

Assessment of Cross-coupling Effects in PV String-integrated-converters with P&O MPPT Algorithm Under Various Partial Shading Patterns

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Abstract—A significant challenge in the progress and development of Building-Integrated-Photovoltaic (B-I-PV) systems is concerned with the extraction of maximum power from PV modules. The PV system architecture is an essential feature to extract the maximum power. The conventional PV-central-inverter architecture consists of various connections among the PV modules, which are sensitive to shading effects and produces mismatching power loss under partial shading conditions (PSCs). Hence, photovoltaic-distributed-maximum power point tracking (PV-D-MPPT) architecture has been proposed to extract the maximum power. In PV-D-MPPT architecture, the output terminals of DC-DC converters are connected either in series or parallel configuration. The main limitation of the series configuration in open-loop MPPT control is the cross-coupling effect. Because of cross-coupling effects, the maximum-power-point (M-P-P) operation of shaded PV modules is lost under PSCs. The lost in M-P-P operation of shaded PV module also affects the unshaded modules M-P-P operation. Under cross-coupling effects, the DC-DC converters are consuming the power instead of delivering to the load. Despite the research activity, there are hardly any papers presenting a clear, comprehensive and mathematical analysis on the existence of cross-couplings in PV string-integrated-converters (S-I-Cs). This article presents a mathematical analysis and also explains the conditions for the existent of cross-coupling effects. The experimental results also validate with the mathematically analysed results. This article also discusses the modeling of the two-diode model of PV module, design of boost type S-I-C, and the Perturb and Observe (P&O) MPPT algorithm implementation.

Index Terms—Cross-coupling effects, mismatching power loss, partial shading conditions (PSCs), PV-central-inverter architecture, PV-D-MPPT architecture, S-I-Cs series configuration.

I. INTRODUCTION

BECAUSE of its sustainable and eco-friendly attributes, the utilisation of renewable energy has got tremendous importance. Among the many renewable energy sources, solar photovoltaic (PV) power generation has increased at a rapid pace of 20%–25% per year over the past 20 years, owing to a decrease in the price of PV modules, government incentives, as

well as creative business models for grid-connected and stand-alone PV system applications [1], [2]. The grid-connected PV systems developed for enhancing the power capability of existed utilities. In contrast, stand-alone PV systems developed for feeding power to the load without the utility. The operation and performance of PV systems depend on many factors, such as PV system architectures [3], [4], PV module configurations [5], [6], MPPT algorithms [7]–[10], converter topologies [11]–[15], inverter topologies [16]–[18], grid-integration techniques [19]–[21] and so on.

The grid-connected or stand-alone PV central inverter architecture consists of various connections among the PV modules. Power output from PV module configurations significantly reduced due to partial shading conditions (PSCs) and mismatching power loss [22]. Partial shading can be caused by moving clouds, shadows of buildings, trees, poles, chimneys, and so on. The power loss due to PSCs is not proportional to the shading field but depends on the PV module configurations, position of shaded modules in the configuration, shading patterns, and etc. [23]. The mismatching power loss is due to non-uniform operating conditions of PV modules, ageing phenomena, potential induced degradation effect, thermal defects, and so on. The mismatching phenomenon not only reduces the power output but also affects the lifetime of PV modules [24]. The mismatching power loss between shaded and unshaded PV modules can be reduced by connecting an anti-parallel bypass diode to a PV module [25]. However, the presence of bypass diode connection results in multiple-maximum-power-points (M-M-P-Ps) in the non-linear I - V and P - V characteristics. The existence of M-M-P-Ps can mislead conventional maximum power point tracking (MPPT) techniques and may get trapped at local-maximum-power-points (L-M-P-Ps) [26]–[28]. The literature offers various optimization techniques to track global-maximum-power-point (G-M-P-P). Still, the G-M-P-P tracking techniques are complex and may fail to follow the GMPP under certain instances [29]–[31].

The PV-distributed-maximum power point tracking (PV-D-MPPT) is one of the most exceptional technique to reduce the effect of shading and mismatching power loss on energy yield. In PV-D-MPPT architecture, there is no electrical connection among the PV strings/modules. A DC-DC converter incorporating with the classical MPPT controller to each PV string/module/submodule, and these topologies referred to as String-Integrated-Converter (S-I-C)/Module-Integrated-Converter (M-I-C)/ Submodule-Integrated-Converter (Sb-M-I-

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C) [32], [33]. Conventionally, S-I-Cs/M-I-Cs/Sb-M-I-Cs output terminals are connected either in series or parallel configuration. The conventional S-I-Cs/M-I-Cs configurations are having certain limitations and also having converters interfacing constraints [34], [35]. The advantages of series configuration are module-level MPPT, lower voltage conversion gain, use of smaller voltage power electronic devices, higher efficiency, and so on. The main limitation of the converters in the series configuration is the cross-coupling effect. The cross-coupling effects are defined as “an undesired property of cascaded DC-DC converters causing disturbances in the converter operation, which affects the generation of power from PV modules” [36]. Because of cross-coupling effects, the M-P-P operation of shaded PV modules is lost, which can also affect the M-P-P operation of unshaded PV modules. Due to the existence of cross-coupling effects, the DC-DC converters are consuming power instead of delivering to the load. The other limitations of the series configuration of DC-DC converters are lesser anti-partial cloudy compatibility, lower flexibility due to limited voltage conversion gain, variations in the output voltage due to failure operation of a single converter, and so on. The parallel configuration is free from cross-coupling effects. Still, the limitations of this configuration are higher voltage conversion gain, the need for high voltage power electronic devices, the use of isolated DC-DC converters, lower conversion efficiency, and so on. The advantages of parallel configuration are panel-level MPPT, higher flexibility, higher anti-partial cloudy compatibility [36], [37]. The Buck, Boost and Buck-boost converters were employed as S-I-Cs/M-I-Cs/Sb-M-I-Cs. The perturb and observe (P&O), incremental conductance (INC), modified P&O, and modified INC MPPT algorithms used for extracting maximum power.

The work carried out to overcome the limitations of a conventional configurations of M-I-Cs by a few of the researchers supported in [38]–[49]. Ho-sung Kim *et al.*, proposed a low cost, high-efficiency isolated fly-back DC-DC converter to the series configuration of M-I-Cs. Here, the PV module operating voltage directly added to the converter output voltage. Hence, the converter generates only the difference voltage between the PV module voltage and the desired total output voltage. Therefore, the power level of the converter reduces and enhances the conversion efficiency to 95%–98% compared with the conventional boost converter [38]. A. I. Bratcu *et al.*, investigated the global power optimization issues for cascaded DC-DC converters irrespective of the PSCs. They also proposed a supervisory control algorithm for operating the series and parallel configured M-I-Cs in sub-optimal power region by avoiding voltage-violations [39]. Z. Liang *et al.*, proposed a high-efficiency dual-mode resonant converter to paralleling configured M-I-Cs. The proposed converter can change its operating modes adaptively based on the PV module operating conditions. They also compared the performance of the proposed converter with conventional L-L-C resonant converter. They examined that the proposed converter gives more than 10% efficiency over the L-L-C converter [40]. A. Bidram *et al.*, briefly describe various approaches to extract maximum power from PV systems. The methods include (i) various modified MPPT techniques (namely, instantaneous

operating power optimization, Fibonacci search, and neural networks), (ii) PV array configurations (namely, S-P, T-C-T, and B-L), (iii) PV system architectures (namely, central inverter architecture, series-connected micro-converters, parallel-connected micro-converters, and micro-inverters), and (iv) various converter topologies (namely, voltage injection circuits, generation control circuits, M-I-Cs, and multiple-input converters) [41]. H. J. Bergveld *et al.*, proposed a delta (Δ)-conversion concept to series configured M-I-Cs. This concept aims at averaging out differences in output power between groups of PV cells within modules and between modules inside the PV system. All groups of PV cells can then output their maximum available power, such that a drop in output power of the total system is prevented. They also compared the performance of Δ -conversion concept with the reference case having no DC-DC converters and Σ -conversion concept. The proposed concept reduces the operation time and thereby increases the reliability of the converters. Moreover, since only power differences are fed through the converters, the converter efficiency can be lower, leading to lower cost [42]. M. Kasper *et al.*, describes various full-power and partial power processing architectures for series and parallel configured M-I-Cs. They identified that a buck-boost converter is most suitable topology to be operated as an M-I-C to full-power processing architectures [43].

CW Chen *et al.*, proposed a four-switch buck-boost converter (FSBBC) for a series configured M-I-Cs, which is having less number of passive components and produces a non-inverted output voltage polarity. The proposed converter operated in three modes, namely, buck, boost, and buck-boost modes. They also derived the small-signal model to the converter and also determined the stability of converter under change of modes of operation [44]. A. D. Grasso *et al.*, experimentally evaluated the performance of multi-string PV module and paralleled configured M-I-Cs. Here, each PV string comprises three numbers of modules. To each PV string, a non-isolated boost converter is integrated. They identified that an M-I-C topology improves the output power range from 11% to 25% over the multi-string PV module topology under PSCs [45]. F. Wang *et al.*, focused on a quantitative and mathematical analysis of different types of PV-D-MPPT architectures under mismatching conditions. They also derived mathematical expressions to specific judging criteria for determining the optimal power region of M-I-Cs. If the PV-D-MPPT structure satisfies the proposed judging criteria, the M-I-Cs operate at ideal maximum power irrespective of the mismatching issues [46]. D. Vinnikov *et al.*, proposed a single-stage isolated high voltage gain quasi-Z-source series resonant M-I-C. The proposed M-I-C features a wide input voltage and load regulation range. It can be operated in multi-mode, *i. e.* the shoot-through pulse width modulation and phase-shift modulation are combined in a single switching stage to realize the boost and buck operating modes, respectively. The experimental test on the proposed converter achieved a maximum efficiency of 97.4%, including the auxiliary power and control system losses [47]. A. Moghadasi *et al.*, designed a three-phase single-stage current source converter (CSC) to grid-tied PV M-I-C systems. The also proposed a model predictive

control technique for independently controlling the active and reactive powers exchanging between the PV system and utility grid to meet the recent grid-code and low-voltage ride-through (LVRT) requirements. The proposed control method was also verified through a 300-VA laboratory prototype [48]. D. Vinnikov *et al.*, proposed the concept of an optiverter to module-level PV systems. It includes the hybrid technology, which combines ultrawide MPPT voltage range of PV power optimizer with the direct AC connectivity and inherent safety of micro-inverter. The performance of the proposed concept is experimentally verified with a 300 W prototype and compared with the industrial micro-inverters [49].

This research article mathematically analyses and also in-detailly explains the conditions for existent the of cross-coupling effects in a 4×4 series configured S-I-Cs shown in Fig. 1. The mathematically analysed cross-coupled S-I-C results are also validated with the experimental results. The mathematically calculated PV string operating characteristics and S-I-C output characteristics are also compared with the experimental results. Section-II addresses the mathematical design of a PV module's two-diode model and its $I - V$ & $P - V$ characteristics. The design of boost type S-I-C is defined in Section-III. Section-IV deals with the application of P&O MPPT controller. The description of shading patterns is given in Section-V, and the assessment of cross-coupling

effects are discussed in Section-VI. Acknowledgement is given in Section-VII, and finally, a brief conclusion about the cross-coupling effects and the other observed limitations of series configuration are discussed in Section-VIII.

II. PV MODULE TWO-DIODE MODEL

The PV module is the primary device of a PV system, assembled by the series connection of 36 to 72 number of PV cells. Fig. 2 demonstrate the various PV module models [50], [51]. Fig. 2(a) shows an ideal PV module model which comprises a controlled current source in parallel to a diode. The ideal model was improved with the addition of series resistance (R_s) and referred to as a simplified model. Fig. 2(b) represents the simplified and practical models of the single-diode model of PV module. The simplified model shows significant flaws if temperature variations are observed. Hence, the simplified model also improved with the inclusion of a shunt resistance (R_p). Although substantial improvement achieved in a single-diode model, its accuracy deteriorates at low insolation. Also, the single-diode PV module model is based on the assumption that the recombination loss of charge carriers is absent in the depletion region. In practical PV modules, the recombination of charge carriers represents a significant loss, which cannot be adequately modeled using a single diode model. Hence, the two-diode model of PV module

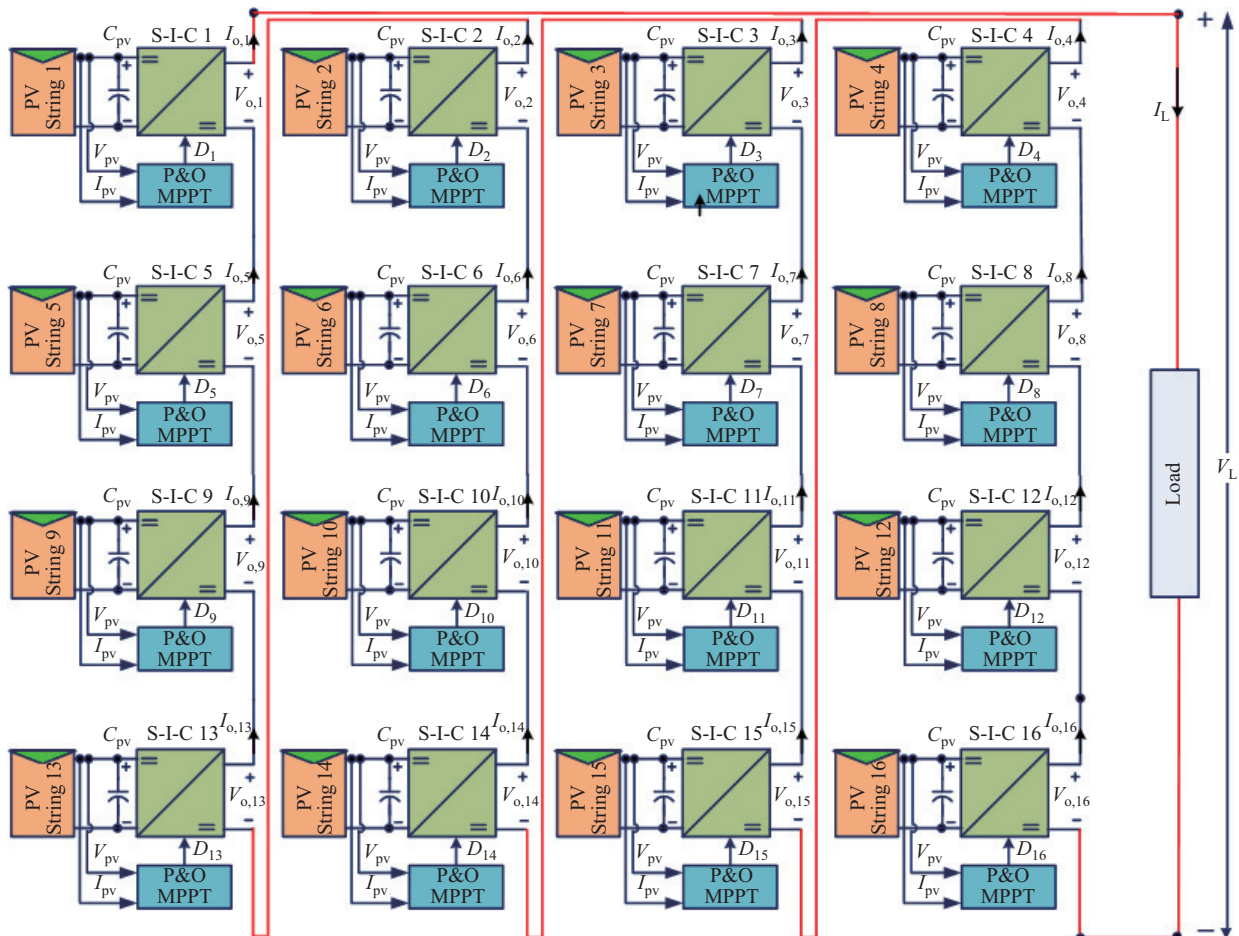


Fig. 1. 4×4 Series configured PV-D-MPPT string-integrated-converter.

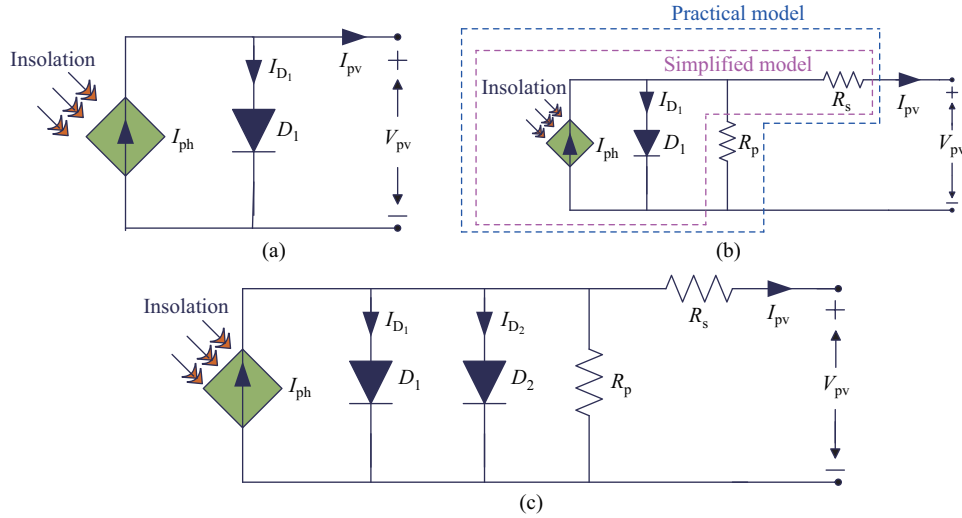


Fig. 2. PV module models. (a) Ideal model. (b) Single-diode simplified and practical models. (c) Practical two-diode model.

shown in Fig. 2(c) is introduced, which includes recombination loss [52]. The relation between the output current (I_{pv}) and voltage (V_{pv}) of Fig. 2(c) demonstrated by (1)–(3).

$$I_{pv} = I_{ph} - I_{D,1} \left[\exp \left(\frac{V_{pv} + I_{pv} R_s}{a_1 V_{T,1}} \right) - 1 \right] - I_{D,2} \left[\exp \left(\frac{V_{pv} + I_{pv} R_s}{a_2 V_{T,2}} \right) - 1 \right] - \left(\frac{V_{pv} + I_{pv} R_s}{R_p} \right) \quad (1)$$

where I_{pv} is photo-generated current; $I_{D,1}$ & $I_{D,2}$ are reverse saturation currents of diodes D_1 and D_2 ; $V_{T,1}$ & $V_{T,2}$ are thermal voltages of diodes D_1 and D_2 ; a_1 & a_2 are diode diffusion and recombination current components; R_s & R_p are series and shunt resistances, respectively. The current component, $I_{D,2}$ in (1) compensates for the recombination of charge carriers in the depletion region. The photo-generated current (I_{ph}) depends on the solar insolation and operating temperature, and is given by (2).

$$I_{ph} = \frac{G}{G_{STC}} [I_{ph,STC} + K_I \Delta T] \quad (2)$$

where $I_{ph,STC}$ is photo-generated current at standard test condition (STC) of 1000 W/m^2 and 25°C ; G_{STC} and G are solar insolation at STC & at any considered insolation level; K_I is temprature coefficient of short-circuit current; $\Delta T = T - T_{STC}$ is change in temperature; T & T_{STC} are ambient & temperatures at 25°C , respectively. The diode reverse saturation currents, $I_{D,1}$ and $I_{D,2}$ are expressed by (3).

$$I_{D,1} = I_{D,2} = \frac{(I_{sc,STC} + K_I \Delta T)}{\exp [(V_{oc,STC} + K_V \Delta T) / \{(a_1 + a_2) / p\} V_T] - 1} \quad (3)$$

where $V_{oc,STC}$ & $I_{sc,STC}$ are open-circuit voltage & short-circuit current at STC; and K_V is temperature coefficient of open-circuit voltage. The value of a_1 must be unity, $a_2 \geq 1.2$, and $p \geq 2.2$.

In this paper, SHARP-ND-62RU2 poly-crystalline PV modules are used to implement the PV-D-MPPT architecture shown in Fig. 1 [53]. The SHARP-ND-62RU2 PV module

generates the power of 62.006 W at an operating voltage and current of 8.60 V and 7.21 A under STC. Each PV string comprises five number of series-connected PV modules. Therefore, at an operating voltage and current of 43 V ($5 \times 8.60 \text{ V}$) and 7.21 A , a single PV string generates the power of 310.03 W ($5 \times 62.006 \text{ W}$). Fig. 1 comprises sixteen number of PV strings and generates the maximum power of 4960.46 W ($16 \times 310.03 \text{ W}$). The $I-V$ & $P-V$ characteristics, operating voltage, current, and power of a single PV string under various insolation levels are represented in Figs. 3(a) and 3(b).

III. DESIGN OF STRING-INTEGRATED-CONVERTER

A non-isolated DC-DC boost converter shown in Fig. 4

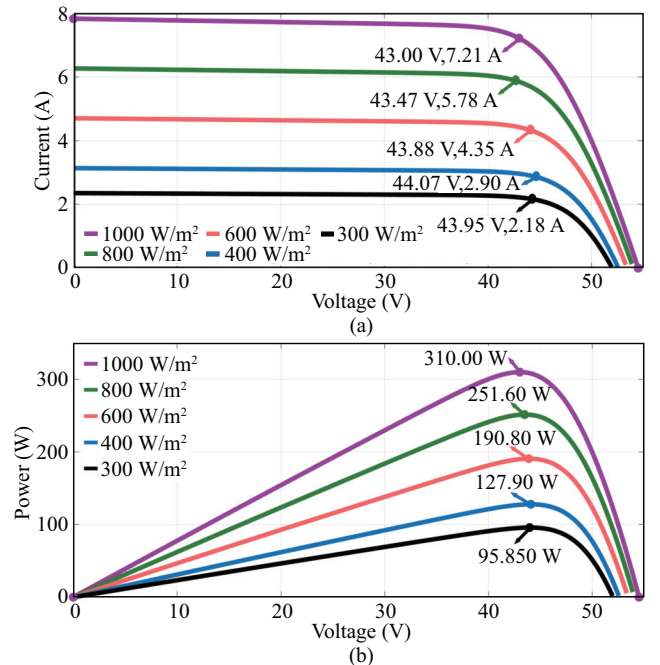


Fig. 3. PV string output characteristics. (a) $I-V$ characteristics. (b) $P-V$ characteristics.

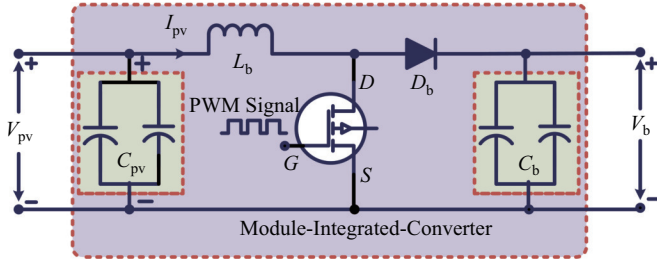


Fig. 4. Circuit connection of string-integrated-converter.

is required to track maximum power. Hence, a single boost converter is integrated into each PV string. In addition to MPPT operation, the S-I-C needs to boost PV string output voltage (V_{pv}). The MOSFET switch (SW_b), output diode (D_b), inductive filter (L_b), input capacitive filter (C_{pv}), and output capacitive filter (C_b) are the electrical components of S-I-C. The PV string parameters V_{pv} and I_{pv} are considered as the input parameters to a S-I-C. The design procedure of various components of S-I-C are given as follows [54]:

A. Input Capacitive Filter Selection

The capacitive input filter (C_{pv}) is interfaced between the input connections of S-I-C and the output connections of the PV string. It is used to smoothen output voltage ripples of PV string. Two capacitors of the same rating are connected in parallel to reduce the effect of equivalent series resistance (ESR) of a capacitor. The input capacitance of the capacitor is calculated by (4).

$$\begin{aligned} C_{pv} &= \frac{\Delta I_{pv}}{8 \times \Delta V_{pv} \times F_{sw}} \\ &= \frac{0.1 \times 7.21}{8 \times 0.03 \times 43 \times 10000} \\ &= 10 \mu F \end{aligned} \quad (4)$$

where ΔI_{pv} is the ripple of inductor current, ΔV_{pv} is the ripple of output voltage from a PV string, and F_{sw} is the frequency of switch (SW_b). To calculate the value of C_{pv} , the values of F_{sw} , ΔI_L and ΔV_{pv} are considered as 10 kHz, 10% and 3%.

B. Inductor Selection

The output current of the PV string (I_{pv}) is continuously passed through the inductor to smoothen ripples present in it. An inductor's current rating is always greater than the short-circuit current of the PV string, *i.e.* the selected inductor must have its current rating higher than 7.21 A. The inductance of inductor L_b is calculated by (5).

$$L_b = \frac{V_{pv} \times D}{2 \times \Delta I_{pv} \times F_{sw}} = \frac{43 \times 0.57}{2 \times 0.1 \times 7.21 \times 10000} = 5 \text{ mH} \quad (5)$$

where V_{pv} is the output voltage from a PV string and D is duty-ratio of the SW_b . The relation between the output & input voltages (V_b & V_{pv}), and the output & input currents (I_b & I_{pv}) of a S-I-C is expressed by the Eqs. (6) and (7). From (6), theoretically calculated 'D' of the S-I-C at STC is 57%.

$$\frac{V_b}{V_{pv}} = \frac{1}{1 - D} \quad (6)$$

$$\frac{I_b}{I_{pv}} = 1 - D \quad (7)$$

C. Output Capacitive Filter Selection

To smooth out the ripples present in the S-I-C output voltage, the capacitive output filter is used. The capacitance of the output capacitor (C_b) is calculated by (8). Two capacitors of the same rating are connected in parallel to reduce the effect of equivalent series resistance (ESR).

$$\begin{aligned} C_b &= \frac{V_o \times D}{2 \times \Delta V_o \times R_b \times F_{sw}} \\ &= \frac{100 \times 0.57}{2 \times 0.03 \times 100 \times 32.256 \times 10000} = 100 \mu F \end{aligned} \quad (8)$$

where V_o is the output voltage of the S-I-C, ΔV_o is the output voltage ripple, R_b is the load resistance, respectively. The load resistance R_b of the S-I-C is determined by (9).

$$\begin{aligned} R_{eq} &= R_b \times (1 - D)^2 \Rightarrow \frac{V_{mp}}{I_{mp}} = R_b \times (1 - D)^2 \\ &\Rightarrow \frac{43}{7.21} = R_b \times (1 - 0.57)^2 \Rightarrow R_b = 32.256 \Omega \end{aligned} \quad (9)$$

where V_{mp} and I_{mp} are the PV string maximum voltage and current at STC.

D. Power Devices Selection

The power electronic switch (SW_b) is selected based on the PV string output voltage and current rating. The selected switch parameters should be higher than the ratings of the PV string. The key specification for selecting the power diode (D_b) is the reverse voltage rating and it relies on the S-I-C output voltage. The current rating of 'D_b' should be lower than the output current of PV string.

IV. IMPLEMENTATION OF PERTURB AND OBSERVE (P&O) MPPT TECHNIQUE

The P&O MPPT approach is the easiest and most conventional way of extracting full power. Fig. 5 demonstrates the PV fed S-I-C functional block diagram along with the P&O MPPT algorithm [55]. As shown in Fig. 5(a), the variables V_{pv} and I_{pv} are sensed from PV strings and fed to MPPT controller (micro-controller) as input variables. The algorithm for P&O MPPT, shown in Fig. 5(b) is executed on the micro-controller and a control signal is generated at the output. The control signal is correlated with the 10kHz frequency saw-tooth signal to generate a PWM signal. To regulate the maximum power, PWM signal is fed to the ' SW_b '. The measures involved in implementing the MPPT approach of P&O are as follows:

- ◇ Initially, from V_{pv} and I_{pv} , the corresponding power $P_{pv}(K) = V_{pv}(K) \times I_{pv}(K)$ is calculated.
- ◇ A small perturbation in duty-ratio (ΔD), in any one of the direction is introduced and corresponding power $P_{pv}(K - 1) = V_{pv}(K - 1) \times I_{pv}(K - 1)$ is calculated.
- ◇ The difference between the corresponding powers is calculated by the expression $\Delta P_{pv} = P_{pv}(K) - P_{pv}(K - 1)$.
- ◇ If the $\Delta V_{pv} [= V_{pv}(K) - V_{pv}(K - 1)] > 0$, and also $\Delta P_{pv} > 0$ [*i.e.* $\frac{dP_{pv}}{dV_{pv}} > 0$], the perturbation is in correct

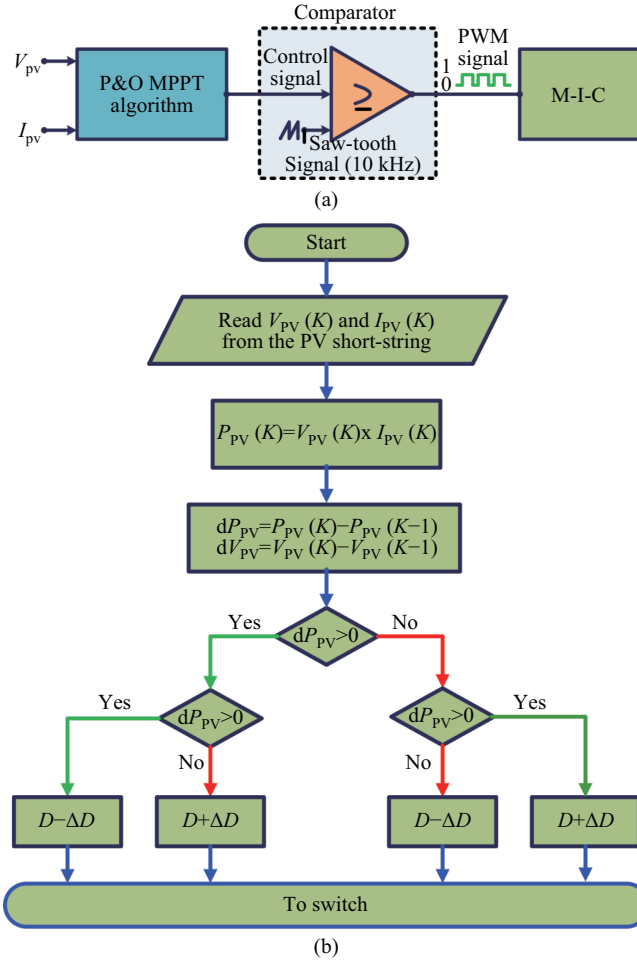


Fig. 5. P&O MPPT technique implementation. (a) PV Fed S-I-C block diagram, and (b) P&O MPPT Algorithm.

direction. At this condition, ‘ D ’ is increased to $D + \Delta D$ until it reaches to steady-state.

- ◇ If $\Delta V_{pv} > 0$, & $\Delta P_{pv} < 0$ [i.e. $\frac{dP_{pv}}{dV_{pv}} < 0$], perturbation should be in the reverse direction. At this condition, ‘ D ’ is decreased to $D - \Delta D$ until it reaches the steady-state.
- ◇ If $\frac{dP_{pv}}{dV_{pv}} = 0$, the initial or pre-defined value of ‘ D ’ is considered as steady-state value, and there is no need of any increment or decrement in ‘ D ’.
- ◇ The perturbations in ‘ D ’ under above referred conditions are summarized in Eq. (10).

$$D_{new} = \begin{cases} \frac{dP_{pv}}{dV_{pv}} = 0, & D \\ \frac{dP_{pv}}{dV_{pv}} > 0, & D + \Delta D \\ \frac{dP_{pv}}{dV_{pv}} < 0, & D - \Delta D \end{cases} \quad (10)$$

Choosing the correct perturbation step-size (ΔD) and step-time (T_a) determines the MPPT algorithm’s tracking efficiency. The value of (ΔD) chosen based on steady-state and dynamic performance. The maximum value of ΔD improves the dynamic performance, while a minimum value of ΔD enhances the steady-state performance. To ensure a minimum number

of the oscillations (i.e., three-level operation), the value of ‘ T_a ’ should be higher than the system’s settling time for a step-change in ‘ D ’. To implement the P&O MPPT technique, the considered MPPT parameter values are $D_{initial} = 0.57$, $D_{minimum} = 0.2$, $\Delta D = 0.01$ and $T_a = 30$ ms.

V. MODELING OF SHADING PATTERNS

The main objective of this article is to analyse and assess the cross-coupling effects under four types of shading patterns. These shading patterns are uneven-row, uneven-column, diagonal, and long-and-narrow (L-A-N). Fig. 6 represents the above-referred shading patterns, and also describes the various levels of insolation present under each of the shading pattern. Each of the shading pattern comprises different types of insolation levels such as full-insolation [1000 W/m^2], clear-cloud [800 W/m^2], centre-cloud [600 W/m^2], dark-cloud [400 W/m^2] and the most dark-cloud [300 W/m^2], respectively. The modeling and description of each of the shading pattern are as follows:

A. Uneven-row Shading Pattern

As shown in Fig. 6(a), the first row of the S-I-Cs is unevenly shaded with different types of insolation levels. The S-I-Cs numbered 11, 12, 13 and 14 are receiving an insolation of 300 W/m^2 , 400 W/m^2 , 600 W/m^2 and 800 W/m^2 , respectively. The rest of the S-I-Cs present in the second, third and fourth row are receiving an insolation of 1000 W/m^2 .

B. Uneven-column Shading Pattern

In this type of shading pattern, with various types of insolation levels, the first column of S-I-Cs is un-evenly shaded. The uneven-column type of shading pattern is shown in Fig. 6(b). The S-I-Cs numbered 11, 21, 31 and 41 are receiving an insolation of 300 W/m^2 , 400 W/m^2 , 600 W/m^2 and 800 W/m^2 , respectively. The rest of the S-I-Cs present in the second, third and fourth row are receiving insolation an of 1000 W/m^2 .

C. Diagonal-shading Pattern

The diagonal type of shading pattern is shown in Fig. 6(c). Under this shading pattern, it is assumed the cloud is spread over the diagonally placed S-I-Cs and receives different types of insolation levels. The diagonally placed S-I-Cs numbered 11, 22, 33 and 44 are receiving an insolation of 300 W/m^2 , 400 W/m^2 , 600 W/m^2 and 800 W/m^2 , respectively. The rest of the S-I-Cs obtaining an insolation of 1000 W/m^2 .

D. Long-and-narrow Shading Pattern (L-A-N)

The cloud is un-evenly distributed over the first two columns of the S-I-Cs in this sort of shading pattern. The L-A-N type of shading pattern along with the insolation level is represented in Fig. 6(d). Here, the cloud is expected to move from top to bottom of the considered PV architecture shown in Fig.1. The S-I-Cs numbered (11, 12), (21, 22), (31, 32) and (41, 42) are receiving an insolation of 300 W/m^2 , 400 W/m^2 , 600 W/m^2 and 800 W/m^2 , respectively. The rest of the S-I-Cs in the third and fourth rows are receiving an insolation of 1000 W/m^2 .

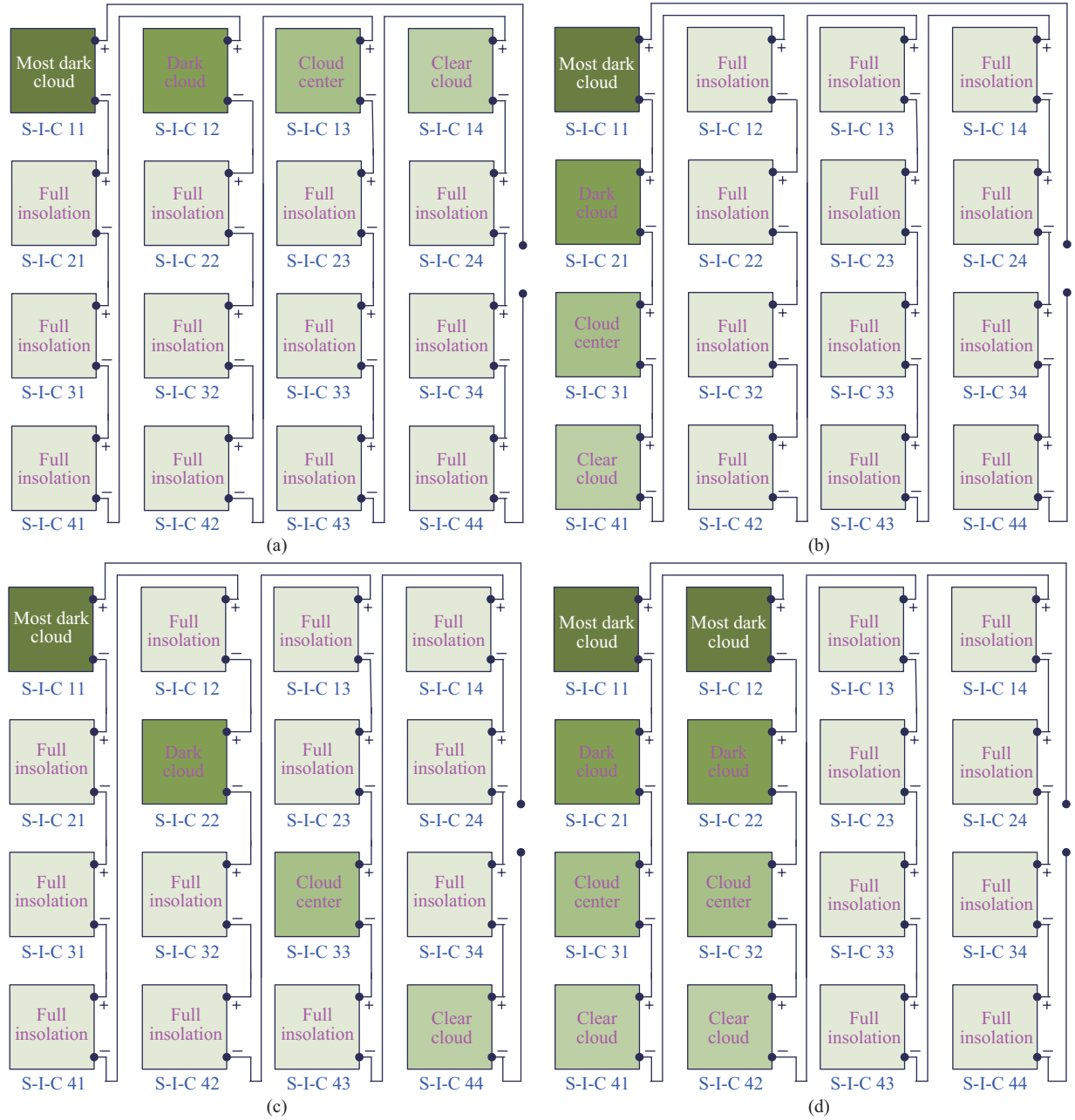


Fig. 6. Representation of various shading patterns and the corresponding insolation values in each type of shading. (a) uneven-row, (b) uneven-column, (c) diagonal, and (d) L-A-N.

VI. RESULTS AND DISCUSSIONS

This section explains the experimental results of the configuration of PV-D-MPPT architecture shown in Fig. 1. It is in-detailly explains the cross-couplings, mathematically analyses the conditions for the existence of cross-couplings, and the effects of cross-couplings. The theoretically calculated PV string and S-I-C parameters are also validated with experimental results. All the S-I-Cs, in each shading pattern, are operated at full insolation from $t = 0$ to 0.3 sec. At full insolation, each S-I-C is operating at a 'D' of 0.57. The V_{pv} and I_{pv} of each PV string at a 'D' of 0.57 are (43 V, 7.21 A), and the corresponding operating power is at 310.03 W. The change in insolation levels under all shading patterns is applied from

$t = 0.3$ to 1.5 sec.

A. Under Uniform Insolation Conditions

The considered 4×4 series configuration is operating under various uniform insolation levels such as 1000 W/m², 800 W/m², 600 W/m², 400 W/m², and 300 W/m². When the PV system (all S-I-Cs) receiving insolation of 1000 W/m², each S-I-C is operating at a voltage (V_{pv}) and current (I_{pv}) of (43 V, 7.21 A) with a duty ratio of 0.57 respectively. The corresponding operating power (P_{pv}) of the S-I-C is 310.03 W. Theoretically, from Eqs. (6) & (7), at 0.57 duty-ratio, each S-I-C has to produce the output voltage ($V_{o,t}$) of 100 V [$43 \times \frac{1}{1-0.57} V = 43 \times 2.32 V$], output current ($I_{o,t}$) of 3.10 A [$7.21 \times (1 - 0.57) A = 7.21 \times 0.43 A$] and output power

($P_{o,t}$) of 310 W [$100 \text{ V} \times 3.10 \text{ A}$]. The experimental values of output voltage ($V_{o,e}$), current ($I_{o,e}$) and power ($P_{o,e}$) of a single S-I-C at 0.57 duty-ratio are 99.40 V, 3.12 A and 310.12 W [$99.40 \text{ V} \times 3.12 \text{ A}$]. The theoretically calculated total output voltage ($T - V_{o,t}$), current ($T - I_{o,t}$) and power ($T - P_{o,t}$) of the 4×4 series configuration is 1600 V [$16 \times 100 \text{ V}$], 3.10 A and 4960 W [$1600 \text{ V} \times 3.10 \text{ A}$], whereas the experimental values of output voltage ($T - V_{o,e}$), current ($T - I_{o,e}$) and power ($T - P_{o,e}$) are at 1590.40 V [$16 \times 99.30 \text{ V}$], 3.12 A and 4957.05 W [$1590.40 \text{ V} \times 3.12 \text{ A}$].

At uniform insolation of 800 W/m^2 , V_{pv} and I_{pv} of an each S-I-C are at (43.32 V, 5.80 A) with a duty ratio of 0.52 respectively. The corresponding P_{pv} of an each S-I-C at 0.52 duty-ratio is 251.25 W. Theoretically, at 0.52 duty ratio, a single S-I-C has to produce the $V_{o,t}$, $I_{o,t}$ and $P_{o,t}$ of 90.25 V, 2.78 A and 250.89 w respectively. The experimental values of $V_{o,e}$, $I_{o,e}$ and $P_{o,e}$ at 0.52 duty ratio are 89.66 V, 2.77 A and 248.35 w, respectively. The theoretically calculated $T - V_{o,t}$, $T - I_{o,t}$ and $T - P_{o,t}$ are at 1444 V, 2.78 A and 4014.32 w, respectively, whereas the experimental values of $T - V_{o,e}$, $T - I_{o,e}$ and $T - P_{o,e}$ are at 1434.56 V, 2.77 A and 3973.73 w.

The experimental results of the 4×4 series configuration under above-refereed uniform insolation levels including at 600 W/m^2 , 400 W/m^2 and 300 W/m^2 are shown in Fig. 7. The comparative study of both the theoretical and experimental results are represented in Table I.

B. Under Partial Shading Patterns

Under an uneven-row pattern of shading from $t = 0.3$ to 1.5 sec, the values of V_{pv} , I_{pv} and P_{pv} of S-I-Cs receiving insolation of 1000 W/m^2 are 42.80 V, 7.21 A and 308.59 w at a duty-ratio of 0.62. Theoretically, at 0.62 duty-ratio, S-I-C has to produce the $V_{o,t}$, $I_{o,t}$ and $P_{o,t}$ of 112.564 V, 2.74 A and 308.42 w, respectively. The experimental values of $V_{o,e}$, $I_{o,e}$ and $P_{o,e}$ of the S-I-C at 0.62 duty-ratio are 110.30 V, 2.75 A and 303.46 w.

The values of V_{pv} , I_{pv} and P_{pv} of the S-I-Cs receiving insolation of 800 W/m^2 from $t = 0.3$ to 1.5sec are 43.79 V, 5.74 A and 251.41 w at a duty-ratio of 0.51. Theoretically, at 0.51 duty-ratio, S-I-C has to produce the $V_{o,t}$, $I_{o,t}$ and $P_{o,t}$ of 89.37 V, 2.81 A and 251.12 w. The experimental values of $V_{o,e}$, $I_{o,e}$ and $P_{o,e}$ of the S-I-C at 0.51 duty-ratio are 89.87 V, 2.75 A and 247.14 w.

Similarly, the V_{pv} , I_{pv} and P_{pv} of the S-I-Cs receiving insolation of 600 W/m^2 are 44.09 V, 4.32 A and 190.51 w at a duty-ratio of 0.35. Theoretically, at 0.35 duty-ratio, S-I-C has to produce the $V_{o,t}$, $I_{o,t}$ and $P_{o,t}$ of 67.90 V, 2.80 A and

190.79 w. The experimental values of $V_{o,e}$, $I_{o,e}$ and $P_{o,e}$ of the S-I-C at 0.35 duty-ratio are 68.38 V, 2.75 A and 190.79 w.

The actual V_{pv} , I_{pv} and P_{pv} of the S-I-Cs receiving insolation of 400 W/m^2 are 44.07 V, 2.90 A and 127.90 w. At this insolation level, the experimentally determined values of V_{pv} , I_{pv} and P_{pv} are 1.10 V, 3.13 A and 3.44 w at a duty-ratio of 0.21. Here, it is observed that the V_{pv} and I_{pv} of the shaded PV strings (or S-I-Cs) deviated from the M-P-P operation. This is because of the cross-coupling effects present in the series configuration of S-I-Cs. From the experimental results, it is determined that the output current $I_{o,e}$ of S-I-C receiving insolation of 1000 W/m^2 is 2.75 A. Since, $I_{o,e}$ of the series configuration is the same for the total PV system. Hence, to deliver $I_{o,e}$ of 2.75 A, the I_{pv} of shaded PV string operating point shifts towards the short-circuit current region. At the same instant, the duty-ratio of the cross-coupled S-I-C reaches its lower limit of 0.21. Theoretically, at 0.21 duty-ratio, S-I-C has to produce $V_{o,t}$, $I_{o,t}$ and $P_{o,t}$ of 1.39 V, 2.47 A and 3.44 w. The experimental values of $V_{o,e}$, $I_{o,e}$ and $P_{o,e}$ of the S-I-C at 0.21 duty-ratio are 0.44 V, 2.75 A and 1.21 w.

Similarly, S-I-C operating at insolation of 300 W/m^2 is also cross-coupled. The actual values of V_{pv} , I_{pv} and P_{pv} of S-I-C at this insolation level are 43.95 V, 2.18 A and 95.850 w. The experimental values of V_{pv} , I_{pv} and P_{pv} of the S-I-C are at -0.80 V, 2.35 A, and -1.88 w at a duty-ratio of 0.21. Theoretically, at 0.21 duty-ratio, S-I-C has to produce the $V_{o,t}$, $I_{o,t}$ and $P_{o,t}$ of -1.01 V, 1.86 A and -1.88 w. The experimental values of $V_{o,e}$, $I_{o,e}$ and $P_{o,e}$ at 0.21 duty-ratio are -1.503 V, 2.75 A, and -4.13 w. The actual short-circuit current of the S-I-C at 300 W/m^2 is 2.35 A, which is lesser than the output current (2.75 A) of the PV system. Hence, to support the flow of 2.75 A, the shaded PV string is operating in the negative voltage region. Because of the cross-coupling effect, instead of delivering power, the S-I-C is consuming power due to negative operating voltage. At the same instant, the S-I-C cross-coupling duty-ratio approaches its minimum value of 0.21. Hence, the switching action of cross-coupled switch SW_b cannot be occurring. At this condition, the anti-parallel internal body diode of the switch is forward biased because of the negative operating voltage. In order to equalise the output current of a series configuration, the internal body diode supports 0.4 A [2.75 A-2.35 A] flow. The current direction and equivalent circuit of the non-cross-coupled and cross-coupled S-I-Cs under PSCs are shown in Fig. 8. Theoretically, the voltage of cross-coupled S-I-C through the internal body diode (V_D) shown in Fig. 8(c) is calculated on the basis of

TABLE I
THEORETICAL AND EXPERIMENTAL FINDINGS UNDER DIFFERENT UNIFORM INSOLATION LEVELS OF S-I-Cs SERIES CONFIGURATION

Irradiance	V_{pv} (V)	I_{pv} (A)	P_{pv} (W)	D	V_o (V)		I_o (A)		P_o (W)		$T - V_o$ (V)		$T - P_o$ (W)	
					t	e	t	e	t	e	t	e	t	e
1000	43.00	7.21	310.03	0.57	100	99.30	3.10	3.12	310.00	309.81	1600.00	1590.40	4960.00	4956.96
800	43.32	5.80	251.25	0.52	90.25	89.66	2.78	2.77	250.90	248.35	1444.00	1434.56	4014.32	3973.60
600	44.05	4.30	189.42	0.44	78.66	78.08	2.41	2.42	189.57	188.95	1258.56	1249.28	3033.13	3023.30
400	43.87	2.91	127.66	0.32	64.51	63.84	1.97	1.98	127.60	126.40	1032.16	1021.44	2041.60	2022.40
300	44.19	2.17	95.85	0.21	55.94	55.22	1.71	1.72	95.89	94.97	895.04	883.52	1534.24	1519.52

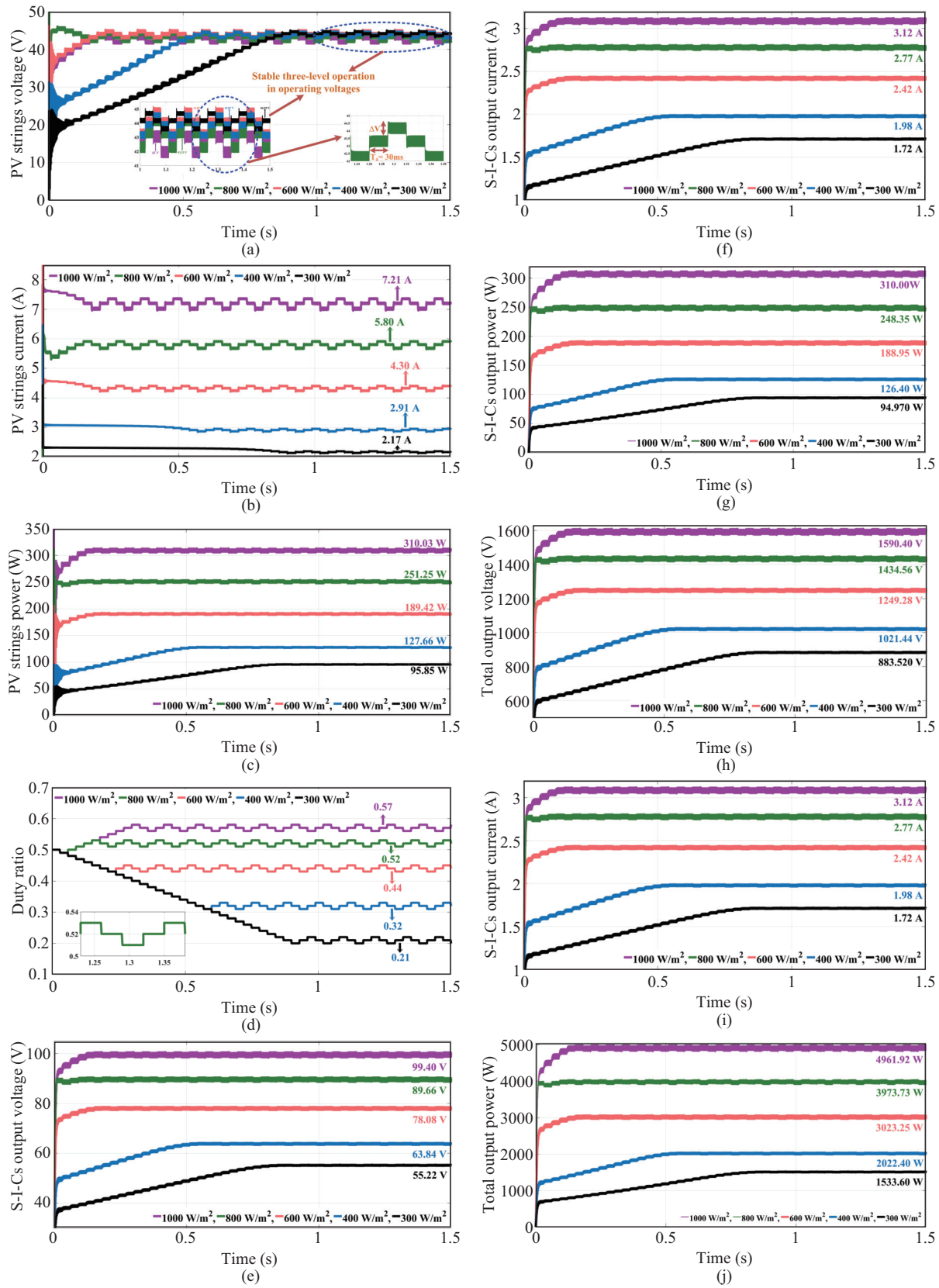


Fig. 7. Experimental results of the 4×4 series configured PV system under various uniform insolation levels. (a) Voltage of PV string, (b) Current of PV strings, (c) Power of PV strings, (d) Duty- ratios, (e) S-I-Cs output voltage, (f) S-I-Cs output current, (g) S-I-Cs output power, (h) total output voltages, (i) total output currents, and (j) total output powers.

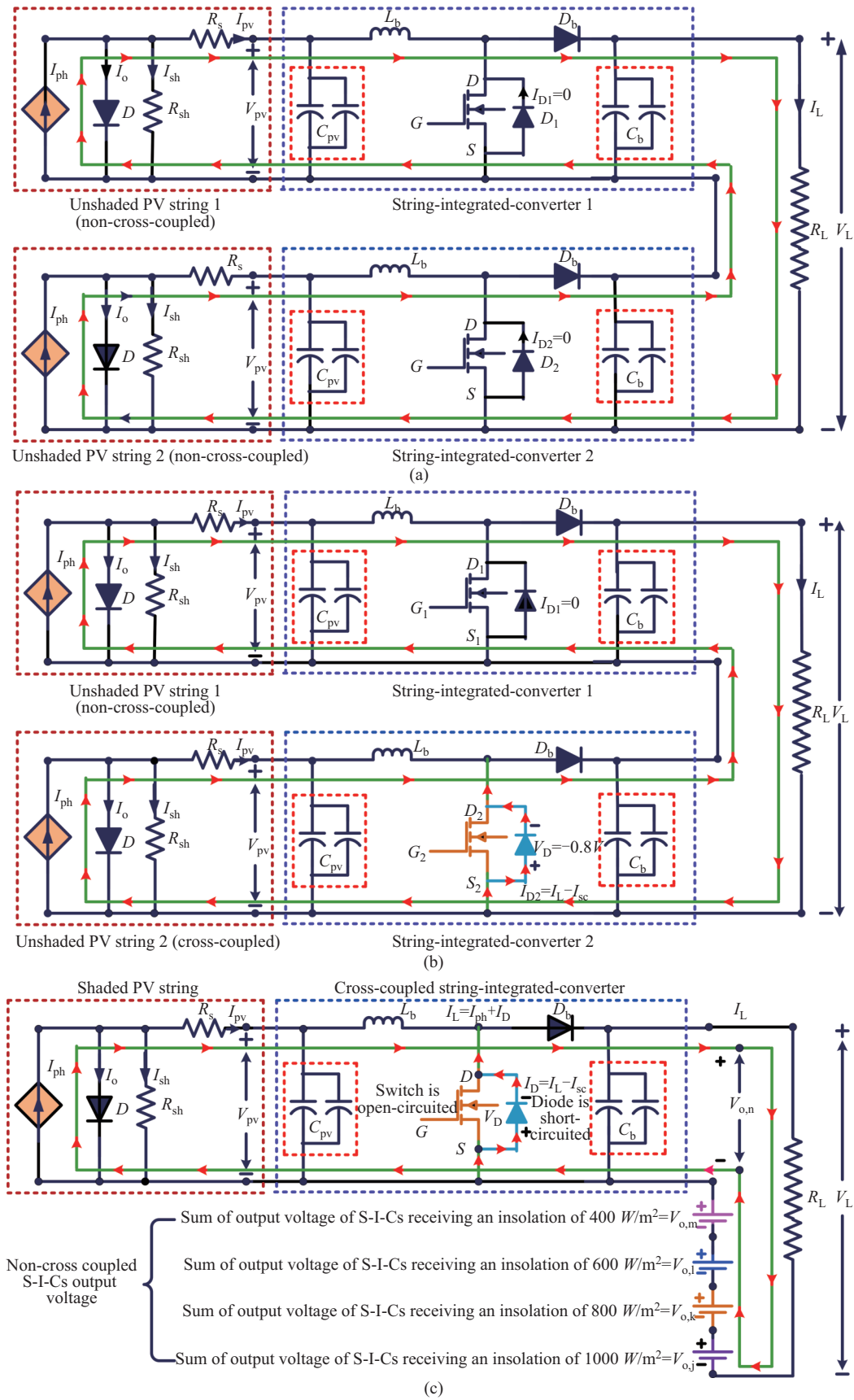


Fig. 8. S-I-Cs current direction under PSCs. (a) Direction of current to the non-cross coupled S-I-Cs, (b) Direction of current to the cross-coupled S-I-Cs, and (c) Equivalent circuit of 4 × 4 series PV-D-MPPT architecture comprising the non-cross coupled and cross-coupled S-I-Cs.

Eq. (11).

$$\left\{ \begin{array}{l} V_{o,1} + V_{o,2} + \dots + V_{o,15} + V_{o,16} = I_o R_L \\ V_{o,j} + V_{o,k} + V_{o,l} + V_{o,m} + V_{o,n} - I_o R_L = 0 \\ V_{o,j} + V_{o,k} + V_{o,l} + V_{o,m} + \\ \quad [V_D + V_{D_b}] - I_o R_L = 0 \\ [12 \times 110.30]V + 89.870V + \\ \quad 68.380V + 0.44V + \\ \quad 2V_D - 1482.29V = 0 \\ V_D = \frac{1481.57V - 1482.29V}{2} = -0.72V \end{array} \right. \quad (11)$$

where $V_{o,1}, V_{o,2}, \dots, V_{o,16}$ are individual S-I-C output voltages; $V_{o,j}, V_{o,k}, V_{o,l}, V_{o,m}$, and $V_{o,n}$ are the sum of S-I-Cs output voltages at an insolation of 1000 W/m², 800 W/m², 600 W/m², 400 W/m², and 300 W/m². Similarly, current flowing through the cross-coupled S-I-C's internal body diode (I_D) is calculated by Eq. (12).

$$\begin{aligned} I_D &= I_L - (\text{short-circuit current of cross-coupled} \\ &\quad \text{PV string with an insolation of 300 W/m}^2) \\ &= 2.75A - 2.35A = 0.4A. \end{aligned} \quad (12)$$

The values of $T - V_{o,t}$, $T - V_{o,e}$, $T - P_{o,t}$, and $T - P_{o,e}$ of the considered PV system subjected to uneven-row, uneven-column, and diagonal shading patterns are calculated by Eqs. (13)–(16).

$$\left\{ \begin{array}{l} T - V_{o,t} = V_{o,1000W/m^2} + V_{o,800W/m^2} + \\ \quad V_{o,600W/m^2} + V_{o,400W/m^2} + \\ \quad V_{o,300W/m^2} \\ = [12 \times 112.56]V + [1 \times 89.37]V + \\ \quad [1 \times 67.90]V + [1 \times 1.39]V + \\ \quad [1 \times (-1.01)]V \\ = 1508.37V. \end{array} \right. \quad (13)$$

$$\left\{ \begin{array}{l} T - V_{o,e} = [12 \times 110.3]V + [1 \times 89.87]V + \\ \quad [1 \times 68.38]V + [1 \times 0.44]V + \\ \quad [1 \times (-1.50)]V \\ = 1480.78V. \end{array} \right. \quad (14)$$

$$\left\{ \begin{array}{l} T - P_{o,t} = P_{o,1000W/m^2} + P_{o,800W/m^2} + \\ \quad P_{o,600W/m^2} + P_{o,400W/m^2} + \\ \quad P_{o,300W/m^2} \\ = [12 \times 308.42]W + [1 \times 251.1]W + \\ \quad [1 \times 190.79]W + [1 \times 3.433]W + \\ \quad [1 \times (-1.88)]W \\ = 4144.50W. \end{array} \right. \quad (15)$$

$$\left\{ \begin{array}{l} T - P_{o,e} = [12 \times 303.4]V + [1 \times 247.1]V + \\ \quad [1 \times 188.05]V + [1 \times 1.21]V + \\ \quad [1 \times (-4.13)]V \\ = 4072.92W. \end{array} \right. \quad (16)$$

The theoretically calculated $T - V_{o,t}$ and $T - P_{o,t}$ are 1507.95 V and 4144.50 w, whereas the experimental values of

$T - V_{o,e}$ and $T - P_{o,e}$ are 1480.78 V and 4072.92 w, respectively. The experimental results of the 4×4 series configuration subjected to shading pattern of uneven-row are shown in Fig. 9. The considered PV system shows similar results as the uneven-row shading pattern due to series connection and the same insolation levels under uneven-column and diagonal shading. The comparative results of both the theoretical and experimental values of 4×4 series configuration under first three shading patterns are listed in Table II.

Under L-A-N type of shading pattern, the the values of V_{pv} , I_{pv} , and P_{pv} of S-I-Cs at an insolation of 1000 W/m², 800 W/m², 600 W/m², 400 W/m² and 300 W/m² are same as under uneven-row, uneven-column, and diagonal shading patterns. Under L-A-N shading pattern, the 'D' S-I-Cs receiving an insolation of 1000 W/m², 800 W/m², 600 W/m², 400 W/m², and 300 W/m² at the corresponding V_{pv} and I_{pv} are at 0.64, 0.56, 0.41, 0.21, and 0.21 respectively. Theoretically, at 0.64, 0.56, 0.41, 0.21 (400 W/m²), and 0.21 (300 W/m²) duty-ratios, S-I-Cs generates the $V_{o,t}$ and $I_{o,t}$ of (118.88 V, 2.59 A), (99.20 V, 2.53 A), (74.73 V, 2.54 A), (1.37 V, 2.48 A), and (-1.01 V, 1.86 A) respectively. The experimental values of $V_{o,e}$ and $I_{o,e}$ at 0.64, 0.56, 0.41, 0.21 (400 W/m²), and 0.21 (300 W/m²) duty-ratio are (120.19 V, 2.53 A), (97.69V, 2.53A), (74.35V, 2.53A), (0.53 V, 2.53 A), and (-1.503 V, 2.53 A) respectively. Theoretically, the $P_{o,t}$ of S-I-Cs at 0.64, 0.56, 0.41, 0.21 (400 W/m²), and 0.21 (300 W/m²) duty -ratios is 307.89 W, 250.98 W, 189.81 W, 3.39 W, and -1.88 W respectively, whereas the experimental values of $P_{o,e}$ are at 304.10 W, 247.15 W, 188.85 W, 1.31 W, and -3.80 W respectively. The S-I-Cs that receive an insolation of 400 W/m² and 300 W/m² are also cross-coupled in the L-A-N shading pattern as referred to in the uneven-row shading pattern. The voltage and current flowing by internal body diode of cross-coupled switch ' SW_b ' in L-A-N shading are determined by Eqs. (17) and (18).

$$\left\{ \begin{array}{l} V_{o,j} + V_{o,k} + V_{o,l} + 2V_D + 2V_{D_b} - I_o R_L = 0 \\ [8 \times 120.19]V + [2 \times 97.69]V + \\ \quad 2 \times 74.35]V + [2 \times 0.53]V + \\ \quad 4V_D - 1309.97V = 0 \\ V_D = \frac{1306.66V - 1309.97V}{4} \\ = -0.82V \end{array} \right. \quad (17)$$

$$I_D = 2.53A - 2.35A = 0.18A \quad (18)$$

The theoretically calculated $T - V_{o,t}$ and $T - P_{o,t}$ are 1299.61 V and 3347.72 W (calculated by Eqs. (19) and (20), whereas the experimental values of $T - V_{o,e}$ and $T - P_{o,e}$ are 1303.65 V and 3299.82 W (calculated by Eqs. (21) and (22)). The experimental results of the considered 4×4 series configuration under long-and-narrow shading pattern are shown in Fig. 10. The comparative values of both the theoretical and experimental results of the considered PV system under long-and-narrow shading pattern are represented in Table III.

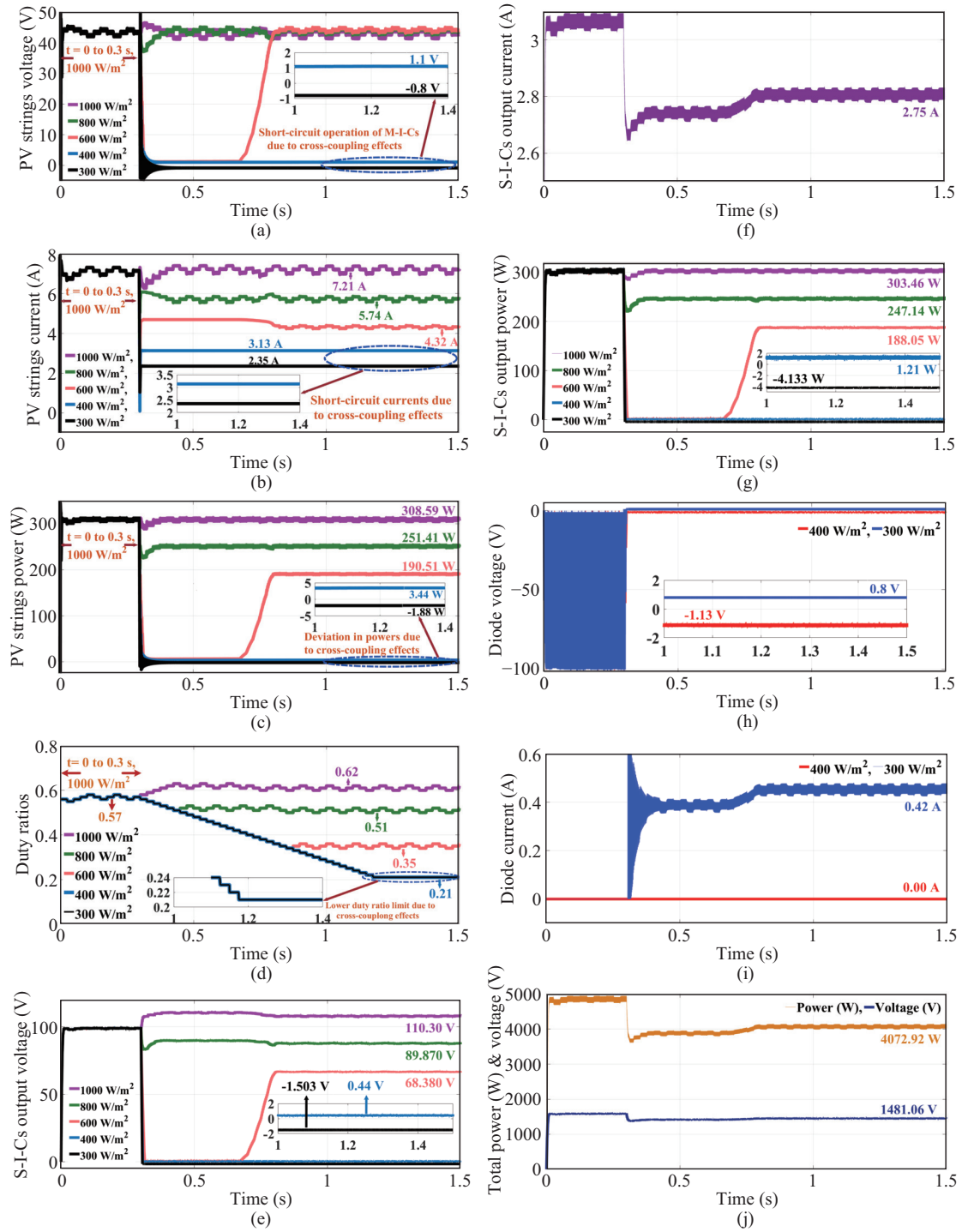


Fig. 9. Experimental results of the 4×4 series configured system under uneven-row, uneven-column, and diagonal shading patterns. (a) Voltage of PV strings, (b) Current of PV strings, (c) Powers of PV string, (d) Duty-ratios, (e) S-I-Cs output voltage, (f) S-I-Cs output current, (g) S-I-Cs output power, (h) voltage across the body diodes, (i) current through the body diodes, and (j) total output voltage and power.

TABLE II
THEORETICAL AND EXPERIMENTAL FINDINGS UNDER DIFFERENT UNIFORM INSOLATION LEVELS OF S-I-Cs SERIES CONFIGURATION

Irradiance	V_{mp} (V)	I_{mp} (A)	P_{mp} (W)	D	V_o (V)		I_o (A)		P_o (W)	
					t	e	t	e	t	e
1000	42.80	7.21	308.59	0.64	118.88	120.19	2.59	2.53	307.89	304.10
800	43.79	5.74	251.51	0.56	99.20	97.69	2.53	2.53	250.98	247.15
600	44.09	4.32	190.51	0.41	74.73	74.35	2.54	2.53	189.81	188.85
400	1.10	3.13	3.44	0.21	1.37	0.54	2.48	2.53	3.39	1.31
300	-0.8	2.35	-1.88	0.21	-1.01	-1.503	1.86	2.53	-1.88	-3.81

TABLE III
THEORETICAL AND EXPERIMENTAL FINDINGS OF S-I-Cs SERIES CONFIGURATION UNDER L-A-N SHADING PATTERN

Irradiance	V_{mp} (V)	I_{mp} (A)	P_{mp} (W)	D	V_o (V)		I_o (A)		P_o (W)	
					t	e	t	e	t	e
1000	42.80	7.21	308.59	0.64	118.88	120.19	2.59	2.53	307.89	304.10
800	43.79	5.74	251.51	0.56	99.20	97.69	2.53	2.53	250.98	247.15
600	44.09	4.32	190.51	0.41	74.73	74.35	2.54	2.53	189.81	188.85
400	1.10	3.13	3.44	0.21	1.37	0.53	2.48	2.53	3.39	1.31
300	-0.8	2.35	-1.88	0.21	-1.01	-1.503	1.86	2.53	-1.88	-3.81

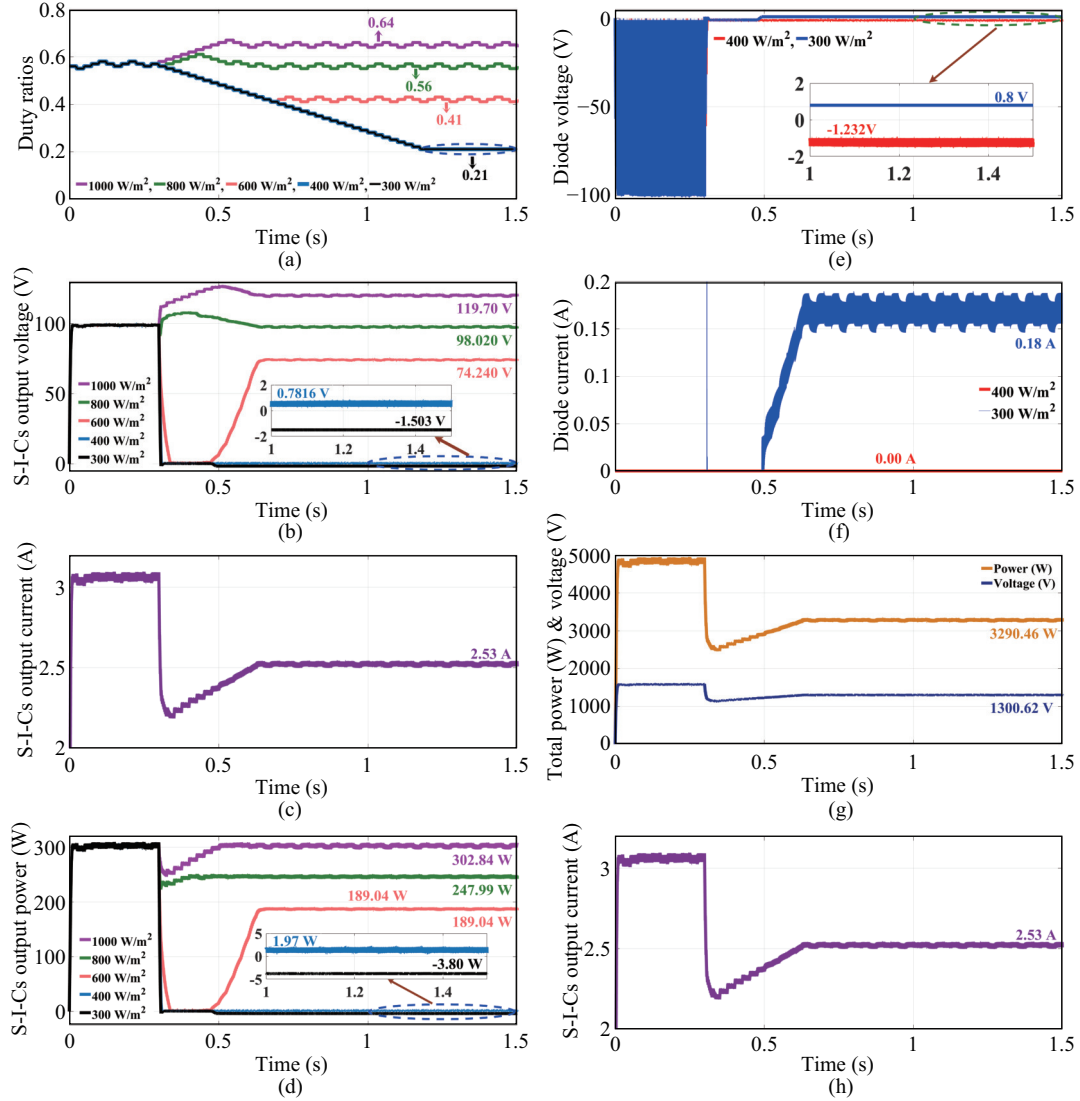


Fig. 10. Experimental results of the 4×4 series configured system under L-A-N shading pattern. (a) Duty-ratios, (b) S-I-Cs output voltage, (c) S-I-Cs output current, (d) S-I-Cs output power, (e) voltage across the body diodes, (f) current through the body diodes, and (g) total output voltage and power.

$$\begin{cases} T - V_{o,t} = [8 \times 118.88]V + [2 \times 99.20]V + \\ \quad [2 \times 74.73]V + [2 \times 1.37]V + \\ \quad [2 \times (-1.01)]V \\ = 1299.61V. \end{cases} \quad (19)$$

$$\begin{cases} T - V_{o,e} = [8 \times 120.19]V + [2 \times 97.69]V + \\ \quad [2 \times 74.35]V + [2 \times 0.53]V + \\ \quad [2 \times (-1.503)]V \\ = 1303.65V. \end{cases} \quad (20)$$

$$\begin{cases} T - P_{o,t} = [8 \times 307.8]W + [2 \times 250.9]W + \\ \quad [2 \times 189.8]W + [2 \times 3.39]W + \\ \quad [2 \times (-1.88)]W \\ = 3347.72W. \end{cases} \quad (21)$$

$$\begin{cases} T - P_{o,e} = [8 \times 304.1]W + [2 \times 247.1]W + \\ \quad [2 \times 188.8]W + [2 \times 1.31]W + \\ \quad [2 \times (-3.80)]W \\ = 3299.82W. \end{cases} \quad (22)$$

From the experimental results shown in Figs. 9 and 10, we are in-detailly analyzed the cross-coupling effects present in the S-I-Cs series configuration. The experimental results are also mathematically analysed and validated. Under cross-coupling effects, we are observed that the S-I-Cs are consuming the power instead of transferring to the load from PV strings. At this condition, the MOSFET switch's internal body diode is operating like an anti-parallel bypass diode connected to a PV module. It is also observed that the unshaded PV S-I-Cs are producing the over-voltage and over-currents at the S-I-Cs output and input terminals.

VII. ACKNOWLEDGEMENT

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VIII. CONCLUSION

In this research paper, we have presented the PV module two-diode model, design of non-isolated DC-DC boost type of S-I-C, and the implementation of direct duty-ratio control P&O MPPT technique. This paper also presents a clear, comprehensive and mathematical analysis on the existence of cross-couplings in the S-I-Cs series configuration. The effect of cross-couplings on the consider PV system is also explained. The experimental results are also validated with the mathematically analysed results. In S-I-Cs series configuration under PSCS, we observed that the S-I-Cs which are receiving the lowest insolation (whose operating current is less than the output current of the system) are cross-coupled and operates under short-circuit current region (and also in the negative voltage region) to equalize the output current same as the non-cross coupled S-I-Cs (un-shaded S-I-Cs) because of the series configuration. At this condition, the M-P-P operation of the cross-coupled PV S-I-Cs is lost, which also affects the M-P-P operation the non-cross coupled PV strings. The internal body diode of the MOSFET switch is forward biased and begins to conduct in order to facilitate the flow of the same amount of output current in the cross-coupled S-I-Cs equivalent to the non-cross coupled S-I-Cs. At this condition, the cross-coupled S-I-C, instead of delivering power to the load, it will consumes the power. Under cross-coupling effects, the over-current protection required at the input, whereas the over-voltage protection needed at output terminals of S-I-C.

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