Platform for Rapid Prototyping of Maximum Power Point Tracking Algorithms in Photovoltaic Systems

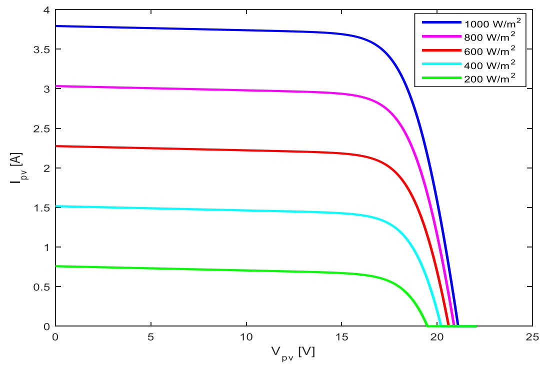
Srđan Lale, Ognjen Petrić, Slobodan Lubura and Marko Ikić

***Abstract*—This paper describes the application of the programmable logic controller (PLC), which is software-implemented on the personal computer (PC), for rapid prototyping and testing of maximum power point tracking (MPPT) algorithms used in photovoltaic (PV) systems. The practical results for Perturb and Observe (P&O) MPPT algorithm, which is used to extract and maintain the maximum power from the PV modules connected to the synchronous buck converter, are given.**

***Index Terms*—PV module; MPPT algorithm; buck converter; software-implemented PLC; rapid control prototyping.**

I. Introduction

RENEWABLE energy sources are becoming an essential part of global trends in the development of low-carbon economy and the so-called "green energy". Among them, the photovoltaic (PV) modules are one of the most important sources. It is well known that the PV modules behave as real (nonlinear) current sources. Their current-voltage (I_{pv}-V_{pv}) and power-voltage (P_{pv}-V_{pv}) characteristics depend on weather conditions, such as intensity of solar radiation and ambient temperature (Fig. 1 and Fig. 2). From the power-voltage characteristics it is obvious that only a single maximum power point (MPP) exists under given working conditions. To find and maintain that MPP, the maximum power point tracking (MPPT) algorithms are implemented.



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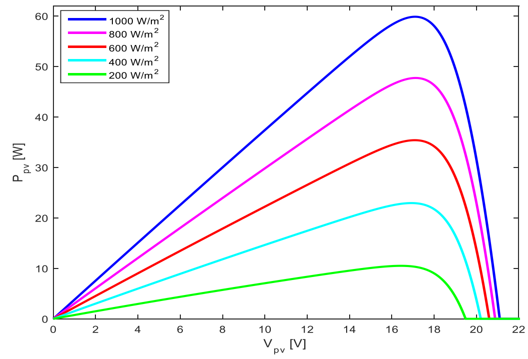

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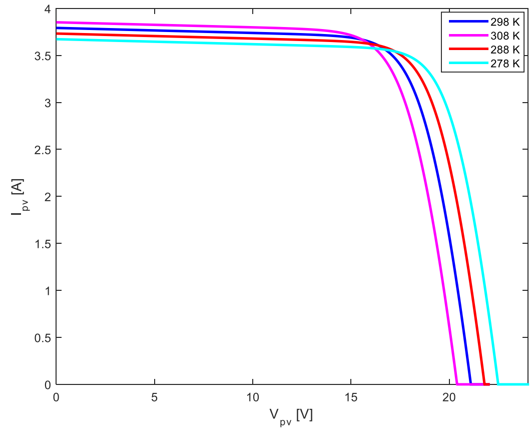
Fig. 1. I_{pv}-V_{pv} a) and P_{pv}-V_{pv} b) characteristics of the PV module for different values of solar radiation.



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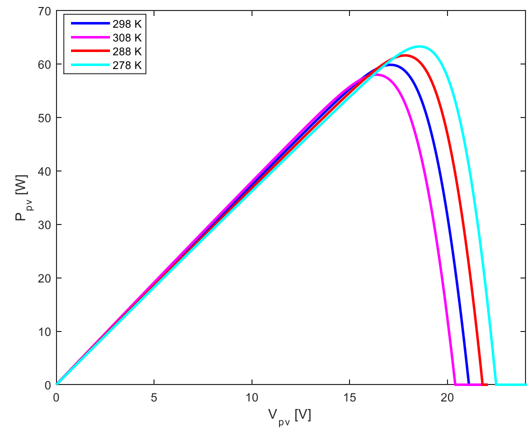

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Fig. 2. I_{pv}-V_{pv} a) and P_{pv}-V_{pv} b) characteristics of the PV module for different values of ambient temperature.

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There are numerous MPPT algorithms proposed in scientific literature [1]. Many new MPPT algorithms and their modifications still continuously appear in scientific papers, because this is a very important and popular scientific topic [2]-[8]. To test the performances of the MPPT algorithms, it is very important to develop an appropriate experimental platform, which enables rapid prototyping of the MPPT algorithms in laboratory environment. Various hardware platforms are used for that purpose, for example data-acquisition boards [9]-[12], microcontrollers or digital signal processors [13], [14], field programmable gate arrays [15], [16], etc. All these platforms have their advantages and drawbacks regarding the complexity of programming and manipulation, processing speed, price, etc., so it is hard to determine the optimal platform which satisfies all criteria.

In this paper, the application of the Beckhoff programmable logic controller (PLC), which is software-implemented on the personal computer (PC)/laptop, is proposed for realization of the MPPT algorithms in the PV systems. The utilization of the Beckhoff PC-based PLC for implementation of the conventional voltage control of the DC-DC buck converter is proposed in [17]. The software implementation of the Beckhoff PLC on PC or laptop is enabled with TwinCAT software environment [18], [19]. As it is shown in [17], the main advantages of this platform are modularity, user-friendly operation, high signal processing speed, simple and fast graphical programming, low price, etc. Because of these performances, the Beckhoff PLC is a good solution for rapid prototyping of different converters' control structures, including MPPT algorithms which are subject of this paper.

This paper is organized in the following way. The conventional Perturb and Observe (P&O) MPPT algorithm, which is implemented on the proposed platform, is briefly explained in section II. The proposed platform, which is based on the application of the Beckhoff PLC, is described in section III. The obtained experimental results are given in section IV. Section V represents the conclusion.

II. Perturb and Observe MPPT Algorithm

The MPPT is not possible without the power electronics converter, which must be inserted between the PV module and load. For that purpose, a synchronous buck converter is used in this paper (Fig. 3).

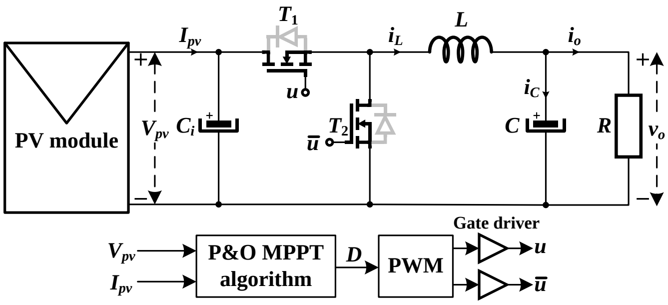

Fig. 3. Proposed PV supply system with MPPT function.

The working point of the PV module is determined by the intersection of the load working line and the I_{pv}-V_{pv} characteristic of the PV module (Fig. 4).

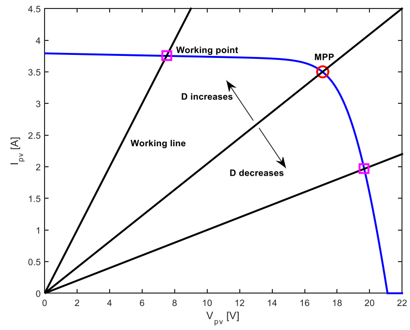

Fig. 4. Dependence of the working point of the PV module on duty cycle *D*.

The load working line for the buck converter from Fig. 3 is equal to:

$$I_{pv} = \frac{D^2}{R} V_{pv}, \quad (1)$$

where V_{pv}, I_{pv}, R and D represent the voltage and current of the PV module, load resistance and duty cycle of the switching signal u, respectively. The slope of the working line and thus the position of the working point, depend on the duty cycle D, as it is shown on Fig. 4.

The P&O MPPT algorithm is one of the first developed and the most popular MPPT algorithms. Its operation is based on the permanent perturbation of the working point of the PV module, by automatic change of the duty cycle D. Once the MPP is reached, it is maintained by the permanent oscillations of the working point close around the MPP. The size of these oscillations depends on the perturbation value ΔD. The well-known flowchart of the conventional P&O MPPT algorithm is shown on Fig. 5.

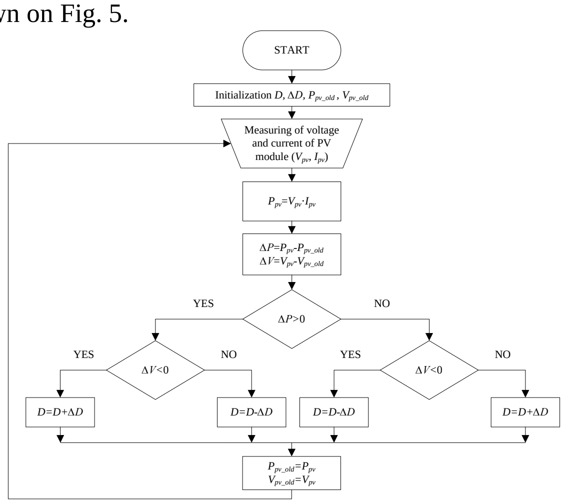

Fig. 5. Flowchart of the conventional P&O MPPT algorithm.

The inputs of the P&O MPPT algorithm are measured voltage V_{pv} and current I_{pv}. The output of the algorithm is the duty cycle D, which is fed to the pulse width modulator (PWM). The PWM generates the switching signals u and $\bar{u}$ for the power switches T_1 and T_2 (Fig. 3).

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III. Proposed Experimental Platform

The block-diagram of the proposed experimental platform, which is used for implementation of the P&O MPPT algorithm, is shown on Fig. 6.

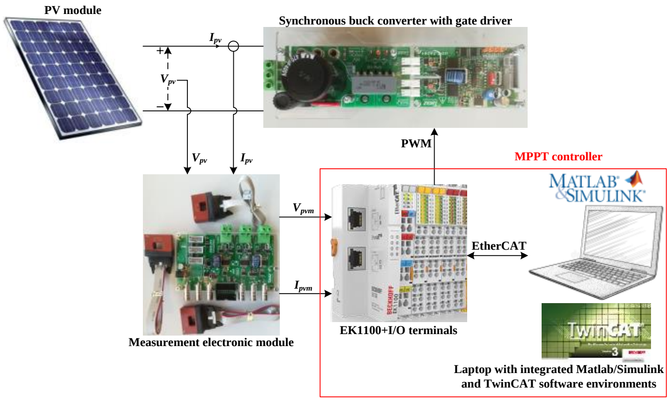

Fig. 6. Block-diagram of the proposed rapid control prototyping platform.

The platform consists of the following main parts.

A. PV Module

Two PROSTAR 75W/24V PV modules connected in series, which are placed at the roof of the Faculty of Electrical Engineering in East Sarajevo, were used. These two PV modules can produce about 150 W in standard test conditions.

B. Synchronous Buck Converter with Gate Driver

SPM-HB SiC half bridge power module [20] is used as the synchronous buck converter, with the connected GDC-2A2S1 galvanically isolated gate driver module [21]. The switching frequency of the buck converter was set to 20 kHz. The other parameters of the buck converter are: input capacitance C_i=470 µF, output capacitance C=1000 µF, inductance L=220 µH, and load resistance R=4 Ω.

C. Measurement Electronic Module

The measurement of the voltage and current of the PV module is performed with the galvanically isolated electronic module USM-3IV [22]. The measured voltage V_{pvm} and current I_{pvm} (Fig. 6) at the output of the USM-3IV module are scaled to the ±10 V range, which is necessary for the analog input terminal of the Beckhoff PLC.

D. MPPT Controller

The P&O MPPT algorithm is implemented on the Beckhoff PLC. A detailed description of the Beckhoff PLC is provided in [17]. The Beckhoff PLC is software-implemented on the laptop by using TwinCAT software environment. The TwinCAT environment converts the laptop into the real-time controller, which is connected to the input/output terminals via EK1100 EtherCAT coupler (Fig. 6). The analog input terminal EL3164 is used for accepting the measured scaled voltage and current of the PV module, i.e., the signals V_{pvm} and I_{pvm}, respectively. The P&O MPPT algorithm is implemented and executed in real time in TwinCAT software environment. The algorithm calculates and updates the value of the duty cycle, which is used by the output PWM terminal EL2502. The EL2502 terminal produces the PWM control signal, which is fed to the input of gate driver GDC-2A2S1.

The Beckhoff PLC is graphically programmed by using the developed Matlab/Simulink model of the P&O MPPT algorithm, which is a great benefit. This is accomplished thanks to the integration of the Matlab/Simulink and TwinCAT software environments. The created Simulink model of the P&O MPPT algorithm is integrated into the TwinCAT software environment, as it is shown on Fig. 7 and Fig. 8. The discretization period, i.e., the sample time of the model is 1 ms, the perturbation value of the duty cycle ΔD is 0.005, and the update period of the duty cycle is 1.5 s.

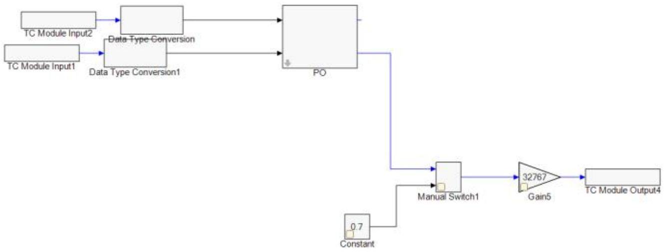

Fig. 7. Implementation of the P&O MPPT algorithm in TwinCAT software environment.

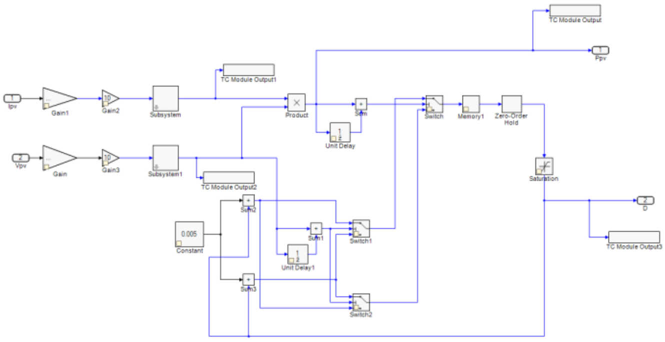

Fig. 8. Implementation of the P&O MPPT algorithm in TwinCAT software environment – scheme of the "PO" subsystem from Fig. 7.

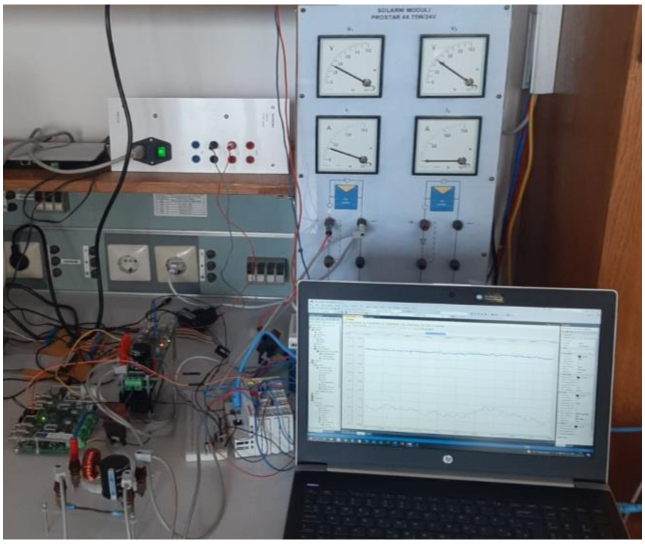

Fig. 9. The experimental setup of the proposed platform for rapid prototyping of the MPPT algorithms.

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The experimental setup of the proposed platform is shown on Fig. 9. The setup is realized at the Faculty of Electrical Engineering in East Sarajevo.

IV. Experimental Results

In TwinCAT software environment, there is a possibility to observe the signals in real time by using special graphs, i.e., virtual scopes, as well as to record them for later (offline) use.

The experimental waveforms of the obtained power of the PV module and the duty cycle are given on the following figures, which represent the real-time graphs within the TwinCAT environment. The left scale on Fig. 10 and Fig. 11 corresponds to the duty cycle (green signal), while the right scale corresponds to the output power of the PV module (blue signal).

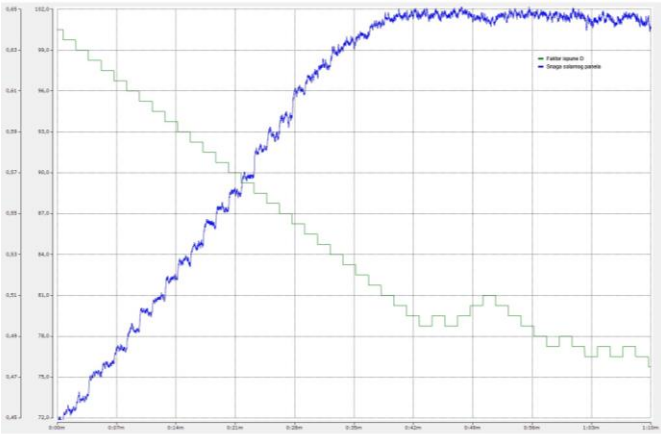

Fig. 10. The experimental waveforms of the duty cycle (green) and the power of the PV module (blue) – reaching the MPP.

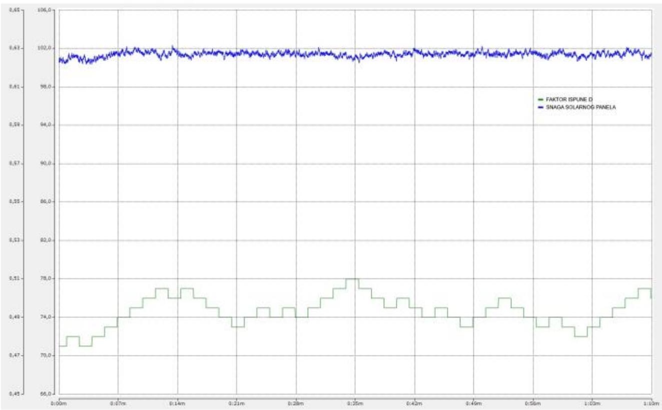

Fig. 11. The experimental waveforms of the duty cycle (green) and the power of the PV module (blue) – maintaining the MPP.

The initial value of the duty cycle *D* was set to 0.65. It is obvious from the given experimental results that the implemented P&O MPPT algorithm successfully reach and maintain the maximum power of the PV module. These results confirm the validity and excellent performances of the proposed experimental platform, which can be successfully used for implementation and testing of the MPPT algorithms.

V. Conclusion

This paper proposes the platform for rapid prototyping of the MPPT algorithms for PV applications. The key part of the proposed platform is the Beckhoff PC-based PLC. There are numerous excellent features of this platform, such as low price, modularity, simple and user-friendly operation, simple and rapid programming by using combination of Simulink and TwinCAT environments, high processing speed thanks to the usage of the computer's processor, possibility of monitoring of different signals in real time within TwinCAT environment, etc. The platform is tested on the example of the conventional P&O MPPT algorithm. However, it can be used for any other MPPT algorithm, by changing the Simulink model and reprogramming the Beckhoff PLC. Also, the existing platform can be upgraded with additional power modules and Beckhoff input/output terminals, so more complex PV systems can be tested. Except scientific research and development, the proposed experimental platform can be very useful for educational purposes.

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