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An Interpretative Review on Partial Shading Mitigation Techniques For Solar PV System

1st
Apeksha.Sonone
M.E (EPS)
Department of Electrical Engineering
Dr.Sau.Kamaltai Gawai Institute Of Engineering And Technology
Darayapur,Amravati,Maharastra 444814

2nd
Prof.N.A.Bodkhe
Assistant Professor
Department of Electrical Engineering
Dr.Sau.Kamaltai Gawai Institute Of Engineering And Technology
Darayapur,Amravati,Maharastra 444814

ABSTRACT
The ways to limit the effect of partial shading for PV systems (basically the grid-connected) are considered for an evaluator review in this work. It includes a module-level solution, other techniques, and several partial shade mitigation solutions. The former improves the energy yield by optimizing each module's power extraction capabilities. Three approaches (stated later in the paper) are taken into consideration and are discussed here. These approaches are basic module-level tactics for partial shading mitigation. This paper focuses on problem trends due to partial shading, few of maximum power point tracking techniques, and feasible solutions involved in partial shading mitigation.

Keywords
Partial Shading (PS), Micro-Inverter (MI), Power Optimizer (PO), Energy Recovery Circuit (ERC).

1. INTRODUCTION
Concerns about environmental consequences of fossil fuel-related global warming have sparked a surge in the use of sustainable/renewable sources of energy. Solar energy, particularly PV electricity is expected as one of the most efficient sources based on the availability and previous current trends. Various PV energy harvesting systems have been used to date, but the GCPV i.e., Grid-Connected PV System seems more economical and cost-effective approach. When sunlight is available in plenty amount, the generated energy (excess power) is sold to the utilities and with unavailability of sun or the sunlight, the entire system is overtaken by grid and is powered by grid itself [1]. Now a days, with continuous reduction in the cost of modules and inverters, the building of PV system is more economical compare to earlier scenario. Furthermore, hefty government incentives could result in significant increase in GCPV installations. The PV modules are connected in either series or parallel.

Strings are formed when these modules are connected in series. With several strings when are connected in parallel to form a series/parallel (SP) array which is used for boosting power. Further, for sharing the generated power to the grid a centralized AC/DC converter is utilized in the system. For the big systems i.e., above 100 kW the benefits pf a central inverter system is increasingly obvious [3,4]. For low to the medium power rating i.e., 1 to 10 kW such centralized string inverter is better option and is economical too. The multi-string inverter may also be used to accommodate strings of modules with varied orientations. Building integrated PV is one of the GCPV versions, is commonly used in metropolitan settings. The availability of rooftop areas on which to install BIPV systems provides a practical alternative to ground-mounted systems.

The BIPV, on the other hand, is thought to be underperforming; the major reason for this phenomenon is called as partial shading. This is a one-of-a-kind mismatch circumstance in which only selected sections are shaded while the rest of array/string is evenly irradiated. Partial shade BIPV system us often produced by shadow cast by surrounding structures, such as buildings, telephone/transmission poles, chimneys and trees. Figure 1 [5,6] shows examples of common partial shade events for rooftop BIPV systems. Because of the high population density, structures in metropolitan areas must be built near to one another, worsening partial shadowing even further Partial shadowing, is primary reason of lower energy production, according to several studies [7,8]. In many cases shading causes inverse loss in generation i.e., around 50% power is loss to overcome 9% of partial shading [9]. Furthermore, the shading caused hot spots to appear in the shaded module. Module ageing is influenced significantly by the inherent temperature increase. Corrosion, EVA discoloration, module delamination, solder bond deterioration, module delamination, fractures, EVA discoloration and bypass diode failures are some of the other adverse effects of hot spots. The difficulty in tracking the global peak can be overcome with the use of enhanced MPPT based metaheuristic algorithms that has recently been developed [10-13].

Differential evolution such as, grey wolf optimization, artificial bee colony, flower optimization, Jaya algorithm, flashing firefly [14] are some of the effective strategies. The ultimate goal is to kindly observe each of the peak until the global peak is found. It's worth noting that the modules may still generate electricity even with lower irradiations. The diodes (bypassed) which when short circuits the partially shaded module, prevents power from being extracted. This accessible energy may be harnessed to a degree by hardware intervention. For the extraction, a variety of procedures were tried, which were divided into two categories. The first is a module-level method and second is array level technique. In first, each module is permitted to involved in energy harvesting. The micro-inverter (mi), power-optimizer (po), and energy recovery circuit (erc) are examples of devices that can accomplish this function. The goal of second procedure is to reduce the effect of partial shading by changing module placements inside the array. The placements of modules are set by observing the shade pattern throughout the year.

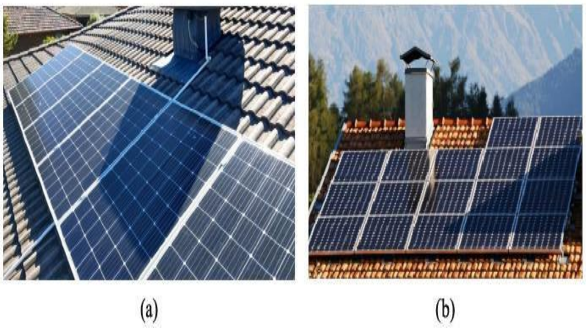

Fig. 1: Shaded panels on rooftop (a) due to chimney (b) due to large structure

The solutions drawn (hardware) has spawned slew of research, based on an examination, it appears that relatively few articles have been produced on this area despite the substantial amount of research done in decades. This is contradictory to the solutions drawn using software where several authors do detailed evaluations at regular periods [15-19]. Despite the fact that there are multiple review articles on micro-inverters use [20-23], the emphasis is on topologies only as the results, other factors were underserved. On the other side, there are number of evaluations on GCPV converter topologies, such as [24] but none of them are focused to partial shading problems and mitigation.

Furthermore, assessment should give a broader picture of the problem, taking into consideration non-technical factors such as cost, product development and market trends. This will provide a PV system designer a more complete picture of the options available. Several preliminaries are offered for the advantages of newcomers to this topic, including the notion of partial shading, its origins and consequences, and the difficulties of solving this problem with software solutions. This paper is having more emphasis on detailed review of partial shading and few of the acknowledged mitigation solutions based on number of key works done.

2. Partial Shading and MPPT Methods

Apart from the typical factors such as overcast skies, the partial shade is a common condition in most of the residential installation due to nearby buildings, trees, and several other structures in surrounding vicinity. Bypass diodes are used to safeguard the different cell strings in a PV module; when shadow affects certain cells in PV module's string, the voltage in those cells drops and they begin to absorb power: this causes their temperature to rise and can cause hot spot which can destroy the PV module. If this occurs, the bypass diode in the shaded string is activated, conducting all current and preventing the shaded cells from sinking any power. The PV module is protected from hot spots in this method, but the power generated by the string's non-shaded cells is lost since the diode bypasses the whole string.

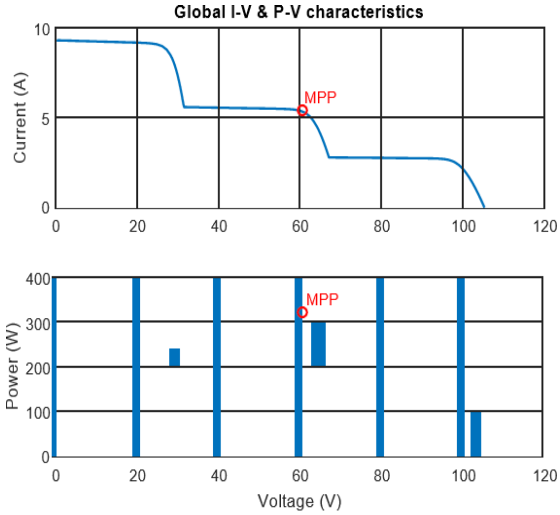

Fig. 2: PV modules with different irradiance (3-local maximum and 1 global maximum

Figure 2 depicts three PV modules with various irradiance simulating partial shading in three distinct stages of a PV module; if partial shading does not occur, there is just one maximum point as can be seen in figure 3. The appearance of these extra maxima might throw the MPP tracking off: most of the algorithms are unable to recognize which of the local maxima are approaching and so can become trapped in one of them without reaching the global maximum i.e., MPP. An overview of many of the most often utilized MPPT approaches is shown in above figure. However, when it comes to partial shading, just a few of them are sufficient. Most of the MPPT tactics can only discover local maximum, therefore there is no guarantee that they will attain the global MPP.

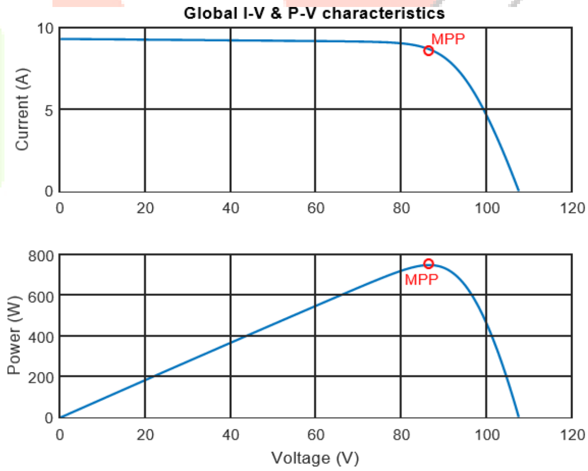

Fig. 3: Three series PV modules with only one maximum point

Current sweep technique, two stage incremental conductance and one-cycle MPPT are all valid ways for tracking the global MPP under partial shade circumstances.

A. Two Step InC Method

The method is general outcome of the derivatives of the P-V characteristics of PV module where,

$dP/dV > 0$ at the left of MPP

$dP/dV = 0$ at the MPP

$dP/dV < 0$ at the right of MPP

Given that,

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V}$$

Or,

$\Delta I/\Delta V > -I/V$ at the left of MPP

$\Delta I/\Delta V = -I/V$ at the MPP

$\Delta I/\Delta V < -I/V$ at the right of MPP

On comparing the instantaneous-conductance (I/V) to the incremental-conductance ($\Delta I/\Delta V$), the MPP can be traced. The two-step incremental conductance method employs a more complex algorithm that, by monitoring the PV modules, the open circuit voltage and also the short circuit current allows for the location of the global MPP before executing the standard IC algorithm. This is accomplished by calculating a load resistance close to the optimal one, allowing the standard conductance algorithm to begin in the global MPP.

B. Current Sweep Approach

This approach methodology entails computing the PV modules I-V curve at regular intervals (as depicted in figure 2) of time and deriving the voltage corresponding to the MPP from it which later referred as VMPP. It takes around 50ms to finish the procedure in which the converters functioning is halted, that is, there is no power output. Because of this inconvenient, a minimum power threshold is required to activate the MPP tracker below this level. The trackers power gain is less compared to the power lost when the converter is turned off.

C. One Cycle Control Method

As can be seen in figure 4, this approach is employed with a single stage inverter that performs MPPT and regulates thee output current. Similarly, figure 5 depicts the one-cycle control system. the MPPT is calculated using an arrangement based on various experimentally determined constants for each installation. This approach was created to accomplish instantaneous control of the average value of the switched parameters, but it is changed in this approach to achieve MPPT and current output control.

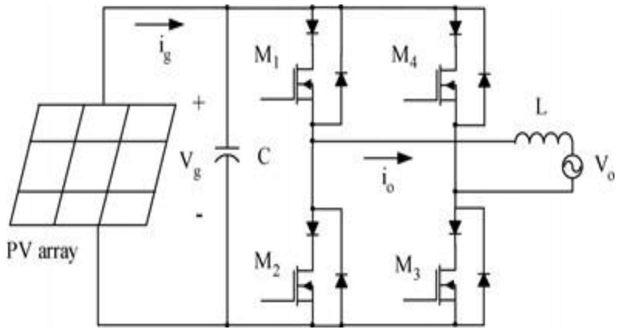

Fig. 4: OCC method (inverter power stage)

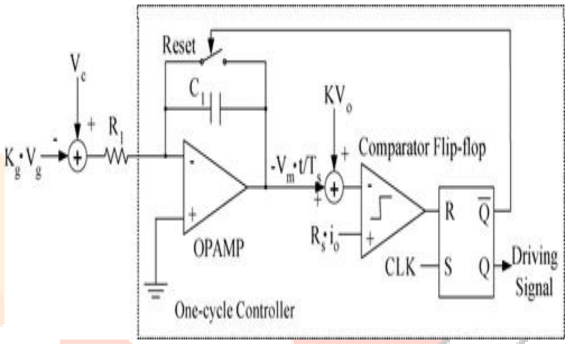

Fig. 5: OCC method for MPPT implementation

3. Module level tactics

A. Micro-inverter

The micro-inverter, in the context of a GCPV system, essentially performs the same tasks as a regular string inverter but in a more compact form. The key distinction is that the micro-inverter is linked one-to-one to the module, while the output feeds the low voltage AC grid directly. The micro-inverter device is now integrated with the module by a number of manufacturers and the combined hardware is supplied as a complete unit [25-26]. Figure 6 depicts the typical micro-inverter connected to GCPV system [26]. As can be seen, the modules are scattered, meaning they are not all connected in the same way. Each of them has their own MPPT allowing each device's output power to be adjusted individually. The key advantage of this setup is that if one module has a problem of shading, it will surely not affect the other modules because they are not directly connected. Another benefit is its independence; because each micro-inverter is self-contained the system may be made up of modules/inverters with varied electrical characteristics of manufacturers.

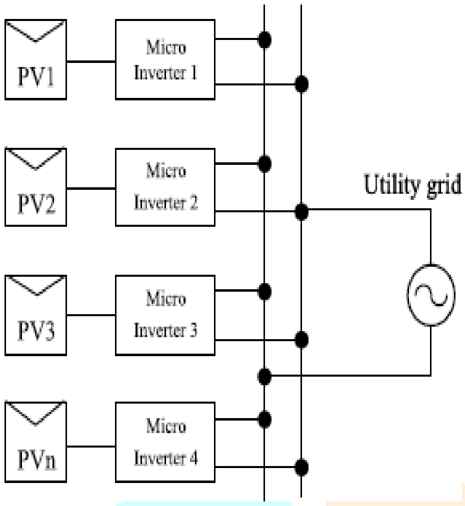

Fig. 6: A micro-inverter connected to GCPV

Figure 6 depicts the typical micro-inverter connected to GCPV system [26]. As can be seen, the modules are scattered, meaning they are not all connected in the same way. Each of them has their own MPPT allowing each device's output power to be adjusted individually. The key advantage of this setup is that if one module has a problem of shading, it will surely not affect the other modules because they are not directly connected. Another benefit is its independence; because each micro-inverter is self-contained the system may be made up of modules/inverters with varied electrical characteristics of manufacturers.

It also gets rid of the typical string's single point of failure. Overall safety is improved due to reduced installation DC voltages. Due to the high DC voltage, the strings system, but at the other hand, is prone to arching and fire. Micro-inverters are distinguished from string or centralized inverters by their ability to harvest energy from a single module without affecting other module in the system [27-28]. Let's say PV1 is shaded in Figure 6, but the other modules in the system are unaffected, and vice versa. As a consequence, the entire energy of the shaded module is gathered and sent to the grid. Furthermore, because the module does not create a string, there is no risk of a hotspot. Traditional MPPT, also known as P&O, is used by the majority of micro-inverters. The method's simplicity and speedy convergence to GP are the main reasons for choosing it. In addition, because partial shading is no longer an issue for micro-inverters, sophisticated MPPT techniques such as metaheuristic search are no longer required. However, due to the low input voltage, a step-up device is expected to assemble to the grid.

- ***Important micro-inverter connections*.**

The flyback converter depicted in figure 7 is the backbone for drawing the most common micro-inverter circuit.

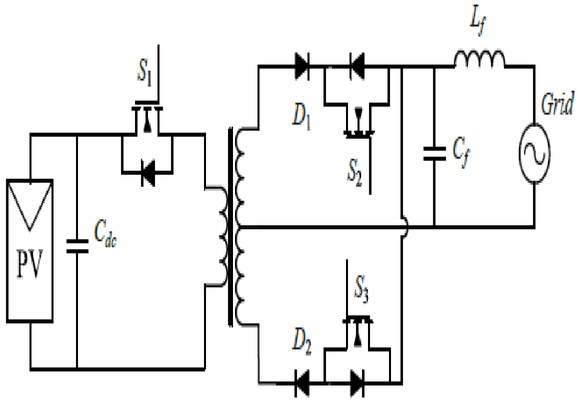

Fig. 7: Flyback converter for isolated micro-inverter.

Three power electronics switches basically MOSFETs and two diodes are used to construct the circuit. MPPT achieves power-voltage matching by modulating the DC voltage into a rectified sinusoidal with S1. The rectified output waveform is unfurled on the secondary side of the transformer using a polarity inversion circuit. The harmonics component of the modulated waveform is then removed using a low pass LC filter. Finally, the grid receives the sinusoidal current. Several flyback circuits are linked in parallel to boost the power rating of main circuitry [29]. On the similar ground figure 8 & 9 shows the micro-inverter circuit using a high frequency transformer and micro-inverter circuit without using any transformer respectively.

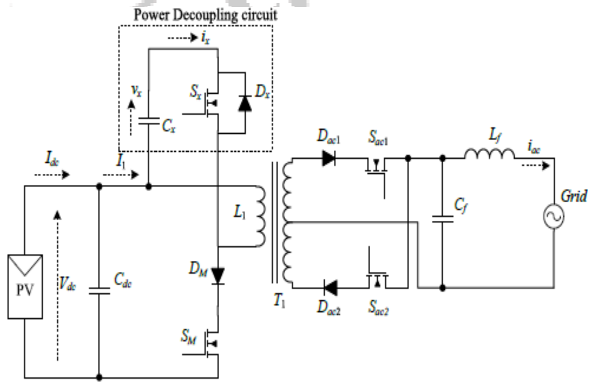

Fig. 8: micro-inverter using high frequency transformer

Here, the absence of transformer plays two major roles i.e., the circuit is free from galvanic isolation and it helps in generating/creating a common voltage mode. In addition to lowering the output quality, leakage current increases losses and exacerbates electromagnetic interference [29].

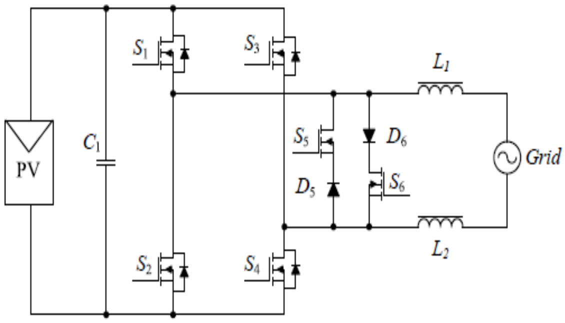

Fig.9: micro-inverter circuit without transformer.

B. Power Optimizer

The power optimizer, also known as a DC-DC converter, is a converter that sits between the module and the string inverter [30-31]. Its primary goal is to boost the system's energy extraction by doing specific MPP tracking for the module to which it is connected. The typical power optimizer is linked to a single module whose output is later linked in series with the several additional devices.

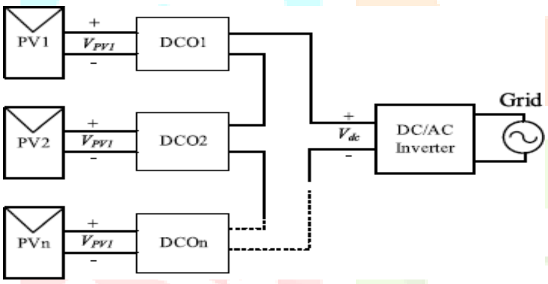

Fig. 10: Power optimizer with series connected output port

This series interconnections output is summed and supplied to the inverter. The arrangement of the power optimizer differs from that of the micro-inverter, as the output is directly linked to the grid. It permits the inverter to handle partial shade conditions more successfully in particular [32-33]. Because the inverters input terminal is accessible for DC connectivity, this layout is also ideal for systems that incorporate batteries. The popular non-isolated topologies such as, boost, buck, buck-boost are commonly utilized for DC-Dc conversion [32-37]. To match the current of the non-shaded modules in the string, the buck-based device reduces the shaded module's output voltage while increasing its output current. As a result, it works best when the shading affects a limited number of modules.

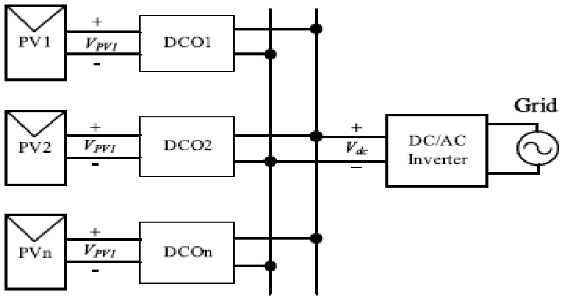

Fig. 11: Optimizer with parallel connected output port

The boost optimizer on the other had raises the module voltage to meet the voltage requested by the string inverter. The buck-boost power optimizer is more versatile, it may reduce or raise the module's output voltage as shown in figure 10. The series interconnectivity is what it called, in this situation, the series connected power optimizers total voltage must be consistent with the inverters input voltage window. The parallel connectivity as shown in figure 11 is another alternative layout. The gain ratio is set high enough to match the inverters input voltage in this case. Due to reduced conversion efficiency, such a scenario is not suitable for a typical boost converter [38].

New designs incorporate compliance between both the power optimizer and the inverter, so that if one of the module outputs drops, the inverter automatically changes the result of many other optimization techniques, leading in a little increase in total voltage. In this way, a constant voltage at the inverter input may be maintained. However, because such a technique requires the use of a single manufacturer for both the inverter and the optimizer, retrofitting alternatives are limited. Smart modules, which have the power optimizer device inserted into the junction box during manufacture [39-40], are another advancement. Smart modules make installation easier, increase safety, and give monitoring at the module level. Furthermore, certain versions have a detachable power optimizer that makes maintenance a breeze.

- ***Important Topologies***

Since the single-phase DC to DC converter gain is limited, most power optimizers are coupled in series. Figure 12 depicts the converter-based device. The primary construction, as can be seen from figure is a standard DC to DC converter with an incorporated MPPT block. The fundamental circuit is interleaved to enhance its power rating. Low output voltage ripple and the ability to use lower-rated switches are two more advantages of the interleave configuration.

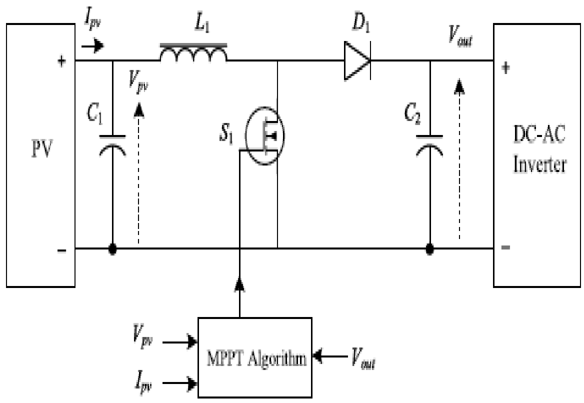

Fig. 12: Boost type power optimizer

The series architecture has one major drawback: the power optimizer must be able to tolerate significant voltage and current stress during partial shading, necessitating the use of higher rated converter switches [41]. The power optimizer is connected in parallel to overcome these constraints. However, as previously stated, parallel connection necessitates a high gain ratio, which necessitates a duty cycle of the converter that is close to unity. As a result, the turn-off period must be extremely brief, resulting in a significant increase in conduction losses [42]. To ensure voltage compatibility, the parallel-type power optimizer gain must be raised to match the string inverters input voltage. A high frequency transformer is often used for such combination. Normally, a hard switching PWM is utilized for the bridge, however soft switching approaches are commonly employed to decrease switching losses [43]. The impulse current present at the input side is one of the challenges that the bridge circuit has to deal with [44]. A big size capacitor is necessary to lessen the amplitude of the ripple. The electrolytic capacitor is required in most design [45,46]. To attain a high gain ratio, a non-isolated boost converter with linked inductor can also be used [47]. The couple indictor is used in combination with a double-phase interleaved boost converter in this manner. The charge pump technique [48] is used in another strategy to attain the high gain of the converter.

C. Energy recovery circuit

The idea of energy recovery is to redistribute energy out from quasi module towards the shaded module. This is done again and again until the two energy levels are precisely the same. In principle, the circuit may be retrofitted into a current string inverter system. In the vast majority of cases, energy recovery comprises the steps below:

a) Turning off the diode bypass
b) Redirecting the energy through PE Switches.
c) Energy Storage in temporary devices
d) Re-entering the system with the stored energy.

Since, the majority of prototypes are only tested in the lab, there are no goods on the market. The potential of this remedy, on the other hand, is admirable. The power equalization and voltage feedback are the most well-known recovery strategies; others might be thought of as modifications or expansion of these circuits.

- ***A typical power equalizer technique***

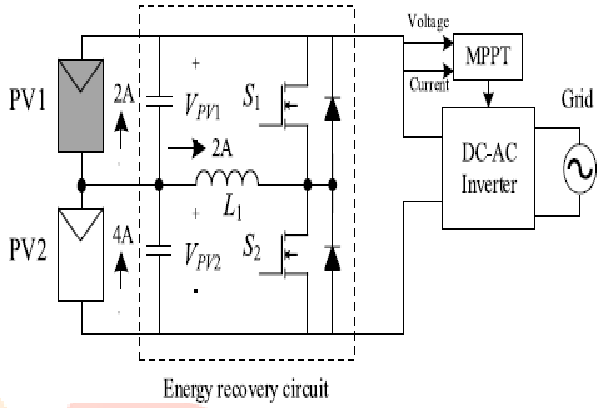

Fig. 13: Energy recovery circuit

The example of energy recovery circuit is depicted in figure 13 [49-50] illustrates the notion of a power equalizer. A string of two modules is utilized in this case, where, PV2 receives full brightness and PV1 is 50% shadowed. The peak current for the former is supposed to be 4 Ampere, whereas the peak current for the later is expected to be 2 A. As a result, the shaded module limits the string current and only 2 A is transmitted to the inverter. PV1 will be short circuited in a typical bypass diode arrangement and 4 A current from PV2 will be routed through diode. No power can be generated/recovered from PV1 since the voltage across it is zero. We can say that, despite the fact that PV1 can generate 50% of its capacity, it is completely ignores. The current from PV2 is separated into two halves when the energy recovery circuit is connected to the modules. The remaining 2A is pushed to flow away from PV1, while the remaining 2 A is permitted to flow in the string. This is accomplished by turning on the switches S1 and S2 in a complementary manner. L1 stores the redirected current as temporary energy. Furthermore, by setting the duty cycle to 50%, the current is split evenly between S1 and S2 resulting in each conducting 1A. Now, 3 A will enter the inverter instead of 2 A for bypass diode. This means that, despite being shaded, this module is permitted to contribute actively to the output power.

4. Conclusion

Numerous references have been studied and following conclusion is drawn for impact and mitigation for partial shading in PV system. The Micro-Inverter can be opted as the efficient option in power boosting output during partial shading because of its dispersed nature and MPPT. The power optimizer can be used in conjunction with the string inverter to achieve the same goal. Other benefits of these devices are their installation flexibility, ability to shut down quickly, and ease of device-level monitoring. It's worth noting that shade changes, length, intensity, and pattern have a big influence on the final result. It has been shown that if there is no shade, employing these devices may be counterproductive due to ongoing power use, which might counteract the extra energy gained. The energy recovery circuit, on the other hand, appears to work better in this circumstance since it is entirely turned off and so does not drain any power from the module. Although dynamic array reconfiguration is theoretically preferable to module- level options, identifying the appropriate switching pattern for maximum power output remains a challenge. Most of the time, sacrifices must be taken in order to reduce the switching's computational cost and complexity.

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