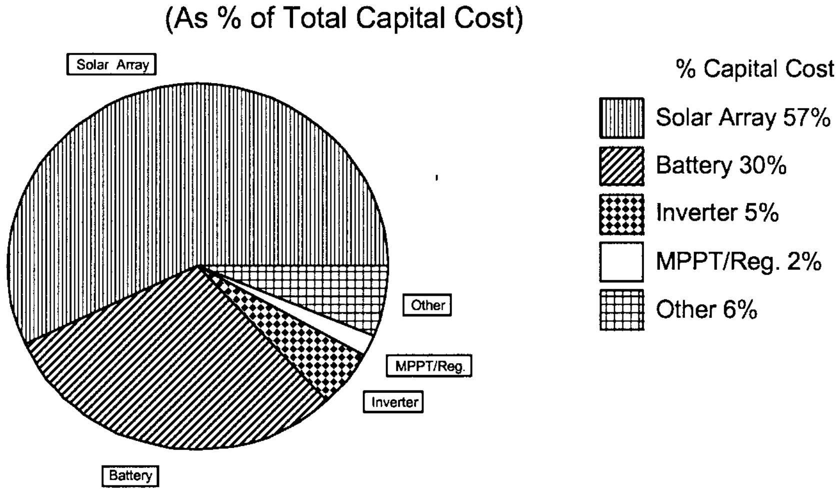

Fig. 3. Cost distribution of a 15-kWh/day PV installation.

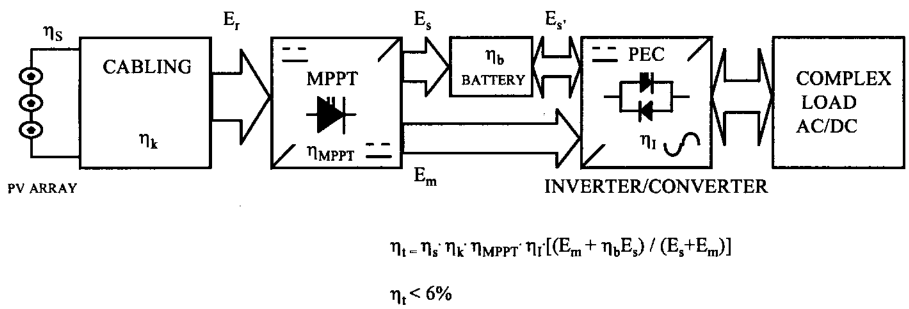

Fig. 4. Traditional PV configuration.

have been introduced with reasonable reliability and efficiency [2], [9], [11]. MPPT's use standard switch-mode power supply technologies, incorporating switching transistors, diodes, capacitors, and control algorithms. The three basic topologies are the Buck (Down), Boost (Up), and Buck–Boost (Up–Down) converters.

The typical battery load, however, requires a constant voltage that is a mismatch to that of the array maximum power point voltage. The main function of an MPPT is to adjust its input voltage, which is also the PV panel input voltage, so that it corresponds to the voltage where the panel delivers maximum power. At its output, the MPPT always provides the voltage required by the battery or machine pump load [1]. Experiments performed in previous work report that an MPPT with an efficiency of 85% can increase the amount of energy stored in batteries, on average, by 17% per solar day [11]. For MPPT efficiencies of 90% and higher, energy gains greater than 25% can be obtained. The main problems associated with prior MPPT's are the cost, efficiency, and reliability of the separate high-power (>1 kW) converter.

II. Integration of MPPT's in PV Panels

In order to alleviate the above-mentioned problems of prior MPPT approaches, it is proposed to implement a small MPPT integrated into a photovoltaic panel. Such an MPPT converter should be extremely efficient and low cost to be integrated cost effectively within the PV panel. Furthermore, the output

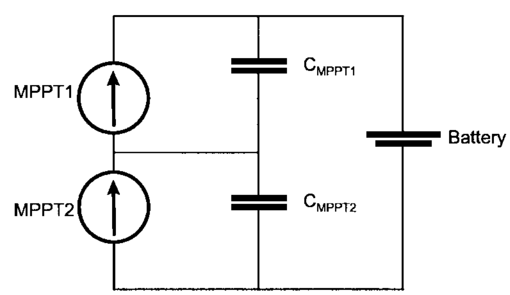

Fig. 5. Equivalent circuit for two-panel PV string.

of the PV integrated MPPT should be capable of matching all traditional loads, e.g., for batteries or water pumps, using series or parallel configurations. The output of the PV panel with its integrated MPPT converter constitutes a two-terminal port. To feed traditional loads, these panels must be capable of being connected in series, to form a string. The string will then provide a high-enough output voltage for the load. If the load requires a higher power level, these strings may be connected in parallel to supply additional current. Each converter will have to incorporate an output filter to decouple the output, so that the converters can be connected in series or parallel. The inductor of each converter will appear as a constant current source, and connecting the output terminals of the converters in series will result in an equivalent circuit, as shown in Fig. 5. It is important to ensure that the load voltage shares between the output capacitors of the converter.

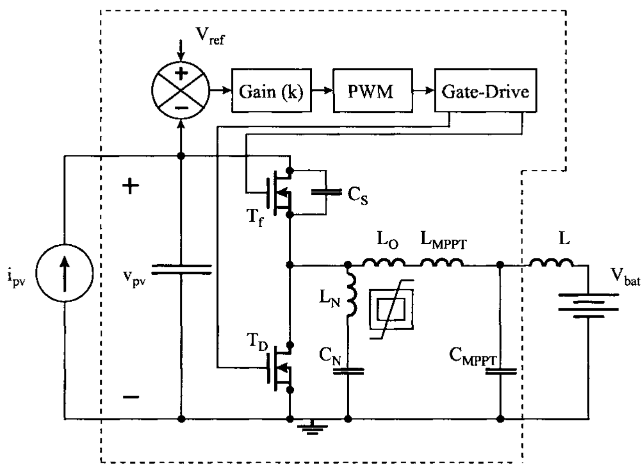

Fig. 6. PV integrated MPPT converter.

The power rating of such an MPPT converter should be in the order of 55–110 W. The power rating is dictated by the ratings in which solar panels are produced, with 55- and 110-W panels being standard. The MPPT converters can be made very economical, due to electronic integration using surface-mount-device technology in the PV panel itself [5], [6]. Such a construction is made possible by using a very economical high-efficiency dc–dc converter topology with a simple MPPT controller [9], [12], [13].

Since inductors and capacitors (used as filter components in converters) are more costly with increasing size, the approach is to reduce their size by choosing a sufficiently high converter switching frequency. Simultaneously, the high efficiency was obtained by selecting an extremely simple soft-switched topology [8], [13], [14]. Since losses are incurred in the driver circuitry, power switches, and magnetics, a simple design that minimizes conversion stages and switching losses is required. The traditional freewheeling diode in this converter was replaced by a reverse-conducting MOSFET (T_D in Fig. 6), since its conduction losses were appreciably lower than those of typical diodes. The controller of such a system should be very simple. The input power to the dc–dc converter has to be maximized, since the output voltage is a function of the loading of the PV array, e.g., induced EMF voltage of a PV pump machine, or battery under charge [5], [6]. A battery under charge through a converter "slaves" the output voltage of the converter to the battery voltage. By changing the converter's duty cycle, the input voltage (solar panel's voltage) varies accordingly. The MPPT controller thus regulates the input voltage to the point where the source delivers maximum power. Barring system losses, this maximum power is transferred to the load.

III. Details of the Proposed Soft-Switching Integrated MPPT Converter

The requirements for the PV integrated converter, formulated in the previous paragraph, are met by the topology proposed in Fig. 6. Normally, this topology is shown with an extra switch in series with the snubber capacitor C_s [8]. The power rating of this converter is 50–150 W [13]. The switch in the capacitor snubber C_s can be left out, since the energy captured by the turn-off snubber is recovered by the nonlinear inductor L_N; detailed analysis can be found in [12] and [13]. This converter has a reduced voltage, but increased current as its output. This is the same as one would expect from a Buck converter. The advantage of this converter compared with a classic Buck converter is that its efficiency is much higher. An added advantage of this topology is its simplicity compared to other high-efficiency resonant converters. The synchronous rectifier (T_D), the internal output filter, panel connection cable (L), and battery as the external output filter are shown in Fig. 6. When the need arises to form strings, a filter capacitor will have to be introduced in shunt with the output terminals of the MPPT, as already mentioned.

The control algorithm used is the same as described in [9]. The principle is that, for crystalline cell structures, the operating point where maximum power is furnished is always close to a fixed percentage of its open-circuit voltage (within $\pm 2\%$). Production spread, temperature, and solar insolation levels cause the position of the maximum power point to vary within this 2% tolerance band. The controller shuts down the converter and samples the panel's open-circuit voltage. 76% of the open-circuit voltage is determined and kept in a hold circuit as reference for the control loop until the next sampling instance. The input voltage of the converter (the panel voltage) is fed back and compared with the reference signal. A proportional controller is used in the forward path. The output of the controller is pulsewidth modulated (PWM) and fed to the drivers of the power switches. (As stated earlier, a battery under charge clamps the converter's output voltage, and varying the duty cycle results in a varying input voltage to the converter. The input voltage can thus be controlled to the operating point where maximum power is furnished by the source.)

This control method results in a quasi-power point tracker. This controller does not constantly seek the true maximum of the power-to-voltage curve, but rather rests on preknowledge of where the maximum power point is. The advantage of this method is its simplicity and cost effectiveness. The control loop can be implemented with a single op-amp and PWM chip. No costly multipliers or digital controllers are needed.

A simplified quasi-MPPT algorithm is also schematically presented in Fig. 6. The details of generation of V_{ref} from the panel open-circuit voltage have been left out of the figure for the sake of simplicity.

IV. Performance of a Soft-Switching Integrated MPPT Converter

This proposed PV integrated MPPT converter, described in Section III [9], [13], [14] was evaluated in the laboratory. The experimental setup for the evaluation of the constructed integrated MPPT is shown in Fig. 7, with the measured efficiency shown in Fig. 8. The peak measured efficiency is around 99%, with a full-load efficiency of 98%. The experimental setup depicted in Fig. 7 was constructed using the PV integrated MPPT switching at 100 kHz. Three 55-W

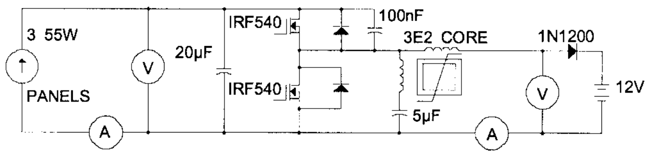

Fig. 7. Experimental setup for measurements.

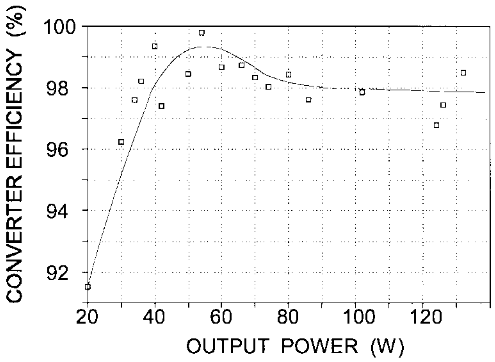

Fig. 8. MPPT efficiency versus output power.

solar panels were used in series as the source, while a PV battery with 20 m of cabling formed the load [13], [14].

In Fig. 9, the sampling of the MPPT controller input voltage is presented. The open-circuit voltage of the PV array or panel is sampled every 30 s. The duration of the sampling instance is approximately 100 ms. During the sampling instance, switches T_f and T_D are turned off. The current to the battery naturally goes to zero during the sampling instance. The PV source charges the input filter capacitor of the converter to its open-circuit voltage. This voltage is sampled, and 76% of this value kept in a hold circuit as reference for the control loop. After the sampling instance, normal operation is resumed, and the reference voltage is tracked, as can be seen from Fig. 9. There is a small steady-state error, since only a proportional controller is used in the forward path. In future work, the optimal choices of duration of the sampling instances and duration between them still has to be determined. It is evident from Fig. 9 that the duration of the sampling instance may be reduced substantially as the open-circuit voltage is reached quickly.

Fig. 10 shows the load current (battery charging current) as a function of the solar input voltage to the MPPT. The power transfer is proportional to the load current, as the dc battery voltage remained constant during the span of the measurements. Two 55-W (peak power) solar panels connected in series supplied the MPPT. A 12-V (nominal) battery was used as the load. The curves of Fig. 10 represent the set of possible operating points for the MPPT. Curve A was measured at 10:30 on a clear, sunny, winter's morning (June 2, 1997, Stellenbosch, South Africa). Curve B was measured at 15:50 on a partly cloudy, winter's afternoon (June 3, 1997). The crosses indicate the operating points of the MPPT under closed-loop control. The operating points are very close to the maximum power points, and the control strategy holds true, even when operating under very different meteorological conditions, as can be seen from the power curves of Fig. 10.

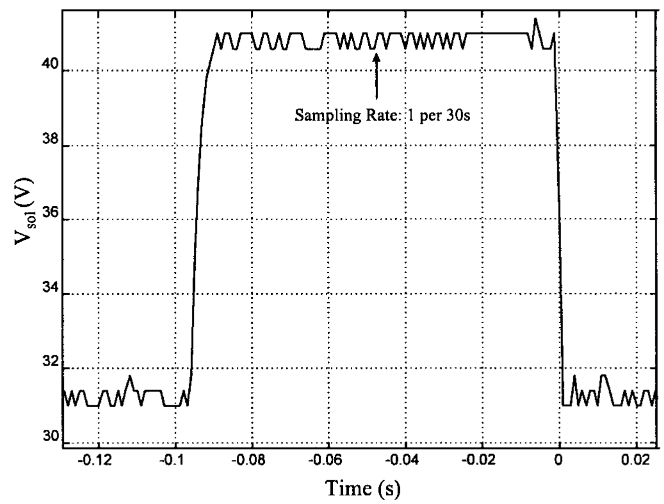

Fig. 9. Sampling of simple MPPT converter.

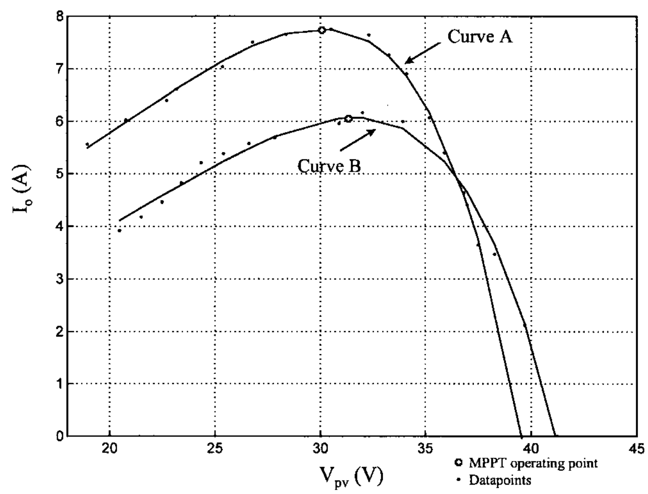

Fig. 10. Performance of simple MPPT controller.

The total materials and component cost of the MPPT system (controller and converter) is currently US$35. This cost does not take volume of manufacturing into account, and it is expected that the price of the MPPT would drop appreciably if fully integrated and mass produced as part of each PV panel.

V. Conclusions

An integrated cost-effective MPPT has been proposed in this paper. The proposed MPPT has several advantages to offer compared to previous MPPT's. The advantages include increased efficiency and a reduction in cost. The cost of PV generation systems will be much lower if this principle is fully integrated into standard 75–100-W PV panels, since 25% less panel area would be required. Future work includes a low-cost true MPPT controller and optimization of the integration of this MPPT into a standard PV panel.

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