Modification and testing of the microinverter development kit for the purpose of connecting the battery system

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***Abstract*— This paper presents the testing of the modified TMDSSOLARUINVKIT solar microinverter development kit manufactured by Texas Instruments. The microinverter consists of two linked converters, one connected to the photovoltaic panel and one to the electrical grid. It is intended for connecting low-power photovoltaic panels to the electrical grid. This paper describes hardware (HW) and software (SW) modifications that were necessary in order to connect the battery system to the platform. In addition to necessary HW and SW modifications, a supervisory control and data acquisition (SCADA) graphical user interface was designed for process control and monitoring. Experimental results demonstrating the possibilities of the modified platform are reported in the paper.**

***Keywords* — (microinverter, photovoltaic, battery)**

I. Introduction

Increasing awareness of the harmful consequences of using fossil fuels significantly impacts the development of energy production from renewable sources. The idea is to switch energy production to low-carbon sources. Electricity production is only one part of total energy production. The other two main components are transport and heating [1]. Heating energy production and transport still rely much more heavily on fossil fuels, so to make significant changes in carbon emissions, the electrification of these two types of energy production is currently the direction in which the world is going. Electric vehicles (EV) and electric heating systems are becoming more common. Many countries encourage the transition to these options by providing incentives for better energy efficiency of homes and reducing taxes on the purchase of EV. Restrictions are also being announced, such as banning vehicles with internal combustion engines in certain parts of some European cities and banning the sale of new vehicles with these engines from the year 2035 [2]. In most countries worldwide, the state provides incentives for installing photovoltaic (PV) panels on buildings, and they are gaining popularity. The use of rooftop PV generation to cover individual electric vehicle demand is a promising solution for reducing carbon emissions from transportation. The recent study [3] suggests that the combination of PV systems with battery energy storage can provide a reliable and cost-effective source of energy for electric vehicles. Overall, the integration of renewable energy sources, such as rooftop PV, with electric vehicles and energy storage systems, is crucial for a more sustainable future. In more extensive solar systems that cover a larger area with panels, the problem of partial shading appears. It can be a cloud making a shade on one part of the area covered in panels. This will decrease overall system productivity so that all the panels connected in a series with the shaded one will be limited to its power level [4]. One of the possible solutions is to use a microinverter. The microinverter connects to the individual PV panel or smaller group of panels, so there is less chance of having different light intensities across the photovoltaic string, and there is better control and overall efficiency of the system. The downside of using multiple microinverters in the PV power plant is increased system price. Usually, the converter that connects the PV panel to the electrical grid has the DC-DC converter at the panel side and the DC-AC converter (inverter) at the output (grid side) [5]. The PV panels do not provide a constant voltage at the output, so voltage regulation at the input to the inverter is required. The power produced by the PV panel can vary depending on the panel's absorbed light intensity and temperature. The more sunlight the PV panel gets, the more power it delivers, unlike the temperature effect, where a higher temperature lowers the output power. The main tasks of solar power converter are tracking the maximum power point of PV panel, efficient voltage level adjusting, and injecting pure sinusoidal current (insignificant influence of higher harmonics) into the electrical grid. It should be considered that energy can only be obtained under special conditions, i.e. while the panels are exposed to sunlight. The electricity production for distribution through the electrical network is regulated according to consumption, so the utilization of PV panels is further reduced if excess energy is produced. The development of battery energy storage technologies opens up the possibility of storing extra produced energy if there is no consumption at the production time. This way, the excess energy produced during a sunny day can be used when needed, even when the panels are not exposed to sunlight.

The following chapters will describe the TMDSSOLARUINVKIT microinverter and the hardware and software modifications that are done. The created graphical user interface (GUI) for battery management is presented. The system was tested, and experimental results were reported.

II. System Description

The TMDSSOLARUINVKIT platform, manufactured by Texas Instruments, was used to develop small microgrid model. The platform is intended for connecting PV panels to the electrical grid. The main parts of the platform are the flyback converter, an inverter, and the measurement and

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control circuits. Control is performed using the C2000 microcontroller unit (MCU) and the Piccolo-B F28035 control card. This platform belongs to the group of microinverters and is intended for a panel input voltage of up to 45V and output power of up to 280W [6]. On the panel side of this microinverter is a DC-DC converter with a flyback transformer (flyback converter) that increases the voltage obtained from the panel and galvanically separates the panels from the higher voltage of the DC bus (DC link). The DC link voltage is maintained at the appropriate level so that current can flow to the grid. The inverter side of the platform has the task of shaping the voltage and current from the DC link according to the grid's requirements, which are sinusoidal waves without mutual phase shift and the total harmonic distortion (THD) must be within the permissible limits. The desired values and forms of voltage and current are achieved using transistor switches in combination with inductors, capacitors and diodes. For the system to function correctly, it is necessary to measure specific values and generate a control signal accordingly. The control signal is a digital rectangular signal with a variable period of individual states (0 or 1), and such shaping is called pulse width modulation (PWM). The platform contains sensors for measuring voltage and current. It is necessary to measure the voltage and current on the side of the PV panels (input to the converter, that is, the DC-DC converter), the voltage of the DC link, and the voltage and current on the grid side (output of the converter, that is, the inverter). In addition to the listed basic functions, the platform contains elements and control algorithms for increased efficiency. The maximum power point tracking (MPPT) algorithm determines the reference current from the PV panel to the converter, and the current control loop maintains the reference value. Depending on the sun exposure of the panel, the power characteristic changes, and the MPPT algorithm adjusts the operating point according to the maximum power point. The basic model of the flyback converter consists of a transistor, transformer, diode, and capacitor. The disadvantage of this converter model is that large voltage stress occurs on the transistor when switching off. The reason for this is the current through the inductance of the transformer, which cannot stop immediately when the transistor turns off, so it induces a large voltage on the transistor. The losses that occur reduce the converter's efficiency, and high voltage can permanently damage the transistor. Fig. 1 shows the more advanced version of the flyback converter with additional components. The additional transistor Q_S and capacitor C_S are implemented to drain the current from the inductance of the transformer when switching off the transistor Q, thus reducing the voltage stress of the transistor Q. The capacitor C_S stores that energy and delivers it back to the system while the transistor Q is switched off. At the input to the converter, there is a capacitor C_{IN} that stabilizes the PV panel's voltage. On the secondary side of the flyback transformer, there are two capacitors (C1 and C2) and two diodes (D1 and D2). The capacitors C1 or C2 at the output are being charged depending on a transformer output current direction. In serial connection, they achieve twice the voltage, and in parallel with them, there is an output capacitor C_{OUT} that reduces the output voltage ripple. A higher voltage (up to 400V) comes to the output of the flyback converter, which is internally connected to the inverter. The inverter uses transistors to modulate the input DC voltage with PWM regulation and, with the use of a low-pass filter at the output, shapes the voltage and current according to the needs of the grid to which it is connected. Fig. 2 shows the model of the inverter. For current to flow into the grid, the DC link voltage must always be higher than the highest value of the grid voltage. The inverter consists of two step-down DC-AC converters and an output filter. Step-down DC-AC converters work so that one forms the positive part of the sinusoid and the other the negative part. Transistor Q3 pairs with transistor Q1 during the positive half-cycle and transistor Q4 with transistor Q2 during the negative half-cycle of the alternating voltage period (sine wave), as shown in Fig. 2. Transistors Q1 and Q2 are controlled by PWM modulation with a frequency of 50kHz. There is an LCL filter at the output of the inverter (on the grid side). The coils L1, L2, Lf1, Lf2 and the capacitor C_f form an LCL filter. There are several basic versions of the filter, and in this case, the best option is an LCL filter with a toroidal transformer, that is, two coils on the same core. The purpose of such a coil is to suppress the noise caused by the parasitic capacitance between the ground and the supply line [7]. Relay RL, controlled by a microcontroller, is used to correctly connect the inverter output to the grid (at the right time). The monitoring of the point of the panel's maximum power was achieved by measuring the voltage and current of the panel and by applying the MPPT algorithm that determines the reference current. The solar irradiance and temperature of the PV panel are relatively slowly changing values, so the frequency of changing the reference value of the panel current is around 10Hz. In comparison, the MPPT algorithm is executed at a frequency of 1000Hz. The switching frequency of the DC-DC flyback converter transistor is 100kHz. The MCU converts the measured analogue signals into digital form and scales them according to the maximum value. The measured values of voltage and current are stored in the corresponding variables. The current reference value is determined by comparing samples of present and previously measured value. By monitoring the change in power, the reference value of the current increases or decreases accordingly. The inverter

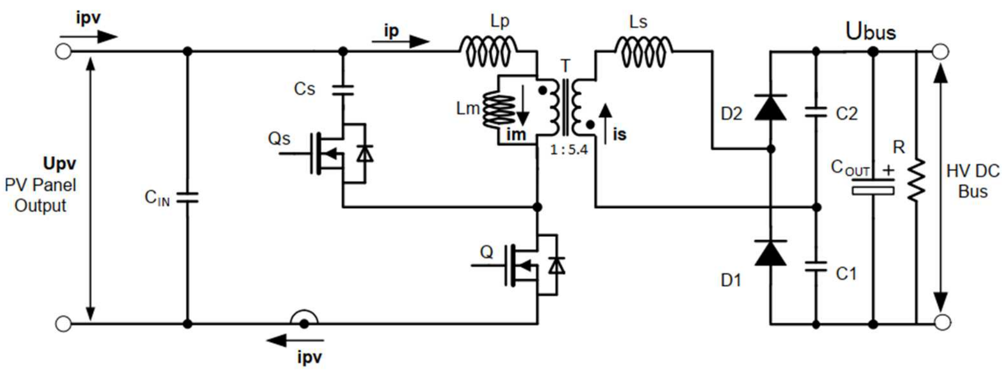

Fig. 1. Flyback converter of the used platform [6]

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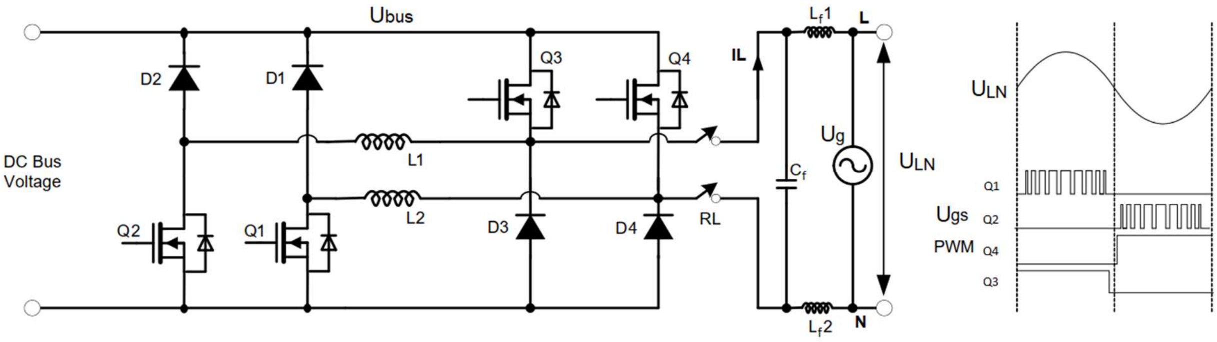

Fig. 2. Inverter of the used platform [6]

control circuit consists of the regulation of the DC link voltage and the current towards the grid, and the Phase Lock Loop (PLL) system for adjusting the phase of the output values. The regulation is performed using nested loops so that the outer loop regulates the voltage of the DC link, and the inner loop regulates the current of the inverter. The voltage loop generates a current reference value for the current loop. An increase in current causes the DC link voltage to drop, so the voltage error signal is calculated by subtracting the reference voltage from the measured voltage value. The current reference value from the voltage loop output is then multiplied by a sinusoidal function in phase with the electrical grid voltage, thus obtaining the current reference value. The current error signal is determined by subtracting the measured value from the reference value. The linearization of the feedback connection is necessary so that the control algorithm can tune the phase, ensuring the maximum working power of the inverter. Introducing a delay between the conductance changes of a pair of transistors avoids the possibility of a short circuit. The software of the platform is written in C programming language. The platform can be connected to a personal computer (PC) via a USB port. Code composer studio (CCS) is an integrated development environment (IDE) provided by the platform manufacturer. It comprises a suite of tools used to develop and debug embedded applications. The platform's control algorithm is provided and can be customized. With CCS installed on a PC connected to the platform, the user can control the platform by changing certain variables to switch states or set reference values. As seen in Fig. 3, the inverter and flyback converter have one state diagram. When the platform is connected to the electrical grid, the platform is in the "Idle" state. By placing variable "Gui_InvStart" to a logical "1" value, the platform switches to the "CheckGrid" state, and in that state, it will remain until the voltage and frequency of the grid are within the permitted values. The platform can return to the "Idle" state from that state by setting the "Gui_InvStop" variable. The grid is monitored in the "CheckGrid" state, namely its voltage and frequency. If the voltage is within interval ±35V_{RMS} and frequency within ±3Hz of the expected grid values, the platform switches to the "CheckPV" state. In that state, the panel and its voltage are monitored. When the voltage on the U_{PV} panel rises above 15V, the current regulator of the flyback converter is active, the default reference value of that regulator is set to 0.1p.u. (10%) and the platform switches to the "MonitorDCBus" state. This current will cause an increase in the voltage of the DC link. In the "MonitorDCBus" state, the DC bus and grid state is monitored. As for the grid, it monitors whether the voltage is within the lower and upper limits, which is signaled by two flags, "Flag_UV" and "Flag_OV", respectively, as specified. At the same time, it is checked whether the bus voltage is above the permitted value, which is signaled by "BusOverVoltageTrip". If the grid or the DC link voltage is outside the permissible values, the platform goes to the state "ResetState1,2", where all the regulators are turned off and power circuits are blocked, after which the platform switches to "FaultState". In case all the parameters are within the specified limits, and the voltage of the DC bus has reached the value of switching on the relay ("DC_BUS_RELAY_CONNECT_VOLT_50HZ"), a signal is sent to the relay to physically connect the inverter to the electrical grid. Even though the relay is on, the inverter bridge (transistor) is still blocked. The inverter bridge is unblocked when the DC bus voltage rises above the set value ("DC_BUS_INV_START_VOLT_50HZ"), the same is for the voltage and current regulator of the inverter. After that, the "EnableMPPT" state is entered. In the "EnableMPPT" state, the grid and the DC bus parameters are still monitored. The logical variable "Gui_MPPTEnable" must be set to the logical "1" for MPPT algorithm to be active; otherwise, it is off. In this state, a delay of 1s is provided until the MPPT algorithm is turned on. The "EnableMPPT" state provides a delay (calculation time) from the moment of switching on the current regulator to switching on the superior MPPT algorithm, which defines the reference value for panel current, i.e. panel power. After one second in this state, it switches to the "PVInverterActive" state. The "PVInverterActive" state monitors whether the grid and the DC bus are within the

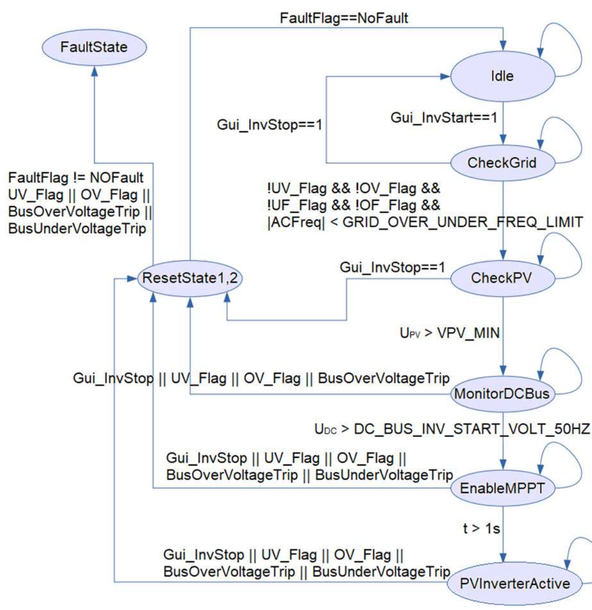

Fig. 3. State diagram of the used platform

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permitted limits. From any state other than "CheckGrid", by setting the variable "Gui_InvStop" to logical "1", the state is changed to the "ResetState1,2" state. While in state "CheckGrid" and setting the variable "Gui_InvStop" to logical "1", the state is changed to the "Idle" state. The state "ResetState1,2" serves to reset the regulators, block the flyback converter and inverter bridges, and check whether the appropriate error flag is in the logical "1". The platform goes to the "FaultState" state if there are errors; otherwise, it goes back to the "Idle" state.

The described platform was initially not intended to connect the additional battery, so changes were made to adapt the system for that option. The idea is to realize the possibility of connecting four battery circuits. It is necessary to increase the capacity of the DC link to stabilize the voltage during the charging and discharging of the batteries. The control algorithm was initially designed to use the relay at the output of the platform inverter to connect to the electrical grid only when the current flow would be towards the grid. Still, for this project, changes were made so that the current from the grid could charge the additional capacitor in the DC link, i.e. the connected batteries. The option of charging the batteries with electricity from the grid is introduced since the used microinverter is designed for low input power from PV panels. Also, the connected battery packs represent the battery of an EV, so the option to charge the battery from the electrical grid is desirable.

III. System Modification

In the manufacturer's platform algorithm, the inverter and the flyback converter are interconnected into one unit and work in strong conjunction. It is necessary to separate the inverter from the flyback converter to enable the connection of additional components. At the same time, it is necessary to convert the inverter to work as a two-way converter, i.e. to direct the energy both ways, to and from the electrical grid. In the following text, the inverter will refer to the two-way converter. It is necessary to make appropriate changes in the state diagram of the platform (Fig. 3). The first step is to separate the coupling of the inverter and the flyback converter to work as two separate units. Because of this, two variables were introduced, namely "PVFlyBackState" for the flyback converter and "PVInverterState", which is only used for the inverter state. State diagrams of the flyback converter and the inverter are shown in Fig. 4 and Fig. 5, respectively, as stated.

A. *Flyback converter modification*

From the state diagram of the flyBack DC converter, it can be seen that it contains states related only to the PV panel. In an inactive state, it is in "Idle". From this state to the "Active" operating state, it goes through two states, namely "CheckPV" and "EnableMPPT". The "CheckPV" state checks whether the panel is connected to the platform terminals. In the "Active" state, the control circuits are switched on, and the only monitored parameter is the voltage of the DC link and current limit protection. If the current or voltage rises above the permissible value, or variable "Gui_InvStop" is set to "1", the system goes to "ResetState1,2". From "ResetState1,2", the system goes to "FaultState" if there are faults; otherwise, the system goes to "Idle" state.

B. *Inverter modification*

From the state diagram of the inverter, it can be seen that there are no more "CheckPV" and "EnableMPPT" states because they are states closely related to the flyback converter.

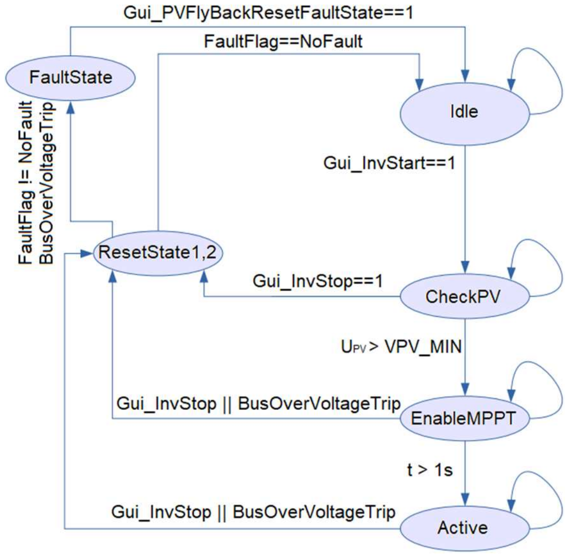

Fig. 4. Modified state diagram, adapted for the flyback converter

When the inverter is not working, it is in the "Idle" state. It will remain in that state until the "Gui_StartInverter" variable is set to logical "1". By setting the "Gui_StartInverter" variable to "1", the inverter goes into the "CheckGrid" state in which it monitors the state of the electrical grid. If the grid is within the acceptable range of values, it switches to the "MonitorDCBus" state. In that state, the voltage of the DC bus is monitored, and if the voltage has reached the set value, the relay between the inverter and the grid is switched on. This relay will stay switched on until the inverter reaches the "FaultState" or "Idle" state. This represents one of the essential corrections in the platform algorithm. Since the batteries (while charging) could take more energy from the DC link than the panel can provide, the inverter must be able to take energy from the electrical grid, i.e. to become a rectifier. When the DC link voltage reaches the set operating voltage ("DC_BUS_INV_START_VOLT_50HZ"), the inverter is started ("PVInverterActive" state), and the current regulator and the DC link voltage regulator are switched on. The regulation circuit works so that if the power supply to the DC link increases, the current that the inverter supplies to the grid also increases. The inverter cannot provide current to the grid while regulation circuits are switched off ("MonitorDCBus" state). The inverter goes back to this state when the DC link

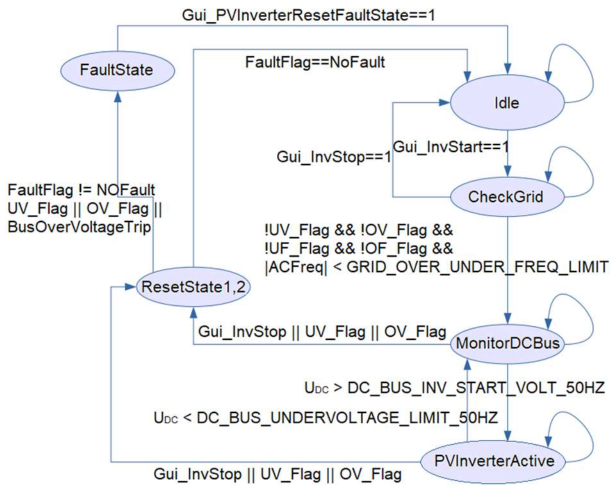

Fig. 5. Modified state diagram, adapted for the inverter

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voltage falls below the value saved in the variable "DC_BUS_UNDERVOLTAGE_LIMIT_50HZ". Still, the output relay remains connected to the grid via a diode bridge, realized using null energy diodes switches (uncontrolled rectifier), so the current can flow from the grid to the DC link. In the status diagram of the inverter in the "MonitorDCBus" state, it is no longer monitored whether the voltage has increased above the maximum allowed DC link voltage of 400V. That task is already transferred to the flyback converter. The inverter will be in one of two states, namely "MonitorDCBus" and "PVInverterActive" until the inverter is turned off using the "Gui_InvStop" variable or if an error occurs, in which case it will go in "FaultState". In the "MonitorDCBus" state, it works as an uncontrollable rectifier, while in the "PVInverterActive" state, it works as an inverter.

C. Monitoring and control interface

The created GUI is part of the supervisory control and data acquisition (SCADA) system intended to manage the microinverter connected to four battery packs. The screen of the main page in GUI is shown in Fig. 6. In the upper left corner there are four options. The first option, "Puni zaslon", minimizes and maximizes the interface window. The second option is "Sustav", which shows a single-pole scheme and switches for controlling individual components. The corresponding measured values are shown next to the components. The power, voltage and current values of the panel and the electrical grid are displayed. The third option in the top left corner ("Logovi") shows the chronological display of state changes and errors for individual components in the system. The "Grafovi” option shows graphs of the selected values as a function of time. Every element of the system shown in tab "Sustav" can be in one of three states, and that is "Run", "Stop", and "Fault". Under the tab "Grafovi", the user can see graphs and monitor how certain values change over time. There is also implemented function for recording the desired time frame or start and stop recording monitored values with time stamps manually. Recorded waveforms are saved in a *.csv* file in the "Home" directory.

IV. Experimental Results

Testing of the adjusted platform and the created GUI was carried out. As described in the previous chapter, the platform control algorithm was adjusted so that the flyback converter and the inverter work separately, and a capacitor was added to the DC link to increase the system's time constant, i.e. to maintain the DC link voltage better. The DC source is connected to the input of the flyback converter instead of PV panels (the MPPT algorithm was turned off during the experiment), and the inverter is connected to the electrical grid. The PC is connected to the platform via the USB interface on the control card. The platform has integrated sensors for measuring the relevant parameters, such as voltage and current, which are then transferred to the PC via JTAG interface. Fig. 7 shows the platform connected to the laboratory DC source, the electrical grid and the computer that runs the monitoring user interface. The testing procedure was to start the recording in GUI and change the input variables to test all possible situations. For each given command within the user interface, the waveforms of the measured parameters were recorded and are shown in Fig. 8. This procedure tested the functionality and communication of the GUI with the platform, and the essential functions of the platform, i.e. operation under normal conditions and protection in the event of an error. At the same time, additional functions of the monitoring user interface were tested, such as recording, i.e. displaying and saving the data. Measured values are grid voltage (U_{ac}), panel voltage (U_{PV}), DC bus voltage (U_{DC}), grid current (I_{ac}), panel current (I_{PV}), power on the grid side (P_{ac}) and panel power (P_{PV}). At the beginning of the test, all the elements were disconnected, and all the switches in the GUI were turned off. The platform is connected to the electrical grid and the external DC source through physical switches, which are turned off. It can be seen on the graph that the voltage of the DC link was around 260V at the beginning of the test. The first step (step 1) was to switch on the DC source connected to the flyback converter on the platform. The measured voltage of the DC source was around 40V. The next step was connecting (switching on) the AC grid to the inverter side of the platform (step 2). The voltage of the electrical grid outlet was around 244V. When the inverter and the flyback converter were turned on via GUI (step 3), the DC link voltage rose until it reached the set value (385V). All default values are implemented in the MCU of the platform. The graph shows that DC link voltage quickly reached and accurately maintained the specified value. In the next step (step 4), the reference flyback converter current was changed from 1.5A to 3.1A. The graph shows that, when the current reached the reference value, the power was doubled, which is appropriate given that the voltage of the DC source has remained the same. The following change occurred at step 5 when the DC source voltage was reduced from 40V to 30V. The flyback converter current regulator keeps the current value at 3.1A. As expected, the power has decreased by 25%. At step 6, the flyback converter is turned off via GUI, the current from the DC source drops to zero, and the DC link voltage drops to 350V. At that point, inverter transistors are turned off and the slow voltage decrease rate (around 1V per 1s) continues until it reaches 325V (the value maintained by the diode bridge while covering all losses within the circuit). The inverter is inactive, and the flyback converter is in an "Idle" state. The reference

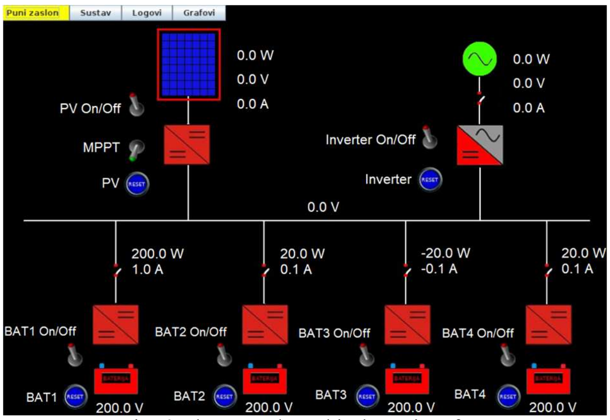

Fig. 6. The created graphical user interface

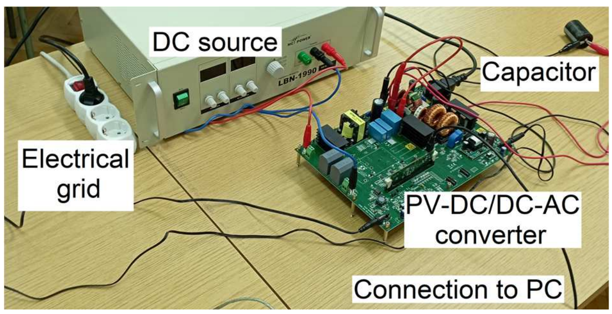

Fig. 7. The modified platform connected to the DC source, electrical grid, and a PC

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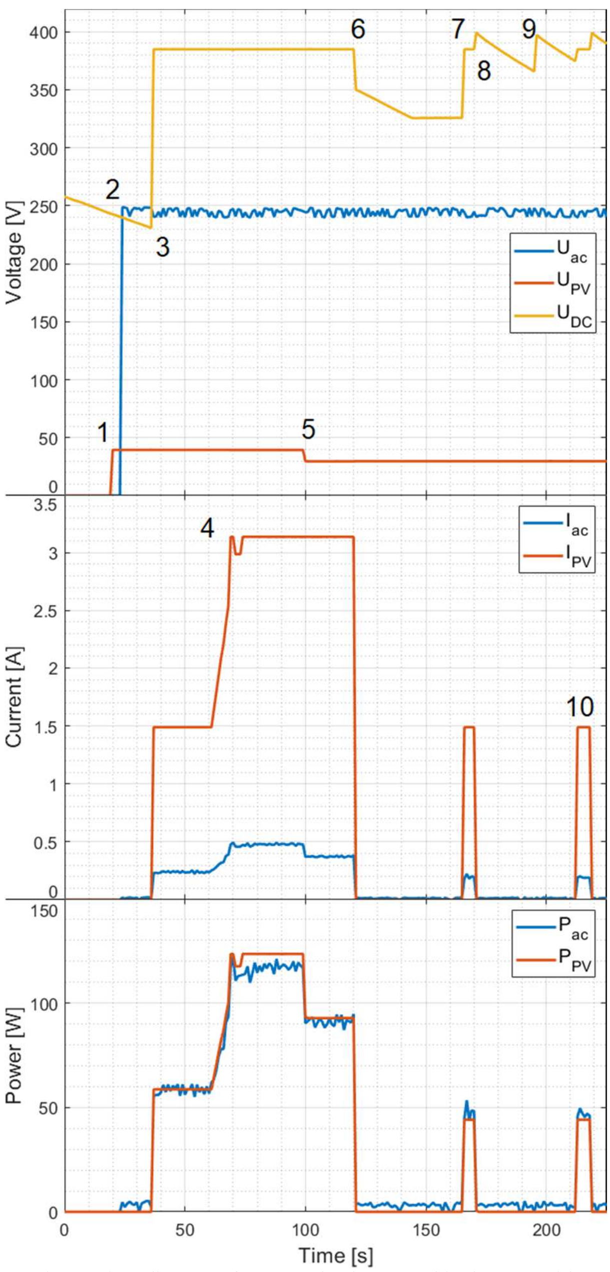

Fig. 8. Time diagram of measured values saved in the GUI with option "Snimanje"

current from the DC source was reduced back to 1.5A. The flyback converter is turned on from GUI at step 7, and the graph shows that the DC link voltage rose to the set value (385V). At step 8, the inverter was turned off from GUI, which caused the DC link voltage to rise, as the current from the DC source is charging the capacitors in the DC link, but no discharge is available. It can be seen that the platform overvoltage protection intervened at the point where the DC link voltage reached 400V, and the flyback converter went to the "FaultState" state. Next, the flyback converter was reset from GUI and turned on again. As the inverter was still turned off, the flyback converter returned to "FaultState" when it reached the overvoltage protection value. At step 9, the inverter was turned on, but nothing happened because the voltage of the DC link was under 385V, so the inverter stayed in the "MonitorDCBus" state. The flyback converter was turned on in step 10, the DC link voltage reached 385 V, the inverter transistors were activated, and the current flowed into the grid. In the end, the inverter was turned off, the DC link voltage reached the upper limit value, and the flyback converter went to "FaultState".

V. Conclusion

This experiment confirms that the modified platform can control the DCDC converter and the inverter separately, follow the set reference values well and that the protection responds as intended. The inverter has been successfully adapted to work as a bi-directional (two-way) converter. An additional capacitor in the DC link increased the time constant of the system and enabled better stability of the DC link voltage. The created GUI provides an overview of the state of individual system components. It is possible to manage states and set reference values. Additionally, functions for collecting and storing data are implemented in the GUI. All the GUI functions have been tested and are working properly. The conclusion is that the customized platform can be used as a link between the PV panels, the electrical grid and the battery system, with power limited to the maximum power of the used microinverter. The next step in the development of this system is to integrate a battery charger with required measuring and control circuits for monitoring and charging the battery. Once this is achieved, the system will be fully functional as a complete solution for integrating solar energy production with battery charging/discharging, providing a practical example of sustainable and efficient energy use.

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