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Low Voltage Photovoltaic System with P-V Curve Evaluation MPPT Algorithm Implementation

***Abstract**. Photovoltaic (PV) modules have I-V characteristics that are affected by temperature and solar radiation. It is essential to equip power conversion modules in Maximum Power Point Tracking (MPPT) function in order to obtain maximum power from PV panels. In this paper the implementation of P-V curve MPPT algorithm in PV system composed of low voltage 3.2 kWp PV panel and interleaved step-up DC-DC converter has been presented. PV panel simulation and DC-DC converter description has been followed by the MPPT algorithm characterization.*

***Streszczenie.** Charakterystyki prądowo-napięciowe modułów fotowoltaicznych (PV) zależą od temperatury i promieniowania słonecznego. Aby uzyskać maksymalną moc z panelu PV nieodzowne jest wyposażenie modułów konwersji energii w funkcję śledzenia punktu pracy w mocy maksymalnej (MPPT). W niniejszym artykule zaprezentowano wykorzystanie algorytmu MPPT oceny krzywej P-V w systemie PV złożonym z niskonapięciowego panelu PV o mocy 3.2 kWp i wielosekcyjnego podwyższającego przekształtnika DC/DC. Charakterystyka proponowanego algorytmu MPPT poprzedzona była badaniami symulacyjnymi panelu PV oraz opisem przekształtnika DC/DC. (**Zastosowanie algorytmu MPPT w ocenie krzywej P-V w niskonapięciowych systemach fotowoltaicznych**).*

Keywords: PV systems, step-up DC-DC converter, MPPT.
Słowa kluczowe: systemy fotowoltaiczne, podwyższające przekształtniki DC/DC, MPPT.

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Introduction

Photovoltaic (PV) systems as a part of renewable source systems has been increasing worldwide. To yield maximum energy from whole PV array Maximum Power Point Tracking (MPPT) function has to be implemented. Usually the PV system for residential use is composed of PV modules connected in serial and parallel which are controlled by common inverter. In that configuration as a result of shading the PV modules suppress their output power each other and make it difficult to track the Maximum Power Point (MPP). Parallel PV module configuration does not suffer with above mentioned phenomena, however to produce high DC bus voltage it requires additional DC-DC converter.

This paper describes successful implementation of P-V curve evaluation MPPT algorithm in low voltage PV system consisted of 3.2 kWp array (10 modules connected in parallel) and high-efficiency step-up DC-DC converter.

Low Input voltage PV system

PV array composed of parallel connected PV panels implies delivering the energy to the converter at low level of voltage. For that instance total current sourcing DC-DC converter (i_{PV}) is a sum of single module currents (Fig. 1). High efficiency high step-up ratio DC-DC converter is required to deliver energy from PV array to high voltage load. MPPT algorithm is hence implemented within step-up DC-DC converter driver.

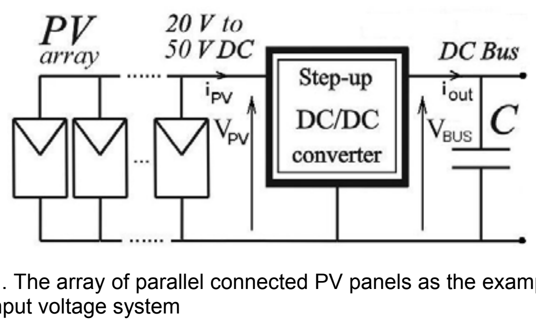

Fig. 1. The array of parallel connected PV panels as the example of low input voltage system

Fig. 2 depicts block diagram of MPPT algorithm implementation and test setup. PV chords feed the power directly to the input of step-up DC-DC converter. Microcontroller (Cortex-M4 core) based driver with MPPT algorithm requires instantaneous values of PV array current (i_{PV}) and voltage (v_{PV}). The measuring front end consisting of scaling circuitry delivers required signals to driver's A/D converter channels. The duty cycle of step-up DC-DC converter switches is controlled by the driver according to current state of MPPT algorithm.

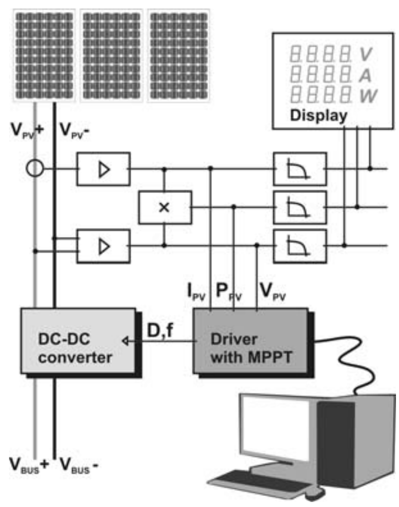

Fig. 2. The diagram of measurement setup destined for MPPT algorithm implementation

For test purposes the control and settings of MPPT algorithm are set by external PC. Moreover the measurements as well as diagnostics information can be transmitted down to a PC application. Additionally instantaneous values of PV array current, voltage and power can be seen at LED display.

PV Array

The PV array is built upon ten KYOCERA KD320GH-4YB PV modules [1] connected in parallel. Datasheet parameters of single module are collated in Table 1. The power generated in PV module strongly depends on environmental conditions such as solar radiation S, and ambient temperature T. Because of nonlinear I-V and P-V characteristics PV module cannot be considered neither as voltage nor current source.

PV module parameters are specified by manufacturers at Standard Test Conditions (STC) which are T = 25ºC and S = 1000 W/m^2 at direct perpendicular solar radiation.

Table 1. Specification of KYOCERA KD320GH-4YB module (STC)

#	Parameter	Name [unit]	Value
1	Peak power	P_{max} [Wp]	320
2	Open circuit voltage	V_{oc} [V]	49.5
3	Short circuit current	I_{sc} [A]	8.60
4	Maximum power point voltage	V_{pm} [V]	40.1
5	Maximum power point current	I_{pm} [A]	7.99
6	Open circuit voltage temperature coef.	μ_V [V/ºC]	-0.178
7	Short circuit current temperature coef.	μ_A [V/ºC]	$5.16 \bullet 10^{-3}$

Accurate simulation model of PV array and PV panel based on datasheet parameters is widely discussed in [2]. I-V characteristic of the 3.2 kWp panel is given by (1).

(1)

$$I_{PV} = 10 \cdot \{ I_S - [I_{sat} \cdot (e^{\frac{q \cdot (V_{PV} + R_S + I_{PV})}{A \cdot K \cdot T}} - 1) + \frac{V_{PV} + R_S \cdot I_{PV}}{R_p}] \}$$

where: I_S - the current under certain solar radiation, I_{sat} - diode saturation current, q - electron charge, K - Boltzman's constant, A - diode quality factor (assumed 1 for the sake of simulation), T - ambient temperature, R_p, R_s - total parallel and series resistances at PV array output.

Matlab simulation of solar radiation S and ambient temperature T has been carried out to find the MPPT algorithm operation region (Fig. 3).

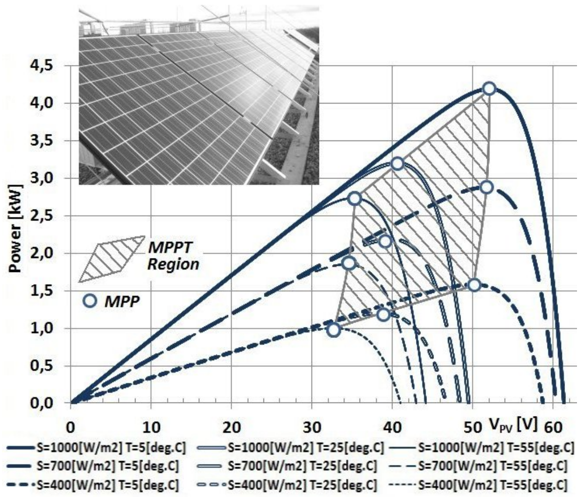

Fig. 3. Simulation of P-V curves S and T dependency of the 3.2 kWp PV array located on the roof of Electrical Engineering Faculty (see the inset)

For given simulation conditions (i.e. temperature T range of 5ºC to 55ºC and insulation S of 400 W/m^2 to 1000 W/m^2) the region of MPPT algorithm operation extents across the range of 32 V to 52 V of V_{PV} and covers the power range of 1 kW to over 4 kW. Above mentioned range of power imposes the constraints for proper DC-DC converter topology choice which can handle the PV array current I_{PV} up to 90 A roughly.

Interleaved Step-up DC-DC converter

Interleaved topology which assures high efficiency due to input current sharing between the number of phases is a proper solution. Proposed step-up DC-DC converter is composed of five identical phases derived from legacy flyback converter topology (Fig. 4a) [3]. The phases are driven phase-shifted with the same duty cycle according to Fig. 4b).

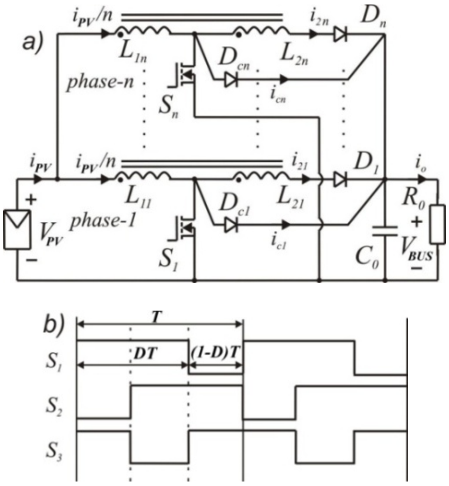

Fig. 4. Interleaved step-up DC-DC converter a) and its driving sequence at the example of 3-phases, b) duty cycle D = 66%

High voltage gain is achieved by using coupled inductors with turns ratio N. The level of output voltage V_{BUS} as well as amount of power converted are controlled by duty ratio D according to (2), [4]

$$\frac{V_{BUS}}{V_{PV}} = 1 + \frac{D(1+N)}{1-D} \quad (2)$$

The prototype of high-efficiency 5-phase interleaved step-up converter has been developed and tested. The converter is built upon SiC diodes and transistors with coupled inductors made of Super-MSS cores. Primary winding inductance is L_{1k} = 64 μH, turns ratio of N = 3. C_0 is composed of two parallel 330 μF low ESR capacitors. The switching frequency f_S is 20.3 kHz. Fig. 5 presents experimental waveforms of converter input current and voltage. Te efficiency of the converter exceeds 91% within wide output power range.

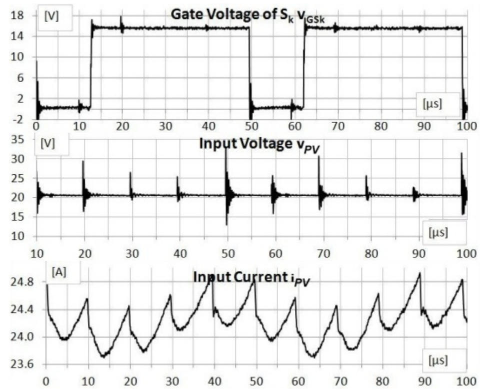

Fig. 5. Five-phase interleaved step-up converter experimental waveforms at 500 W of output power and 75% duty cycle, 20.3 kHz of switching frequency

P-V Curve Evaluation MPPT Algorithm

A number of MPPT algorithms has been discussed in literature [5], [6]. Since PV array consists of parallel modules its P-V characteristic does not demonstrate multiple peaks [6] caused by shading which occur in serial PV module strings. For that reason an extreme seeking control MPPT such as for instance Incremental Conductance (IncCond) or Perturb and Observe (P&O) algorithms seem sufficient to efficiently track MPP under changing atmospheric conditions.

In contrary to above mentioned methods where only two consecutive measurements need to be done to track MPP proposed method evaluates P-V curve by the means of three consecutive sub-measurements analyzing.

Fig. 6 depicts P-V curve evaluation algorithm work flow. Each full measurement consists of three sub-measurements at three different duty cycles: D_k, $D_k+\Delta D$ and $D_k-\Delta D$ producing calculated results of P_{PV_k}, P_{PV_k+}, and P_{PV_k-} respectively. The algorithm utilizes P-V curve slope calculation dP/dV_{PV} and automatic P-V curve slope dependent ΔD correction to achieve fast tracking speed. Once the MPP is reached, the operation of the PV array is maintained at this point for configurable full measurement delay time unless next full measurement demonstrates that condition (3) is not satisfied.

$$\left(\frac{dP}{dV_{PV}}=0\right)\&\,(P_K>P_{K-})\,\&\,(P_K>P_{K+}):\text{at MPP}$$
$$\frac{dP}{dV_{PV}}<0:\text{left of MPP, rising P-V curve slope}$$
$$\frac{dP}{dV_{PV}}>0:\text{right of MPP, falling P-V curve slope}$$

(3)

The capacities of both V_{PV} and I_{PV} channel buffers are 3200 samples each. At 160 kHz of sampling frequency each sub-measurement lasts for 20 ms, P_{PV} is then calculated as a result of averaged values of $\overline{V_{PV}}$ and $\overline{I_{PV}}$ multiplication.

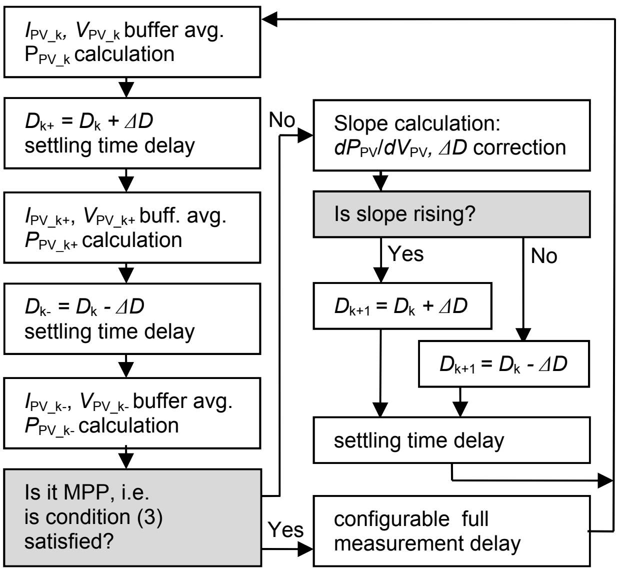

Fig. 6. P-V curve MPPT algorithm diagram

Experimental Validation

The waveforms of long term tracking (over 6 minutes) of proposed MPPT algorithm are shown on Fig. 7a) whereas short term tracking ones are depicted on Fig. 7b). The settling time delay was 480 ms and full measurement delay was set to 0. Total full measurement period is then 1.5 second long. First sub-measurement at D_K is followed by two consecutive sub-measurements at D_{K+} and D_{K-}. Condition (3) is checked afterwards and D_{K+1} duty cycle is calculated according to dP/dV_{PV} which is P-V curve slope estimation result. In the long term measurement plot (Fig. 7a) it can be seen, that the proposed algorithm successfully tracked MPP in changing atmospheric conditions within the power range of 2.4 kW up to 3.1 kW.

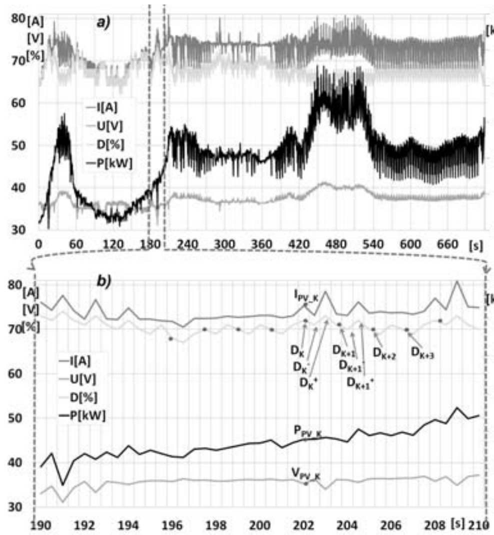

Fig. 7. P-V evaluation MPPT algorithm performance plot

Conclusion

Low voltage 3.2 kWp PV system has been introduced. Proposed P-V curve evaluation MPPT algorithm takes full advantage of measured and estimated P-V curve slope, approaching rapidly MPP. Circuit experiments has been carried out with interleaved high-efficiency step-up DC-DC converter and its microprocessor based driver with MPPT algorithm implemented in. Main advantage of proposed method is its simplicity. The paper makes contribution to photovoltaic area since proposed method is not dependent on datasheet PV module parameters and it can be easily adopted in numerous low-voltage parallel PV systems.

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