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Conversion of Conventional Switching Mode Power Supply in a Photovoltaic Array Emulator

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Abstract—**The paper discusses the development of a solar photovoltaic array emulator based on the conversion of a conventional switching mode power supply. The current-voltage characteristic of the power supply is adjusted according to the photovoltaic array model due to the injection of current into the junction of the feedback voltage divider circuit through an additional resistor. NI data acquisition device and LabVIEW software are used to build the emulator control system. The photovoltaic array model was implemented into the software algorithm as a look-up table to reduce the processing time and improve the system response. An "off-the-shelf" switching mode power supply having the flyback architecture and 230V ac input was selected for the practical experiment. The proposed approach to emulator development ensures rapid system prototyping at a low cost.**

Keywords—photovoltaic array, PV emulator, solar energy, SMPS

I. Introduction

Photovoltaic (PV) installations utilising solar energy have been rapidly expanded over the last decades to bring a significant input to the global energy balance. The latest REN21 report [1] shows that the solar PV generation over the world was increased by 175GW in 2021 to top up the global PV capacity to 942GW. Such a massive growth of solar PV generation share in energy production was ensured by the intensive activity of a large number of science, business and government bodies providing research, manufacturing, installation, and policy development in the area of solar energy conversion and utilisation.

Further research, development and manufacturing of PV-based industrial applications require the implementation of solar PV array emulators for the efficient prototyping and testing of power electronic converters designed to provide the energy transfer from the solar array output to the utility network [2],[3]. Ram et al. [2] discussed that physical solar PV arrays are considered an inconvenient energy source to conduct tests and experiments in real-time mode. The disadvantage is related to several factors, including cost, deployment area/space, and unpredictable/variable weather conditions. An important feature of the PV conversion system is the maximum power point tracking (MPPT) algorithm. MPPT fully determines the efficiency of the PV system operation and must be investigated/tested in the entire range of the sun irradiation potentially illuminating the PV array surface. An effective approach to the detailed analysis of the MPPT algorithm embedded into the PV system controller is the use of the emulator as a PV energy source having a variable output following a variety of solar irradiance conditions [3],[4].

In many previously published works, cost and rapid prototyping options are highlighted as two main requirements applied to the solar PV array emulator design; particularly for educational, research, and small business purposes where finance and time issues are crucial [5]-[10]. A common solution to the development of PV emulators is a switching mode or linear power supply having a non-linear I-V characteristic that follows the output parameters of a solar PV array. In terms of rapid prototyping, the non-linear output characteristic is often achieved by the implementation of feedback via an external controller based on dSPACE [11]-[13] or LabVIEW [6],[14] control prototyping systems. However, PV system controllers based on relatively simple analogue [15] and digital circuits/microcontrollers [8],[10],[16]-[18] are also widely used for rapid prototyping. The cost of the emulator is basically cut by the selection of a power supply produced by industrial manufacturers to use it as the core component of the emulator. Such an "off-the-shelf" device requires a certain modification (or software control in the case of a programmable power supply [6]) to have the capability of providing I-V output characteristics according to the solar PV array parameters [10]. Therefore, the modification of an "off-the-shelf" power supply with the assistance of a standard control prototyping system (e.g. LabVIEW) is considered the most promising approach to rapid designing and building a low-cost solar PV array emulator.

This paper discusses the technical details of the circuitry conversion of a conventional switching mode power supply (SMPS) into a solar PV array emulator. The modification is based on the approach suggested in [10] and provides an injection of current from an external voltage source into the junction of the voltage divider used in the conventional power supply as a feedback network. A National Instruments data acquisition (DAQ) device is implemented as an external controller generating the current injection into the feedback according to the PV parameters to build up the power supply I-V characteristic following a solar PV array output curve.

II. Structure of the Emulator

The structure of the proposed solar PV array emulator is shown in Fig. 1. The emulator structure consists of a conventional SMPS, USB-6008 DAQ device, two Op-Amps, a current sensor resistor, and an additional resistor R_3. The conventional power supply has a voltage divider consisting of two resistors R_1 and R_2, which forms a voltage feedback network to monitor and stabilise the output voltage of the SMPS. The feedback voltage from the junction point of the divider is applied to the power supply controller,
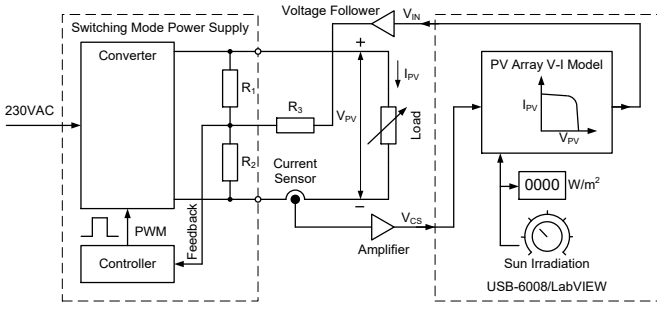
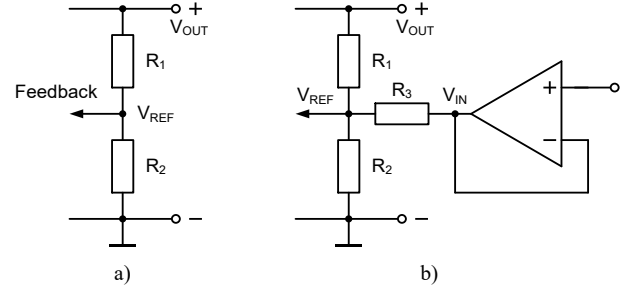Fig. 1. Structure of the solar PV array emulator.

Fig. 2. (a) Conventional feedback circuit based on the voltage divider principle; (b) modified feedback circuit having an additional resistor R_3 to inject the current into the junction.

where it is compared with the reference voltage V_{REF} to produce an error for further processing. The proposed modification of the power supply is similar to the approach suggested in [10] and based on the connection of the additional resistor R_3 to the junction point of the voltage divider (between R_1 and R_2). The current sensor is a small value resistor connected to the ground terminal of SMPS, in series to the output load. The voltage across the current sensor (proportional to the current through the load) is amplified and then read by the analogue input of DAQ.

The conventional power supply is designed to ensure a constant voltage across the output terminals within the range of the rated output current. However, it can be seen (Fig. 1) that the standard feedback circuit is modified with the purpose to provide a non-linear output I-V characteristic. Such an intrusion into the feedback circuitry affects the constant voltage at the output. If the voltage from the voltage follower is higher than the reference voltage V_{REF} at the divider junction point, then the current is injected through R_3 into the junction and the controller consequently reduces the voltage across the output terminals.

Therefore, the principle of the emulator operation is based on the injection of the current from the voltage follower through the resistor R_3 into the junction of the SMPS feedback voltage divider. Initially, the reading of the voltage from the current sensor is amplified and processed by the DAQ device. At the next stage, the current (represented by the current sensor voltage) is applied to an I-V model of a selected solar PV array to obtain the corresponding voltage across the output terminals. Then, the model via a DAQ analogue output generates a required voltage to be applied to the resistor R_3 in order to produce an injecting current into the junction. At the final stage, the power supply controller adjusts the output voltage following the PV model output.

The model of the I-V characteristic of the solar PV array is represented as a look-up table (LUT). The LUT of the model is part of the software developed for the DAQ device. The LUT-based approach to represent the I-V characteristic is selected to reduce the processing time and to improve the dynamic response of the emulator system.

III. Feedback Circuit Analysis

Fig. 2a shows a conventional feedback circuit based on a voltage divider principle applied for the control of a power supply output. This circuit is a very common approach to the feedback design in power supplies. The feedback voltage provided by the divider is compared with the reference voltage V_{REF} to produce an error for further control processing. Under the steady-state condition, the feedback voltage of the divider equals the reference voltage V_{REF} and, therefore, the output voltage of the power supply is defined by the following equation:
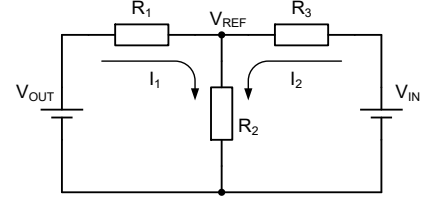
Fig. 3. Equivalent circuit of the modified feedback divider.

$$V_{OUT} = V_{REF}\left(1 + \frac{R_2}{R_1}\right) \tag{1}$$

where V_{OUT} is the output voltage of the power supply; V_{REF} is the reference voltage of the divider; R_1 and R_2 are the voltage divider resistors as shown in Fig. 2a.

Usually, in power supply controllers, the reference voltage is generated by a device or circuit having a highly stable voltage output, e.g. Zener diode or specialised reference voltage source. The power supply selected for the modification is equipped with the adjustable voltage regulator TL431 operating as the reference voltage circuit. This device is widely used in many switching mode power supplies and has a reference voltage of 2.5V; therefore, $V_{REF} = 2.5$V.
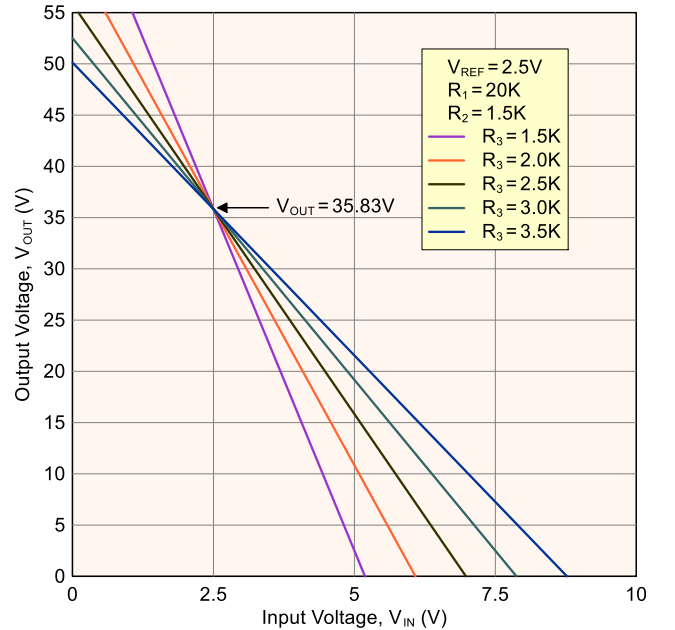

Fig. 4. Voltage across the output terminals of SMPS V_{OUT} versus input voltage V_{IN} applied to the resistor R_3. V_{IN} is produced by the DAQ device analogue output.
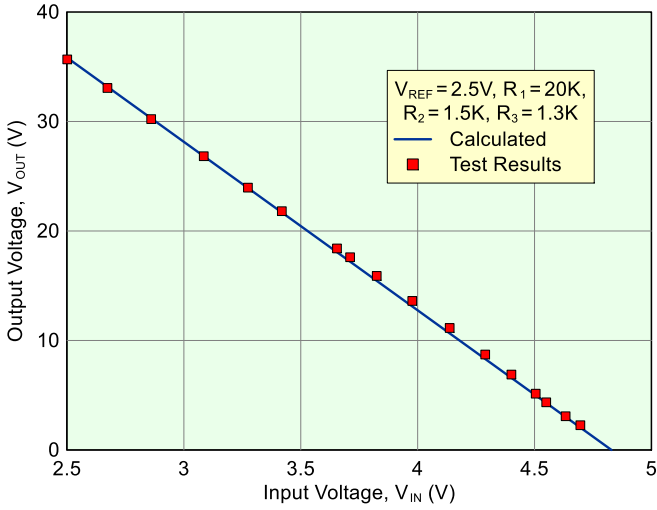
Fig. 5. Comparison of the line obtained analytically (blue line) and test results (red squares) for the resistor $R_3 = 1.3K\Omega$.

In general, the output voltage of the power supply can be regulated by varying the voltage divider resistors. However, most industry-manufactured power supplies have a simple voltage adjustment option and are designed to provide a fixed voltage across the output terminals. As discussed above, the output voltage of such power supplies can be controlled by injection of the current from an external voltage source V_{IN} into the divider junction through a resistor R_3 as explained in Fig. 2b. This approach ensures enchantment in controlling the power supply without any changes in the device circuitry.

An equivalent circuit of the voltage divider and an external voltage source is shown in Fig. 3 where V_{IN} is the input voltage generating current into the divider junction. The circuit is represented by a system of equations as follows:

$$V_{REF} = R_2 \left(I_1 + I_2 \right)$$
$$I_1 = \frac{V_{OUT} - V_{REF}}{R_1}$$
$$I_2 = \frac{V_{IN} - V_{REF}}{R_3}$$
(2)

From (2), the output voltage of the power supply is derived as follows

$$V_{OUT} = V_{REF} \left[1 + R_1 \left(\frac{R_2 + R_3}{R_2 R_3} \right) \right] - V_{IN} \frac{R_1}{R_3}$$
(3)

The value of the resistor R_3 can be found using the following equation:

$$R_3 = \frac{R_1 R_2 \left(V_{IN} - V_{REF} \right)}{\left(R_1 + R_2 \right) V_{REF} - R_2 V_{OUT}}$$
(4)

The SMPS selected for the emulator design has the feedback voltage divider comprising $R_1 = 20K\Omega$ and $R_2 = 1.5K\Omega$. Fig. 4 shows the family of lines representing the voltage across the output terminals of SMPS V_{OUT} versus the input voltage V_{IN} applied to the resistor R_3. The lines are obtained analytically for various values of the resistor R_3. It can be seen that at the voltage $V_{IN} = 2.5V$ (equal to the reference voltage $V_{REF} = 2.5V$) all lines are intersected at the same point corresponding to the output voltage $V_{OUT} = 35.83V$.

The max. analogue output voltage of the DAQ is limited by 5V. Therefore, the resistor $R_3 = 1.3K\Omega$ is selected to allocate V_{IN} within the 5-V range. The line showing the relation V_{OUT} versus V_{IN} is given in Fig. 5 (red line). It can be seen that the output voltage of the power supply is regulated in the range from max. value ($V_{OUT} = 35.83V$) to 0V under varying the input voltage from 2.5V to 4.8V which is suitable for the standard DAQ analogue output ($< 5V$). Fig. 5 also demonstrates the test results obtained from the practical experiment (red squares) – it shows a good correlation between the analysis and test results.

IV. EMULATOR HARDWARE

Fig. 6 demonstrates the emulator circuit diagram. The conventional SMPS circuit is shown in grey. The additional components brought in to modify the SMPS are shown in blue. The DAQ device USB-6008 is black.

The selected power supply is an "off-the-shelf" SMPS based on flyback architecture. Originally, the SMPS was designed to provide the conversion of 230V ac input into 36V dc output. As discussed above, the resistor R_3 was installed to ensure the current injection into the feedback junction is 1.3KΩ. The current sensor is a low-value resistor of 0.1Ω. The max. current expected in the emulator output is 3A, therefore, the max. voltage across the current sensor resistor is 0.3V. This voltage is amplified by OpAmp A_2 having a gain of 10. The amplified voltage (3V max.) corresponding to the emulator current is applied to the DAQ analogue input AI0+. The input voltage V_{IN} generated by the DAQ analogue output AO0 goes through the voltage follower A_1 and varies in the range 2.5-4.8V.

Unlike a conventional power supply, the emulator has to provide a normal operation at a low value of the output
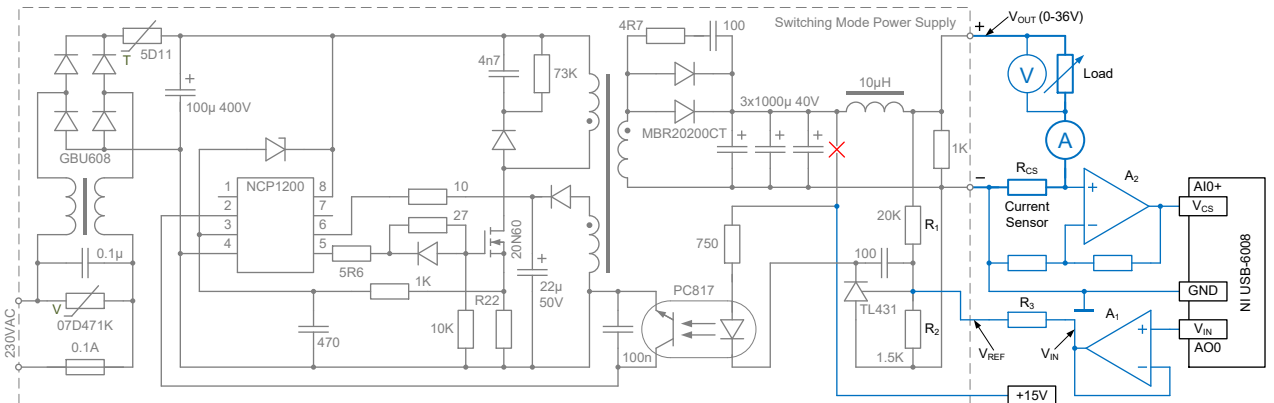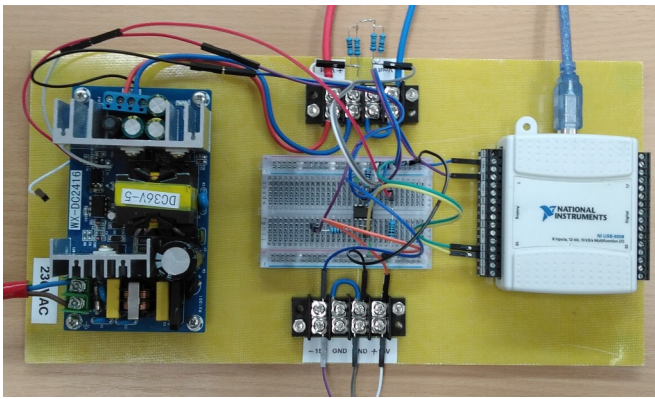

Fig. 6. Emulator circuit diagram.

Fig. 7. Test setup of the solar PV array emulator.

voltage (close to 0V under the short circuit condition). Therefore, the SMPS circuit requires an additional modification to improve the reliability of operation at low voltage values. The link supplying the optocoupler PC817 should be disconnected from the output terminal (where the voltage is varied) and connected to an external stable voltage source (for example, a positive voltage source used to energise OpAmps).

A photo of the practical test setup of the solar photovoltaic array emulator is shown in Fig. 7.

V. RESULTS OF THE EXPERIMENT

The prototype of the solar PV array emulator was built and tested to validate the analysis results. The family of the I-V PV curves selected for the experiment is shown in Fig. 8. Three examples of the I-V curves (Fig. 8a) were digitised to represent it as LUT in order to embed the tables into the LabVIEW software.

A high power variable resistor (manually controlled) was connected to the output terminals of the emulator prototype to play the role of the load. The readings of the output voltage and current were taken by the Voltech Power Analyser PM100.

Fig. 9 demonstrates the results of the practical experiments to produce three I-V characteristics approx. corresponding to the curves in Fig. 8a under sun irradiation of 800W/m^2, 600W/m^2, and 400W/m^2.

VI. CONCLUSION

Over the last decades, photovoltaic technologies and installations have been intensively researched, developed and massively expanded in terms of global energy
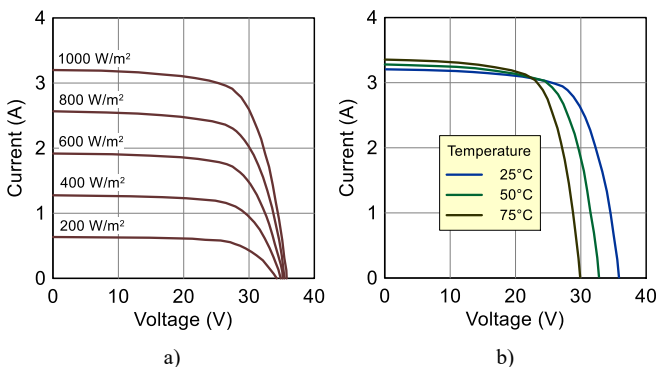

Fig. 8. Families of I-V PV curves: (a) the family related to sun irradiation; (b) the family related to array temperature.
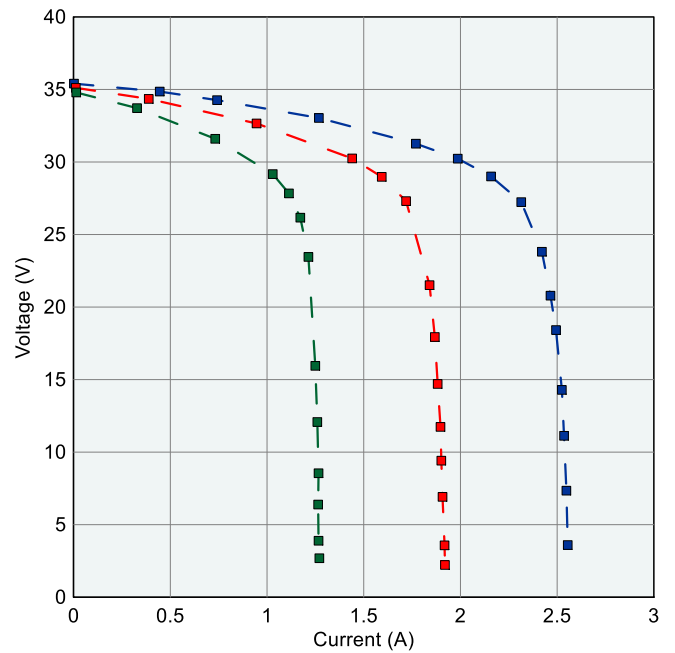

Fig. 9. The results of the practical experiments.

generation. Nowadays, the interest in PV technologies is extended to many areas including small businesses, education and academic research. Further development and investigation of photovoltaics at this level require rapidly prototyped PV emulators at a low cost.

This paper provides the development details of the conversion of a conventional SMPS into a solar PV array emulator. The proposed approach is based on an insignificant modification of the power supply and ensures rapid emulator prototyping at a low cost. The emulator is designed to be controlled by a National Instruments DAQ device and to operate under LabVIEW software.

The emulator prototype was developed, built and tested in order to verify the proposed approach. The results of the practical experiments have shown good correlations between the analytical outcomes and the emulator test readings.

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