This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Single-Panel Voltage Zeroing System for Safe Access on PV Plants

F. Di Napoli, P. Guerriero, V. d'Alessandro, and S. Daliento

***Abstract*—In this paper, an effective circuit for both voltage and current zeroing of single solar panels embedded in a solar field is presented. The circuit interrupts the panel current by means of a solid-state power switch and zeros the panel voltage by means of an electromechanical relay. Each solar panel can be either connected or disconnected from the string independently from each other. The circuit is connected to the existing junction box and does not require additional wiring, neither for its power supply, which is always derived from the solar panel, nor for its data transmission, which is achieved through a special suited power line communication scheme exploiting the existing dc power bus. Experiments performed on a test solar field equipped with in-house made circuit prototypes evidence the reliability of the proposed approach.**

***Index Terms*—Fire protection, photovoltaic (PV) plant, reconfigurable systems, safety.**

I. Introduction

OVER the past decade, photovoltaic (PV) technology has reached full commercial maturity: 200 GW worldwide installed capacity at the end of 2015. One major strength of PV systems is the extreme modularity, which allows designing and assembling arbitrary large installations by simply adding elemental components, i.e., solar cells to form PV modules, PV modules to form PV strings, and so on. As a consequence, even medium-size solar fields are composed of hundreds or thousands of solar panels permanently connected to each other. This specificity implies some weaknesses as well [1]–[3], among them the fact that a PV system cannot be effectively switched OFF as long as sunlight reaches solar panels. This issue entails potentially harmful security risks; series connection of solar panels, indeed, involves the presence, during daylight hours, of voltages greater than hundreds of volts, well exceeding the safety human body threshold. Such high voltages can be hazardous in case of maintenance or blaze alarms. It should be noticed that the latter occurrence is nowadays dramatically rising because, even if fire probability is low, the large number of installed PV plants makes the absolute number of alarms high. In Italy, which owns about 600 000 PV fields, interventions raised from 1 in 2003 to 298 in 2011, with a total number of 453 cases during this period [4]. Often, firefighters could not perform effective actions because they required the absence of dangerous voltages with the consequence that fire could not be promptly extinguished, and the solar plants were destroyed. Standardization rules do not prescribe specific constraints so far, mostly because reliable equipment for voltage zeroing have yet to be proposed. As a consequence, interventions in case of blaze alarms, as well as usual maintaining operations, require extreme care and highly skilled people.

In a recent paper [5], optimal features that a reliable PV plants safety system should provide have been discussed. It was concluded that individual modules short-circuiting would be the most effective solution. In other words, it was recognized that an effective safety system should operate at single-panel level, by allowing some form of active control on its interconnections.

It is worth noting that solar systems exploiting distributed conversion topologies, such as AC module converters [6]–[8] or PV optimizers [9]–[12], are inherently safe because they are connected in parallel with solar panels and can be easily disconnected from the power bus. Thus, we only focus on those systems adopting centralized conversion schemes, where many solar panels are series connected in order to reach the converter operating voltage.

In the recent literature, only a few works deal with single panel approaches, mainly for monitoring purposes. In [13]–[16], it was proposed to equip solar panels with an electronic board performing the measurement of both the operating voltages and currents; measured data were then transmitted to a central unit by means of either wireless [13]–[15] or PLC [16] communication protocols.

In [17], a specifically designed safety system was proposed. It is made by remote-driven switches, parallel connected to each solar panel, that, either automatically, in case of specific alarms, or after pushing a devised button, short-circuits the solar modules. The main drawback of this system is the need for a pervasive additional wiring scheme, which provides separate buses both for power supplying the boards and for data communication.

In this paper we present an advanced single module safety circuit that, as in [18], de-energizes PV panels. The system, embedding single panel diagnostic/monitoring features, is capable to zero both voltages and currents in a solar field in a fully controllable way. The circuit we propose is an upgrade of the electronic system proposed in [19] and [20], originally developed for only diagnostic/monitoring purposes. The operation of the proposed circuit does not require extra-wiring neither for power supply nor for data exchange.

The key characteristic of the systems [20], was the "disconnection function," allowing sectioning of a solar string at single panel level thanks to series-connected power metal–oxide semiconductor filed-effect transistors (MOSFETs) driven in the off-state.

With respect to [20], the new circuit provides two additional features: 1) a parallel-connected bistable relay with the corresponding driving circuitry and 2) a specifically developed, more

Manuscript received March 3, 2015; revised May 22, 2015 and April 17, 2015; accepted June 2, 2015.

The authors are with the Department of Electrical Engineering and Information Technology, University Federico II, Naples 80125, Italy (e-mail: fabio.dinapoli@unina.it; pierluigi.guerriero@unina.it; vindales@unina.it; daliento@unina.it).

Digital Object Identifier 10.1109/JPHOTOV.2015.2448416

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

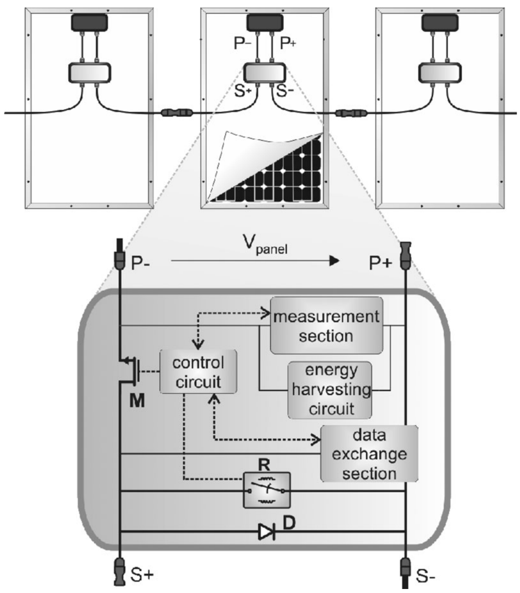

Fig. 1. Schematic block diagram of the proposed circuit.

robust, communication scheme based on the power line communication (PLC), exploiting the solar panels dc bus.

To this regard, it should be noticed that dc bus PLC is not a standard application for series-connected PV panels because data signals should travel throughout the solar panels. The circuit we propose originally overcomes this problem by means of a high-frequency *LC* bypass filter, parallel connected to each solar panels, thus providing a signal path circumventing the solar panels [21].

The paper is organized as follows. In Section II, the block diagram scheme of the electronic board is presented. In Section III, the disconnection circuit is described and the effectiveness of the circuit for the monitoring and diagnostic of PV plants is evidenced. In Section IV, the communication section based on the PLC technology is presented. In Section V, the voltage zeroing system is presented and experimental results gained on a pilot PV plants are discussed. Conclusions are drawn in Section VI.

II. Circuit Overview

The block diagram of the proposed circuit is shown in Fig. 1. As can be seen, it is composed of several subsections, supervised by a control circuit adopting a PIC Microchip PIC18LF4620 MCU belonging to the low-power 8-bit family, which provides both timing and enabling signals. The main feature that should be noted in Fig. 1 is that the terminals of the solar panel P+ and P−, exiting the junction box, are physically separated from those (S+ and S−) exploited for series connecting the solar panels to each other, the latter terminals being the output terminals of our circuit. When the MOSFET M is driven in the off-state by the control circuit, it behaves like an open circuit and "disconnects" P− from S+. After that, even if the relay R is closed (in order to zero the voltage across the solar panel), the circuit board is still powered because the energy-harvesting circuit is directly connected to the "internal" terminals P+ and P–, always providing a positive voltage V_{panel}. Indeed, when M is in the off-state, V_{panel} equals the open-circuit voltage V_{oc} of the solar panel; otherwise, it coincides with the operating voltage. As a consequence, the circuit is always controllable, and the solar panel can be eventually reconnected by opening the relay and by driving M in the on-state.

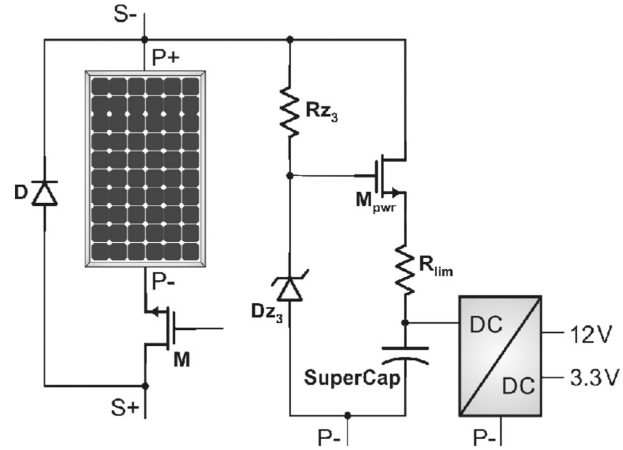

Fig. 2. Circuit details of the harvesting section.

The harvesting section is crucial for the reliable behavior of the system; its detailed schematic is shown in Fig. 2. It is based on a supercapacitor (2 F, 3.7 V) designed to sustain device switching and data exchange without affecting the solar panel normal operation. It provides energy for the operation of a dc/dc converter supplying both the voltage (12 V) needed for the operation of both relay and PLC sections, and the voltage (3.3 V) needed by the microcontroller. The current leaked from the solar panel is limited by the resistor $R_{\text{lim}}(10\,\Omega)$ designed to avoid overcurrent in the control MOSFET M_{pwr}. Finally, the Zener diode Dz_3 limits both the SuperCap voltage and the charge current thanks to the feedback action provided by R_{lim}.

Other sections of the circuit will be detailed and discussed in the following paragraphs.

III. Disconnection and Measurement Circuit

The operation of the circuit for monitoring/diagnostic purposes has already been discussed elsewhere [20].

However, for a better readability of the paper, the main qualifying characteristics are briefly recalled here.

As already mentioned above, the key element of the circuit is the power MOSFET M. When the input signal, provided by the control circuit, is high, the MOSFET is in the on-state and the solar panel is series connected to other panels of the string; when the input signal is low, the MOSFET is driven in the off-state, and the solar panel is disconnected.

Three significant features should be noted. First, the bypass power diode D [22] allows continuous flowing of the string current even when the MOSFET is OFF (conversely, it is reverse biased when the MOSFET is ON); hence, continuous power delivering from the string is guaranteed when, for some reasons (for example, because the solar panel has been recognized as malfunctioning or for reconfiguration purposes), just one solar panel requires disconnection. Second, as already said, the harvesting circuit, providing power supply for all sections of the electronic board, is connected to the internal terminals of the

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

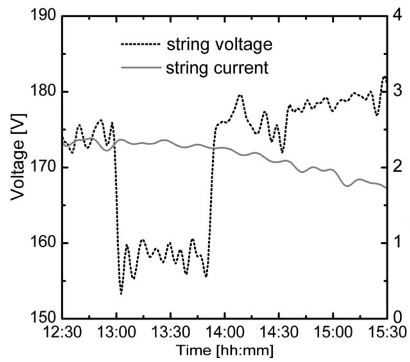

Fig. 3. Disconnection behavior. Experimental string voltage (dotted line) and string current (solid line) against the time.

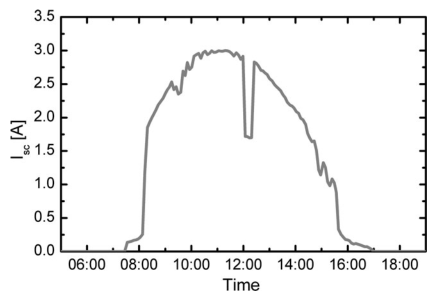

Fig. 4. Short-circuit current I_{sc} against the time. At about 12:00 noon, a remarkable current drop occurs due to an intentional shading.

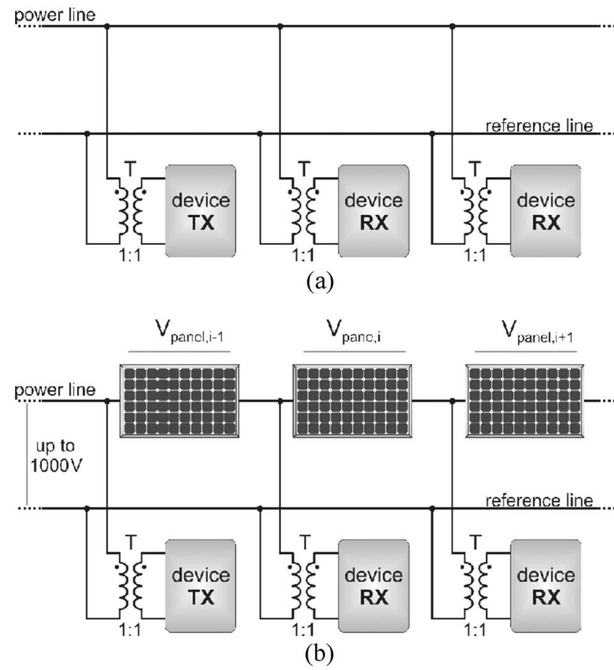

Fig. 5. Schematic drawing of two PLC standard approaches. (a) Parallel insertion on a standard physical bus and (b) parallel insertion on a bus consisting in a PV string.

solar panel. Third, when the MOSFET is OFF, the measuring section works on the isolated panel (see Fig. 1); hence, measured quantities (the open-circuit voltage and the short-circuit current) are not affected by the operating point of the remaining string panels and can be used to individually characterize the healthy state of each solar panel (the last two features distinguish this system from all others single-panel monitoring circuits presented elsewhere); on the other hand, when the MOSFET is ON, the operating point of the solar panel is monitored, and its actual power production is recorded.

For applications to safety the correct operation of the disconnection MOSFET is of paramount importance; its reliable behavior is evidenced in Fig. 3, showing the voltage measured at the terminals of a ten-panel solar string during normal operation (i.e., at its maximum power point: MPP).

At 1 P.M., a disconnection command is sent to a single solar panel. As can be seen, the string voltage decreases of about 20 V, a value coinciding with the voltage contribution of one solar panel, which is, therefore, effectively disconnected. On the other hand, the string current does not show any interruption thanks to the bypass diode D (in this experiment, the relay R was left open).

Just as an example of the monitoring features, Fig. 4 reports the short-circuit current I_{sc} of one solar panel measured over a whole day. The abrupt drop observable at 12 noon was intentionally induced by partially shading the solar panel by means of a semitransparent optical filter. It is important to consider that during the shading time, the solar panel is in bypass conditions because of the greater current of other panels; nevertheless, monitoring continues to work properly, thus demonstrating that the harvesting section always provides energy to the board.

IV. Data Transmission by Power Line Communication on Direct Current Bus

During normal operation, the data exchange section of Fig. 1 supervises the traffic of data measured for monitoring/diagnostic purposes; in case of alarm, it recognizes a specific codified word and starts up the safety procedure involving the closure of the relay R. Given the importance of this task and the need for the solar system to get safe conditions even in the case of unexpected events (wire breaking, communication loss, and so on), a very robust communication channel is needed. In principle, in order to avoid extra wiring, either wireless communication or PLC could have been adopted; in this study, we opted for PLC because it gave inherent safety in case of wire breaking, as discussed below. The problem we had to face is that series-connected solar panels do not behave like a standard dc bus; thus, a devised PLC scheme, especially suitable for data transmission through solar strings, was developed.

In order to understand why a devised design was needed, a standard PLC scheme [25] is shown in Fig. 5(a). It consists of transmitting/receiving (TX/RX) transceivers communicating by exchanging codified messages traveling on a physical bus, the latter being the same adopted for electrical power delivering. Information data are transferred by TX to the bus in the form of high-frequency signals, which are superposed to the power signal; this operation is accomplished by means of the high-frequency (1:1) transformer T. In the same way, information signals are revealed by RX. From the scheme, it can be inferred that PLC is an inherently ac technology; nevertheless, transmission on a standard dc bus can be straightforwardly performed

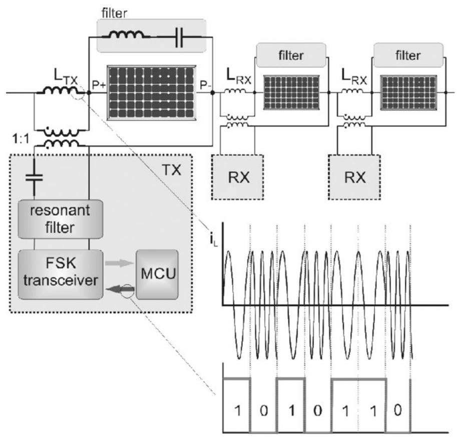

Fig. 6. Schematic drawing of the proposed PLC approach.

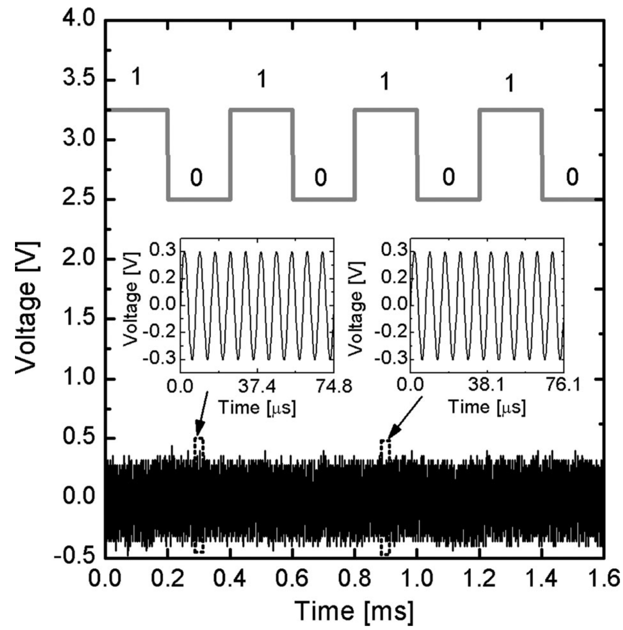

Fig. 7. Binary sequence generated by the microcontroller (gray solid line) and the corresponding FSK modulated signal across RX (solid black line). In the insets, two magnifications of the signal corresponding to bit 0 and bit 1.

because the high-frequency information signal can be viewed as a small disturbance superposed to the dc power signal.

However, when the dc bus consists of series-connected solar panels, the scheme of Fig. 5(a) does not work properly. In fact, from Fig. 5(b), where, instead of Fig. 5(a), the power line was substituted by the solar string, some problems clearly appear. First, the high-frequency signal should travel through each solar panel, but the solar panel is characterized by a strong reactive behavior; thus, the signal would probably be lost; furthermore, the operating point of the solar panel could be jeopardized by the voltage signal with a resulting degradation of the MPP tracking efficiency. Second, each transceiver sees a different voltage along the power line; thus, they should be either all oversized, in order to sustain the larger possible voltage appearing in the circuit, or singularly adjusted, in order to match each transceiver with the voltage corresponding to the particular position along the string; moreover, as the string can exhibit very high voltages, possible faults on the power line that could be reflected by the 1:1 transformer on the signal side would destroy the transceiver. Third, the reference cable is actually not available in a solar string; thus, additional wiring should be provided.

All aforementioned issues can be solved if the codified data are brought by injecting a current signal into the power line; in other words, if communication can be achieved on a single wire scheme.

The solution we adopted is shown in Fig. 6. The main difference with respect to conventional PLC schemes relies on the presence of the inductor L_{TX}, which is connected to the transformer secondary winding of TX. As the signal current flowing through the receivers is unique, the voltage signal across L_{TX}, imposed by the PLC transceiver, corresponds to an analogous perturbation of the voltage across the inductors L_{RX} of the receiving systems (RXs). As an example, Fig. 7 shows a binary test sequence generated by the microcontroller and the corresponding frequency shift keying (FSK: bit 1 and bit 0 are associated with a low-frequency sinusoidal signal and a high-frequency sinusoidal signal, respectively) codified voltage measured at the input of an RX block (the dc PV component is not shown); the insets of Fig. 7 show two magnifications of the FSK signal corresponding to bit 1, the lower frequency sinusoid in the left inset, and to bit 0, the higher frequency sinusoid in the right inset (actually the frequencies are very close each other as they are 131.4 and 133.7 kHz, respectively). The impedance of the inductor is chosen to allow the correct operation of the transceiver; this latter, indeed, guarantees the rated output voltage (2 V peak in our case) up to an assigned maximum current (500 mA) supplied to the inductor, as a consequence a minimum value for LTX can be determined (3.38 μH @ 132.5 kHz in our case). However, in order to reduce power consumption, an higher value is recommended (50 μH in our experiments) with an upper limit given by saturation of the inductor which might be caused by the DC photovoltaic current. In order to prevent signals from passing through the solar panels, a LC series impedance (indicated as "filter" in Fig. 6) is parallel connected across each solar panel. That second order filter is designed to exhibit a zero impedance bypass path at the signal frequencies, thus avoiding any possible influence of the parasitic capacitance of the solar panel.

The reliability of the proposed communication scheme was evidenced by performing devised experimental tests on a ten-panel solar string. First, the control unit of a specific solar panel, which drives the corresponding MOSFET M, was programmed to wait for two specific 16-bit words messages in order to get the MOSFET in either the off-state (panel disconnection) or the on-state, respectively.

Then, randomly generated 16-bit words were transmitted by a remote TX, and only at a specific instant ($t = 25$ s in Fig. 8), the disconnection word was sent. As can be seen from Fig. 8, reporting both the voltage across the whole string and the voltage across the controlled panel (measured at the "internal" terminals P+ P− of Fig. 1), before $t = 25$ s, the solar panel is connected to the string; this can be recognized thanks to the fluctuation in the measured voltage, which is caused by the oscillations around the MPP due to the Perturb and Observe tracking algorithm [24], [25].

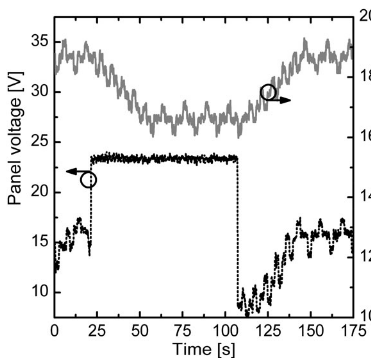

Fig. 8. Panel voltage V_{P+P} (black dotted line) and string voltage (gray solid line) against the time.

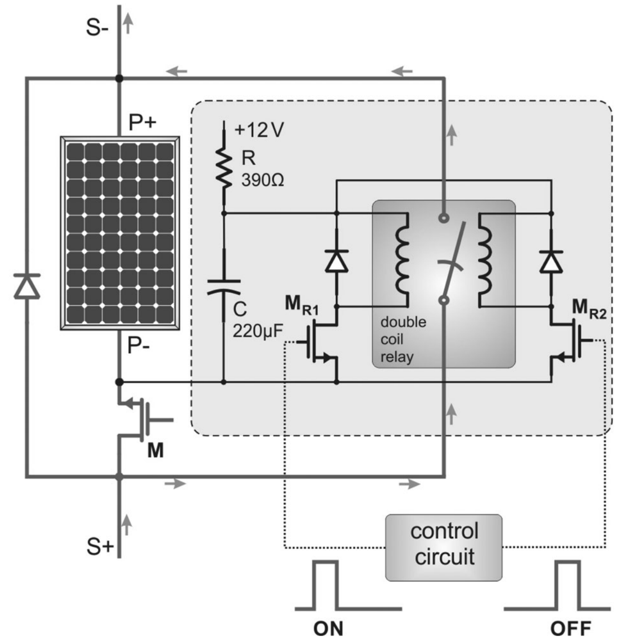

Fig. 9. Short-circuit current $I_{\rm sc}$ against the time. At about 12:00, a remarkable current drop occurs due to an intentional shading.

The same fluctuations are observable in the string voltage. At $t = 25$ s, the voltage across the solar panel sudden increases to reach the open-circuit voltage; the absence of the oscillations indicates that the solar panel is really disconnected from the string. In the same time interval, the string voltage decreases by the operating voltage of the disconnected panel. Voltage decreasing is quite slow because the tracking algorithm is looking for the new MPP of the string. At $t = 100$ s, the connection command is sent and the MOSFET M recovers the on-state so that the panel is newly series connected to the string.

The input terminals of the inverter where the string is connected are, indeed, "short-circuited" for the signal frequencies by means of an *LC* filter. This precaution prevents communication signals from affecting the inverter behavior and confines those signals to the string side. Hence, the series of the RX inductances behaves as parallel connected to the TX inductance, and the voltage perturbation imposed by the TX across its output inductor is shared among the input inductances of the RXs. In order to correctly decode a message, the amplitude of the voltage at the input of each RX should be high enough for the correct operation of the transceivers (in our experiments, an ST7540 with a detection range of $250\,\mu V_{\rm rms}$ was exploited [26]). According to the KVL, the amplitude of the signal $V_{\rm rx}$ manifesting at the input terminals of all RX blocks, when a signal with an amplitude $V_{\rm tx}$ is transmitted by a TX, is simply described by the following equation:

$$V_{\rm rx} = \frac{V_{\rm tx}}{N-1} \tag{1}$$

where N is the total number of transceivers connected to the power line; hence, the amplitude of the transmitted signal (2 $V_{\rm rms}$) should be accordingly adjusted. In case of grounded systems (e.g. U.S.), it should be considered that the earth resistance would appear as series connected to the inductors; thus, a further signal degradation term should be accounted for.

V. Fire Protection

The availability of both reliable disconnection and robust communication systems allowed the designing of the single-panel true-zeroing system shown in Fig. 9.

It is worth noting that the disconnection system based on the MOSFET M could be, in principle, considered, by itself, as a safety system. However, norms on circuit sectioning usually require the adoption of electromechanical devices. As will be shown shortly, the adoption of both the device M and an electromechanical single-pole single-throw bistable relay, parallel connected to the externally accessible connectors (S+ and S− in Fig. 9), gives very effective performances by allowing simultaneous zeroing of both current and voltages throughout the string.

The driving section of the relay is shown in Fig. 9 as well. The relay (a SCHRACK model RT424F12 was adopted) is pushed in either the open or closed state by means of the MOSFETs M_{R1} and M_{R2}, which are driven by control signals directly provided by the microcontroller. In normal operating conditions, the microcontroller waits, as in [17], for a broadcast "heartbeat" coming, through the PLC, from a remote control unit; the detection of the "heartbeat" is interpreted as no alarms conditions and the relay is left open [see Fig. 10(a)]. If the heartbeat is missed, the microcontroller first opens the series MOSFET M, thus disconnecting the panel (the diode D immediately turns ON and assures the continuity of the string currents during the longer switching time of the relay) and then closes the relay [see Fig. 10(b)].

A lack of the heartbeat can be induced by simply disconnecting the string by means of a hand-operated sectioning device; thus, voltage zeroing happens both when the string is voluntarily disconnected, as it is the case when someone has to intervene on the solar field, and when interruption is caused by a fault (for example, when a wire is broken by fire). The system straightforwardly intervenes when there is lack of voltage on the grid side as well because the remote control is powered by the grid. From Fig. 10(b), the importance of the disconnecting MOSFET is clearly in evidence. The solar panel keeps indeed its open-circuit voltage even if its externally accessible terminals have

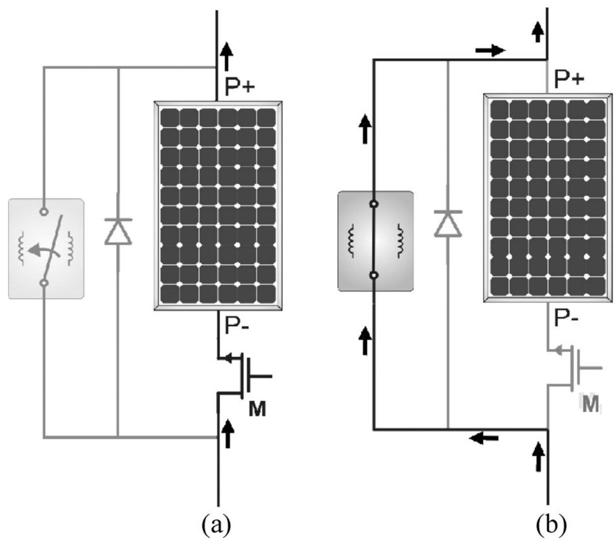

Fig. 10. Schematic drawing. Normal operation and short-circuit current $I_{\rm sc}$ against the time. At about 12:00, a remarkable current drop occurs due to an intentional shading.

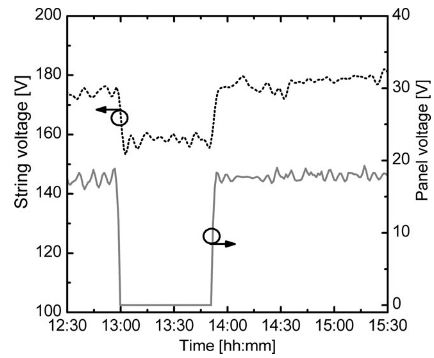

Fig. 11. Experimental panel voltage and string voltage against the time.

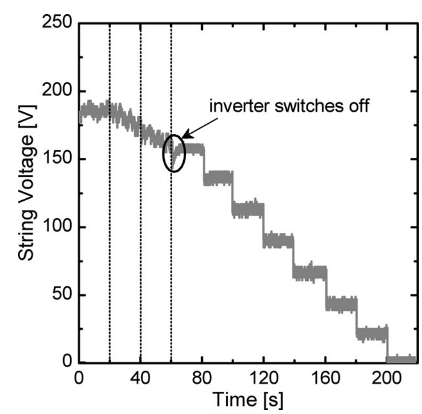

Fig. 12. String voltage zeroing sequence.

been short-circuited; hence, the system is always powered, and normal operating conditions can be recovered by simply restoring the heartbeat signal. Proper codified messages can be sent to eventually disconnect just single PV modules of a string as well. This option could be exploited for field reconfiguration applications [27]. The presence of the disconnection MOSFET, which imposes zero current in the off-state, implies another important feature as well. Contrary to what happens when the solar module is directly short-circuited, indeed, our circuit annihilates the possible occurrence of hot spot effects that are eventually caused by the presence of localized shadows.

Moreover, it should be noted that the bistable relay has zero power consumption in both stable states. A current spur is only required to sustain the switching. In order to avoid an undesired drop in the supply of the digital microcontroller, the devised RC branch shown in Fig. 9 is exploited; during normal operation, the capacitor C stores the amount of energy required to commutate the relay, while the resistor R limits the charging current (the time constant corresponding to capacitor charging is about 80 ms). At the switching, the capacitor provides the driving energy.

The correct behavior of the proposed system was experimentally verified by equipping all ten panels of our solar string with a devised board. Fig. 11 shows measurements performed on a single solar panel that, unique in the string, received a disconnection command; the string voltage is shown as well. As can be seen, the voltage across the panel (measured at the "external" terminals) gets zero and remains at this value until a subsequent reconnection command is sent.

Fig. 12 shows what happens when all voltages must be zeroed. In this case, the heartbeat is on purpose annihilated ($t = 20$ s in Fig. 12), thus starting the switching of all the relays. However, as can be inferred from the figure, in order to avoid the insurgence of a huge current spike in the input capacitance of the converter, each control circuit was instructed to wait a proper delay time before closing the corresponding relay. In the experiment, the control circuits individually calculate the corresponding delay as the product of an assigned time period (i.e., 20 s) and their own identification number. The initial gradual decrease of the voltage observable in Fig. 12 depends on the attempt of the converter (SMA SB4000 TL-20) to track the new MPP of the resulting "shorter" string. After about 60 s, the string voltage becomes lower than the minimum converter input voltage, which, therefore, automatically switches OFF. After that, the string is effectively disconnected from the converter, each solar panel exhibits its open-circuit voltage, and the string voltage decreases step by step according to the relays short-circuiting sequence.

VI. Conclusion

A circuit prototype for effectively zeroing all voltages and currents in a solar field has been presented and experimentally verified. The circuit allows free access in case of maintenance or blaze alarms, it is fully self powered and does not require additional wiring. It is based on the cooperation of a solid-state switch that allows single panel sectioning and an electromechanical relay that effectively short circuits the external terminals of the solar panel. The short-circuit condition is fully reversible thanks to the availability of the open-circuit voltage of the solar panel that continues to power supplying the electronic board. A further result is that sectioning prevents the possible formation of hot spots so that the method could be safely used in field reconfiguration schemes as well.

REFERENCES

[1] P. B. Quater, F. Grimaccia, S. Leva, M. Mussetta, and M. Aghaei, "Light unmanned aerial vehicles (UAVs) for cooperative inspection of PV plants," *IEEE J. Photovoltaics*, vol. 4, no. 4, pp. 1107–1113, Jul. 2014.

[2] T. Takashima, J. Yamaguchi, and I. Masayoshi, "Fault detection by signal response in PV module strings," in *Proc. IEEE Photovoltaic Spec. Conf.*, 2008, pp. 1–5.

[3] A. J. Hanson, C. A. Deline, S. M. MacAlpine, J. T. Stauth, and C. R. Sullivan, "Partial-shading assessment of photovoltaic installations via module-level monitoring," *IEEE J. Photovoltaics*, vol. 4, no. 6, pp. 1618–1624, Nov. 2014.

[4] G. Zaccarelli, (2013, Sep. 17). "Pannelli fotovoltaici & incendi-quali i principali rischi?" [Online]. Available: http://orizzontenergia.it

[5] S. Spataru, D. Sera, F. Blaabjerg, L. Mathe, and T. Kerekes, "Firefighter safety for PV systems: Overview of future requirements and protection systems," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2013, pp. 4468–4475.

[6] D. Meneses, F. Blaabjerg, O. Garci´a, and J. A. Cobos, "Review and comparison of step-up transformerless topologies for photovoltaic ac-module application," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2649–2663, Jun. 2013.

[7] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1292–1306, Sep. 2005.

[8] M. Coppola, P. Guerriero, F. Di Napoli, S. Daliento, D. Lauria, and A. Del Pizzo, "A PV AC-module based on coupled-inductors boost DC/AC converter," in *Proc. Int. Symp. Power Electron. Electr. Drives, Autom. Motion*, 2014, pp. 1015–1020.

[9] N. Femia, G. Lisi, G. Petrone, G. Spagnuolo, and M. Vitelli, "Distributed maximum power point tracking of photovoltaic arrays: Novel approach and system analysis," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2610–2621, Jul. 2008.

[10] G. Petrone, G. Spagnuolo, and M. Vitelli, "An analog technique for distributed MPPT PV applications," *IEEE Trans. Ind. Electron.*, vol. 59, no. 12, pp. 4713–4722, Dec. 2012.

[11] B. V. P. Chong and L. Zhang, "Controller design for integrated PV-converter modules under partial shading conditions," *Sol. Energy*, vol. 92, pp. 123–138, Jun. 2013.

[12] S. M. Chen, T. J. Liang, and K. R. Hu, "Design, analysis, and implementation of solar power optimizer for dc distribution system," *IEEE Trans. Power Electron.*, vol. 28, no. 4, pp. 1764–1772, Apr. 2013.

[13] M. Resadi, S. Costa, and M. Cesana, "Control and signalling device for photovoltaic modules," Eur. Patent Appl. EP2 159 766 A1, 2010.

[14] Technical datasheet, "Spim Classic, Monitoring System." (2012, Mar.), SEM s.r.l., [Online]. Available: http://www.semtechnologies.it/

[15] L. Ciani, L. Cristaldi, M. Faifer, M. Lazzaroni, and M. Rossi, "Design and implementation of an on-board device for photovoltaic panels monitoring," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf.*, 2013, pp. 1599–1604.

[16] F. J. Sanchez-Pacheco, P. J. Sotorrio-Ruiz, J. R. Heredia-Larrubia, F. Perez-Hidalgo, and M. Sidrach De Cardona, "PLC-Based PV plants smart monitoring system: field measurements and uncertainty estimation," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 9, pp. 2215–2222, Sep. 2014.

[17] *BFA-EX Solteq Datasheet*. (2013, Nov.). [Online]. Available: http://www.solteq.eu

[18] A. Pozsgay, "System for managing and controlling photovoltaic panels," U.S. Patent 2012/0306289 A1, Dec. 6, 2012.

[19] M. Gargiulo and P. Guerriero "Circuito Autoalimentato per Monitoraggio Remoto Wireless di Pannelli Fotovoltaici," Italian Patent 0001402319, Aug. 30, 2013.

[20] P. Guerriero, V. d'Alessandro, L. Petrazzuoli, G. Vallone, and S. Daliento, "Effective real-time performance monitoring and diagnostics of individual panels in PV plants," in *Proc. IEEE Int. Conf. Clean Elect. Power*, 2013, pp. 14–19.

[21] F. Di Napoli, P. Guerriero, V. d'Alessandro, and S. Daliento, "A power line communication on DC bus with photovoltaic strings," in *Proc. Renewable Power Gener. Conf.*, 2014, pp. 1–6.

[22] V. d'Alessandro, P. Guerriero, and S. Daliento, "A simple bipolar transistor-based bypass approach for photovoltaic modules," *IEEE J. Photovoltaics*, vol. 4, no. 1, pp. 405–413, Jan. 2014.

[23] N. Ginot, M. A. Mannah, C. Batard, and M. Machmoum, "Application of power line communication for data transmission over PWM network," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 178–185, Sept. 2010.

[24] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Trans. Energy Convers.*, vol. 22, no. 2, pp. 439–449, Jun. 2007.

[25] P. Guerriero, F. Di Napoli, V. d'Alessandro, and S. Daliento, "Accurate Maximum Power Tracking in Photovoltaic Systems Affected by Partial Shading," *IEEE J. Photovoltaics*, vol. 2015, art. no. 824832 (10 pages), 2015. doi:10.1155/2015/824832

[26] *Technical datasheet ST7540, FSK Power Line Transceiver*. (2006, Sep.). [Online]. Available: http://www.st.com

[27] P. Guerriero, F. Di Napoli, V. d'Alessandro, and S. Daliento, "Dynamic reconfiguration of solar systems for avoiding MPPT faults due to architectural partial shading," *Proc. IEEE Int. Conf. on Environment and Electrical Engineering*, 2015, pp. 1229–1234.

Fabio Di Napoli received the M.S. (*Laurea*) degree in electronics engineering from the University Federico II, Naples, Italy, in 2012, where he is currently working toward the Ph.D. degree with the Department of Electrical Engineering and Information Technology.

His research interests include circuit simulation of photovoltaic plants, power converters, and the design of microinverters.

Pierluigi Guerriero received the Laurea and Ph.D. degrees in electronics engineering from the University Federico II, Naples, Italy, in 2007 and 2012, respectively.

From 2009 to 2012, he was an R&D Project Head, working on photovoltaic applications with ISET Srl, Valle di Maddaloni, Italy. He is currently a Postdoctoral Researcher with the Department of Electrical Engineering and Information Technology, University Federico II, Napoli, Italy. He has coauthored 30 papers in refereed international journals and conference proceedings and three inventions. In 2014, he coauthored the book *Dispositivi e Sistemi Fotovoltaici*. His research interests include monitoring systems for photovoltaic arrays, development of effective MPPT algorithms, and dc–ac converters.

Vincenzo d'Alessandro is currently an Associate Professor with the Department of Electrical Engineering and Information Technology, University Federico II, Naples, Italy, where he teaches semiconductor devices and digital circuits. His current research interests include thermal modeling and electrothermal simulation of semiconductor devices, circuits, and systems, with particular emphasis on bipolar technology, and modeling/simulation of photovoltaic plants.

He has coauthored more than 130 papers in refereed international journals and conference proceedings, as well as a book, two book chapters, and one patent. He is a Reviewer for the IEEE TRANSACTIONS ON ELECTRON DEVICES, the IEEE ELECTRON DEVICE LETTERS, the IEEE JOURNAL OF PHOTOVOLTAICS, *Solid-State Electronics, Microelectronics Reliability, International Journal of Numerical Modeling,* as well as for international conferences.

Santolo Daliento received the Laurea and Ph.D. degrees in electronics engineering from the University Federico II, Naples, Italy, in 1992 and 1996, respectively.

He is currently an Associate Professor with the Department of Electrical Engineering and Information Technology, University Federico II, where he teaches analog electronics and photovoltaic devices and systems. He has coauthored more than 80 papers in refereed international journals and conference proceedings. In 2014, he authored the book *Dispositivi e Sistemi Fotovoltaici.* His research interests include modeling of power devices, lifetime engineering treatments, semiconductor characterization techniques, and innovative photovoltaic devices.