STUDY ON MPP MISMATCH LOSSES IN PHOTOVOLTAIC APPLICATIONS

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ABSTRACT: One of the major sources of losses in a photovoltaic (PV) system is the mismatch between the amounts of energy generated by two or more modules inside an array. This mismatch can be caused for instance by partial shading of the modules. This paper investigates the performance decrease of PV-modules under non-optimal irradiance conditions, and also some techniques used to mitigate this problem. Firstly, mathematical modeling of the PV module is simulated under different level of shading. Performance comparison is done between PV string configuration and those based on module level MPP tracking units in terms of mismatch losses. Further, promising technologies which increase the efficiency and reliability of such systems under mismatch conditions such as active bypass, AC-Modules and power optimizers are discussed.

Keywords: Maximum Power Point (MPP), Mismatch Losses, AC-Modules

1. INTRODUCTION

Photovoltaic modules are connected in series and parallel in order to match the requirements regarding DC voltage and current of the inverter input [1]. The total DC power in such network is, however lower than the sum of the individual rated power of each module. The main reasons are static mismatch, environmental stress and shadow problems. The first aspect is related to manufacturing tolerances and aging of the module connected in the array. The second aspect instead refers to the effect of module defects due to weather conditions [2] [12]. Dynamic mismatches occurs when the modules operates far from its maximum power point. The PV modules connected in parallel or in series can not operate in their individual maximum power point because the voltage (in case of parallel connection) or current (in case of series connection) is forced to be equal in all the modules of the string [3].

Solar PV arrays are susceptible to large amounts of energy losses, due to partial shading. Partial shading is caused by light barriers like trees, chimneys, roof obstructions, power lines, debris, dust and bird droppings. In addition, mismatching can also occur if the photovoltaic modules are installed in different orientation or tilt. When it comes to series connected strings, the current of the solar array is only as strong as the weakest-performing panel and this can reduce the solar array efficiency significantly [10] [11]. The MPP mismatch caused by shading is the main subject of the present work. The paper presents a study on this problem, and on the techniques which can be used to mitigate the performance decrease of the photovoltaic system.

When part of the panel is shaded, the shaded cells will produce less current than the non-shaded cells. Since all cells are connected in series, the same amount of current must flow through every cell. The non-shaded cells will force the shaded cell to pass more current than its new short circuit current. The shaded cell operates in reverse bias region to match this condition and cause a power loss to the system. The product of the current and negative voltage gives the power dissipated by the shaded cells. This power is dissipated as heat and hence, causes ‘hot spots’. The probability that some cells in module or some modules in the string are potentially able to deliver strongly different currents in operating conditions is very high [12] and can not be neglected. Hence, it is important to study mismatch effect in PV applications.

The PV plant can be connected to grid via three different DC/AC inverters system configuration namely, central inverter, (multi-)string inverter and module integrated inverter [1]. In large PV system (>10 kW) the large number of PV modules are connected to strings, while these strings are connected in parallel via string diodes or string fuses. The PV generator structured like this is then connected to DC input of one of the central inverter. Central inverters are characterized by high efficiency and lowest specific costs. However, the energy yield of the PV plant decreases due to the module mismatching and partial shading conditions [7]. Moreover the reliability is limited as whole system is dependent on single power conditioner. In (multi-) string inverter just as with central inverters the PV array is divided into strings. Each of these strings is assigned to their own inverter, called string inverter. Each string operates at its individual (maximum power point) MPP and hence partly minimizes mismatching, reduces losses resulting from shading and avoids losses due to the string diodes and large scale DC-cabling compared to central inverter. The third type, also called AC-modules has individual MPP tracking system for each module and many additional system advantages to the state of the art system. Sometimes, Power optimizers such as distributed maximum power point tracking (DMPPT) are also used to get maximum possible power output from PV plant.

To study mismatch losses, mathematical modelling is done for the PV system and the simulation has been performed using MATLAB® environment. Further, the effects of partial shading with and without bypass diodes are investigated. Then, the performance of state of the art string inverter system is compared with module based

MPPT. Finally, for mismatch losses reduction promising technologies such as active bypass, AC-Modules and power optimizers (DMPPT) are discussed.

2. MATHEMATICAL MODELLING

The electrical equivalent circuit of a solar cell is commonly represented by two diodes model [4].

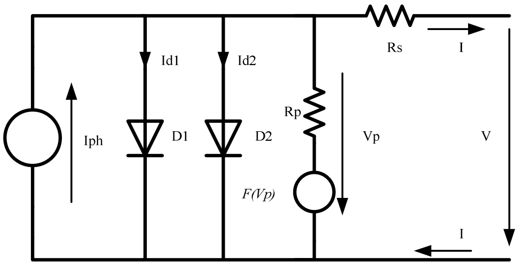


Fig. 1 Electrical equivalent of solar cell

2.1 Forward Characteristics

The forward characteristics of solar cells can be represented by following equation obtained from applying Kirchhoff's law in the two diode equivalent circuit of solar cell.

$$I = I_{ph} - I_{01}\left[\exp\left\{q\frac{(V+IR_s)}{n_1 kT}\right\}-1\right] - I_{02}\left[\exp\left\{q\frac{(V+IR_s)}{n_2 kT}\right\}-1\right]\frac{(V+IR_s)}{R_p} \quad (1)$$

Where, k is Boltzmann's constant, q is electronic charge, n_1 and n_2 are ideality factor of diodes, I_{01} and I_{02} are diode saturation currents which are function of cube of temperature, T is cell temperature, R_s is series resistance, R_p is parallel resistance and I_{ph} is photo-generated current. The single diode equation assumes a constant value for the ideality factor. In reality the ideality factor is a function of voltage across the device. At high voltage, when the recombination in the device is dominated by the surfaces and the bulk regions the ideality factor (n_1) is close to one. However at lower voltages, recombination in the junction dominates and the ideality factor (n_2) approaches two. The junction recombination is modeled by adding a second diode in parallel with the first and setting the ideality factor typically to two. The two-diode model is derived from the physics of the p-n junction, especially those of poly crystalline silicon. Amorphous silicon doesn't exhibit a sharp knee in the curve, and thus the model containing only one diode is more appropriate for it. [8]

Inside a PV module, the cells are connected in series to increase the voltage. Several of these series string of cells may be connected together in parallel to increase current as well. Significant amount of solar irradiation is blocked and filtered by atmosphere, dust particles and clouds [7]. The amount of insolation is never constant and it may vary from modules to modules in the PV array field. This causes the I-V curves and hence MPPs of PV module to change as well as shown in fig.2. Further, the cell temperature variation causes significant change in open circuit voltage and causes MPP to change significantly along voltage-axis. This phenomenon can cause significant MPP mismatch losses.

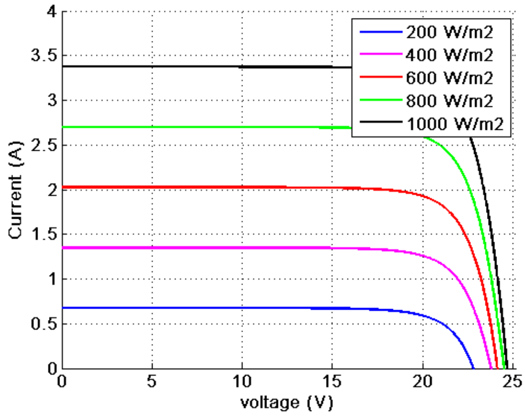


Fig. 2 Effect of irradiance in I-V characteristics (25°C)

2.2 Reverse Characteristics

In the absence of bypass diodes, if the solar radiation is not uniform across all solar cells in the series connected modules, the mismatching causes the shaded solar cells to be driven into the negative voltage region. This phenomenon of reverse breakdown is not taken in account in two diodes model. Hence, the extension term is added from model of Bishop in equation (2) to describe diode breakdown at high negative voltages [4]. The solar cell can generate around one volt when forward biased but the reverse bias voltage can go as high as twenty volts or even more and can dissipate much more power than it actually produce(fig 3). Hence for partial shading analysis study of reverse characteristics is very much important. The dark I-V or reverse I-V characteristics of solar cell has been modelled using following equation.

$$I = \frac{sI_{ph}}{100} - I_{01}\left[\exp\left\{q\frac{(V+IR_s)}{kT}\right\}-1\right] - I_{02}\left[\exp\left\{q\frac{(V+IR_s)}{2kT}\right\}-1\right] - \frac{(V+IR_s)}{R_p} - a\frac{(V+IR_s)}{R_p}\left(1-\frac{(V+IR_s)}{V_{Br}}\right)^{-n} \quad (2)$$

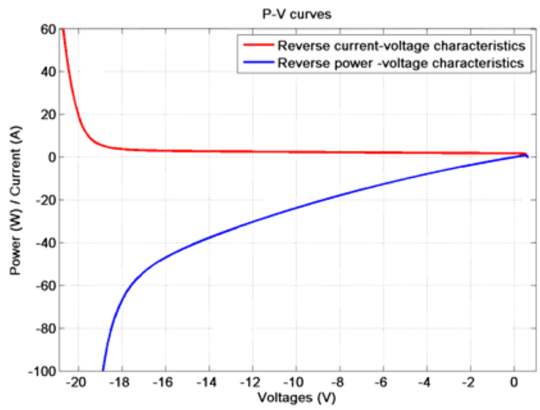


Fig.3 Reverse characteristics of a solar cell.

Where, s is shading percentage, V_{Br} is the solar cell reverse breakdown voltage, a is correction factor and n is avalanche breakdown exponent. Partial shading largely affects the irradiance falling on the cell surfaces, hence can be modelled by adding the shading factor s to reduce photo-generated current as done in equation (2).

3 Mismatch Losses

3.1 Static Mismatch

According to [1] the figure for static mismatch due to manufacturer's tolerance is below 1% for Si-based Modules. For thin film modules the manufacturing tolerances are generally higher. However, the fractional power loss due to manufacturing tolerances is about 2% [2]. Furthermore the effect of aging is investigated. Considering aging the mismatch losses may rise up to 12% in series strings. The studies make clear that the losses may be reduced drastically by means of an appropriate series parallel connections and a pre-selection of the modules. Thus the expected mismatch even in consideration of aging effects is in the range of 0.4 to 2.4%.

3.2. Dynamic Mismatch

3.2.1 without Bypass Diodes

I-V curve of the PV module is affected decisively when solar cells are irradiated at different levels. It is already well known that the energy output decreases dramatically without bypass diodes compared to the lost total irradiation. In order to demonstrate this, the module in which all the 36 solar cells are series connected without bypass diodes and out of which one cell is partially shaded to different levels is simulated. Resultant characteristics of the whole module in partial shading have to be obtained. For this, as the solar cells are connected in series, for the given current the voltage has to be calculated by adding the corresponding voltage of shaded cell and non-shaded 35 cells. The shaded solar cell has significantly narrowed the current path in the module.

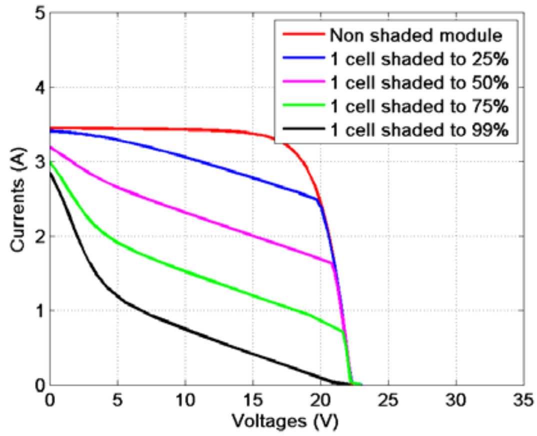


Fig. 4 Effect of partial shading in I-V curves

The partial shading is very dangerous for solar modules as a single cell shading out of 36 or 72 cells module can reduce most of the power output drastically. The shaded cell acts as load, dissipating power on itself which may lead to hot spot conditions and ultimately damages the cells. It is found that with the increase of percentage of single cell shading, mismatch losses increases. When single cell is shaded to 99% (100% shading is not possible because of diffused irradiation) the reduction in irradiance falling on the module is less than 3% but maximum power output in watts is reduced by more than 86%.

In the real world situations more complex shading situation than this can occur and lead to much higher mismatch losses. Further, different number of solar cells shading situation are simulated as shown in fig 5. It has been observed that the power loss because of partial shading is not proportional to the shaded area in the module as it was expected before. As seen in fig 5, with the increase in number of shaded cells, the effect in I-V characteristics is almost constant.

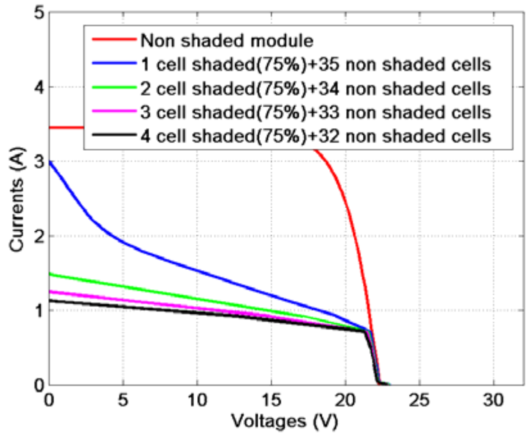
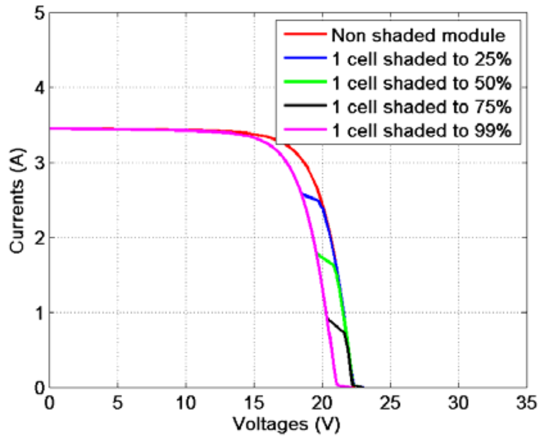


Fig.5 Effect of different number of cells shading

3.2.2 Bypass Diodes

To prevent shadowed cells from narrowing the current path in a string, and downgrading the performance of other cells in series and reducing the power production of the whole string , bypass diodes are usually placed in anti parallel (reverse biased) to small group of series connected cells(normally 18 or 24 cells). Module manufacturers employ bypass diodes to preserve array voltage and to minimize hot spot heating and the potential for cell failure when shaded [7]. For very sophisticated application (example: space applications), bypass diode are used across each cell. However in practice this is avoided because of the cost.



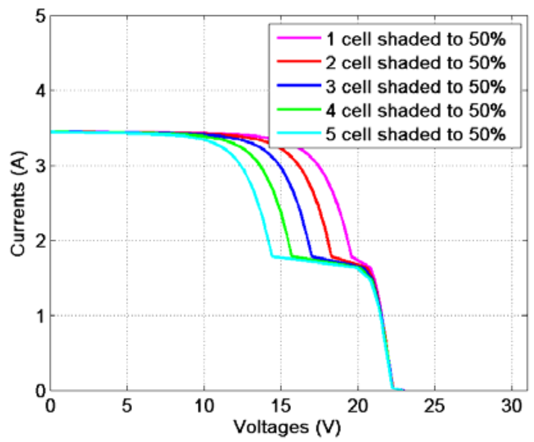


Fig 6.Effect of using bypass diodes across each solar cell

Bypass diodes will allow current to pass around shaded cells and thereby reduce the power losses through the module. When the module becomes shaded the bypass diode becomes forward biased and begins to conduct current through itself. All the current greater than the shaded cells new short circuit current is bypassed through the diode , thus reducing drastically the amount of local heating at the shaded area.

To demonstrate the effect of using bypass diodes across number of series connected cells, the characteristics of 18 cells among which one cell shaded across bypass diode is modelled and series connected to the normal 18 cells. The diode limits the reverse voltage to -0.7 volts and become forward biased as the current in the series connection changes because of shading. It bypasses the photo generated current more than that of shaded cell. The arrangement of bypass diode in solar module is shown in fig 9.

In case of mismatching this measure increases the power production of the PV arrays but introduces multiple local maximum in its power versus voltage characteristics as seen in fig.8, fig.10 and fig.11 which can confuse maximum power point tracking (MPPT) algorithm leading it to lower performances.

3.2.3 Homogeneous Shading

When all the modules in the string do not receive same amount of irradiance, the effect can be termed as homogeneous shading. This phenomenon can occur when different modules connected in series has different tilt angle (for example building integrated PV applications) so that they can receive different irradiation. In this conditions bypass diodes may conduct as the modules in the string have different current. This can cause significant mismatch effect. Further, the power and efficiency of the string will be reduced. To continue further on this discussion 10 series connected modules were considered at operation in homogeneous shading conditions (fig 7). As an example, 6 modules are assumed to have 100% irradiance with MPP of 56.53 W each whereas remaining 4 modules receives only 75% irradiance because of different tilt angle. The MPP power of the shaded string is 460.9 W. Due to this situation shading loss is 18.47% including MPP mismatch loss of 8.95 %. The module based MPPT can harvest more energy than conventional string system because of individual MPP tracking.

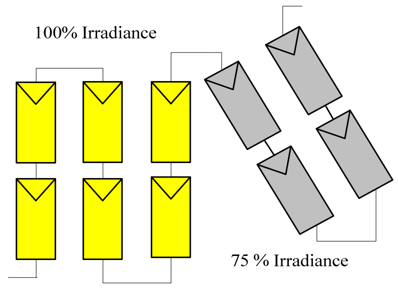


Fig. 7 Homogeneous Shading (different tilt angle)

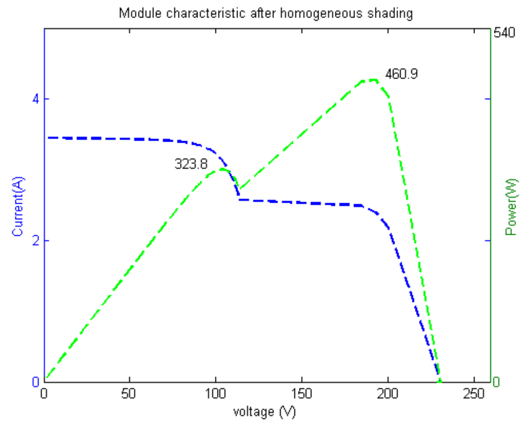


Fig 8: Effect of Homogeneous shading in string (fig.7) characteristics.

Table I: Performance comparison between state of art string configuration and module level MPPT (1 module irradiance reduced homogeneously to 75%)

No. of Modules	MPP of strings (W)	MPP of Module based MPPT (W)	Benefit of Module based MPPT (%)
1	41.74	41.74	0.00
4	188.9	211.33	10.61
6	287.9	324.39	11.25
10	486.1	550.51	11.70

Table II: Performance comparison between state of art string configuration and module level MPPT (4 modules irradiance reduced homogeneously to 75%)

No of Modules	MPP of strings (W)	MPP of Module based MPPT(W)	Benefit of Module based MPPT (%)
4	167	167	0.00
6	268.8	280.06	4.01
10	460.9	506.18	8.95

3.2.3 Partial Shading

Bypass diodes can reduce performance degrading when partial shading occurs. In order to demonstrate this string configuration as shown in fig. 9 is used. The single cell of a module is shaded to 25%. The MPP of this module is 45.61 W. This in turn is series connected to the normal modules having 56.53 W MPP each. When the shaded module is series connected with other non shaded module, additional mismatch losses occurs. The shading effect results in degraded string output because the current of series connected string in module is affected by shaded cell.The interesting phenomenon in fig. 10 is when the 5 modules are connected in series and diode conduct to bypass the shaded cell string, the peak power becomes 252.5 W, which is higher than the value 243 W when all cell strings work together. It means it is more efficient to completely remove the compromised cell than to have it operate at partial capacity and degrade the performance of other cells in string [7]

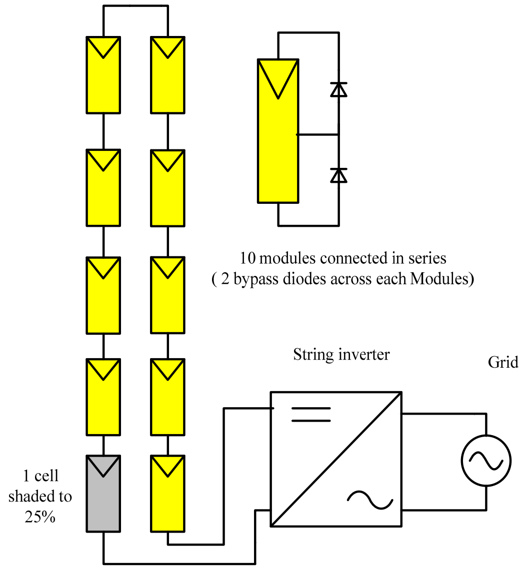


Fig. 9 Series connection of 10 modules

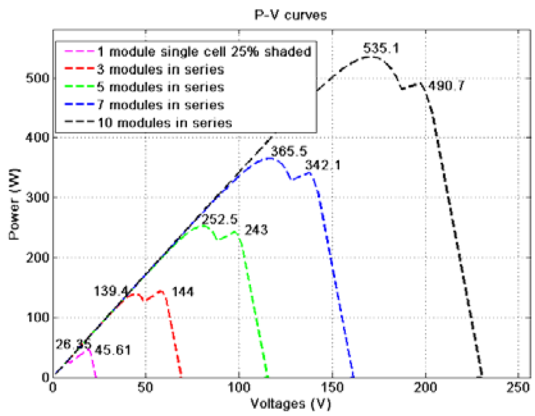


Fig. 10 Effect of partial shading in series connection

Table III: Performance comparison between state of art strings configuration and module based MPPT (one cell of a Module shaded to 25%)

Total No. of Modules	MPP Power of strings (W)	MPP of Module Based MPPT (W)	Benefit of Module Based MPPT (%)
1	45.61	45.61	0
3	144	158.67	9.25
5	252.5	271.73	7.08
7	365.5	384.79	5.01
10	535.1	554.38	3.48

Further, complex shading situation than this is considered. 3 cells of different modules (one cell each) of the string are shaded to 25% and resulting characteristics is shown in fig. 11 and table IV.

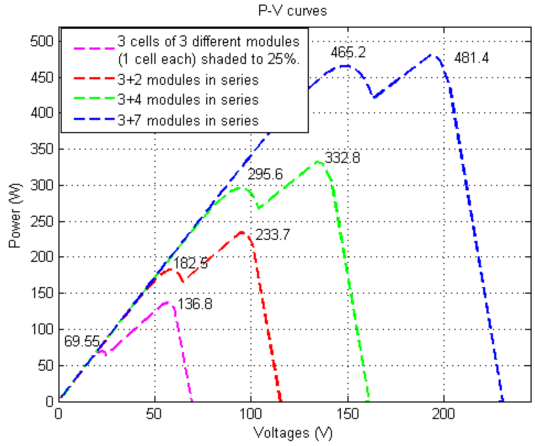


Fig. 11 Effect of Partial shading in series connection

Table IV: Performance comparison between state of art strings configuration and Module based MPPT (3 cell of different Module (1 cell each) shaded to 25%)

Total No. of Modules	MPP Power of strings (W)	MPP of Module based MPPT (W)	Benefit of Module based MPPT (%)
3	136.8	136.8	0
5	233.7	249.86	6.47
7	332.8	362.92	8.30
10	481.4	532.51	9.60

4 DIFFERENT TECHNOLOGIS TO REDUCE MISMATCH LOSSES

4.1 Active Bypass

Though the bypass diodes are advantageous during partial shading conditions, they still have number of disadvantages. The forward voltage of the bypass diodes is usually of the order of 0.5 to 1 Volts and depends on the type, junction temperature and the current. Few problems associated with bypass diodes are excessive heat development due to the forward voltage drop, normal failures, energy losses in the form of leakage currents and failures due to over voltages such as lighting surges, switching surges etc.

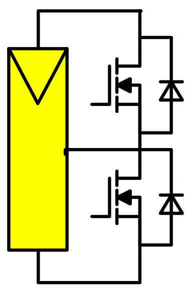


Fig. 12 Active Bypass technology

Spelsberg Photovoltaik have realized diodeless bypass technology which are integrated into a standard connection box (PV 1410-DBT 15) [14], [15]. In the same line active diode of OKE (ADO) is an active electronic smart circuit which can replace bypass diodes in PV-Modules. The maximum voltage drop in these so called smart PV diodes are approximately 0.05 volts resulting in corresponding reduction in heat dissipation [13][15]. These active diodes are extremely thin and can be integrated in PV-laminate. The idea of one-to-one replacement of conventional diodes using MOSFETs as bypass element is presented in [15] (fig 12). Low power will be dissipated as voltage drop is low (mV range). Active bypass can have additional functionalities such as monitoring or active enhanced short circuiting of the module for safety. Monitoring can lead to the optimum power output as each module can be monitored.

With active bypass conduction losses in mismatch situations can be mitigated. The performance comparison of string system with real bypass diode and active bypass element is given in table V for homogeneous shading situations

Table V: Performance comparison between state of art string configuration and module level MPPT
(4 modules irradiance reduced homogeneously to 75%)

No of Modules	MPP of strings (W)	MPP of Active bypass (W)	Benefit of Active bypass (%)
4	167	167	0.00
6	268.8	282.19	4.75
10	460.9	474.29	2.82

4.2 MIC (AC-Modules)

A photovoltaic system achieves the highest output when every solar module is continuously operated at its maximum power point. This can be reached by using module-integrated inverters. In AC-modules the output from the module is AC. As several of these modules can be connected in parallel, it is a modular system [16]. Since the current mismatch has a larger impact on the energy yield than the voltage mismatch, it is to be expected that systems consisting of parallel connected PV-modules have a higher energy yield. Module-integrated inverters lead to higher yields especially with solar modules that are partially shaded or aligned with different angles [9]. Other advantages are that the design of the PV system is more flexible and that it can easily be expanded; in addition, costs for DC wiring do not apply [1].

The performance of AC-modules will be similar to module based MPPT. The additional yield of AC-Modules could be significant under non-ideal operating conditions. However, it must be considered that AC-modules do not avoid shading problem completely.

The potential of AC modules with similar performances and reliability as larger PV systems with central or string inverters is significant [1]. Because of inherent simplicity, the concept will be welcomed by both do-it-yourself installers as well as by architects and construction companies for integration into facades and roofs of houses to be built. This shows that AC-modules can open the new areas of photovoltaic applications in non-coplanar surfaces and automobiles. The cost benefits and additional energy yield of this technology is not quantified explicitly so far though it is extremely important for a successful market introduction and return on investment calculation and vice versa. Demonstration of AC-modules has been successfully realized in the currently running project PV-MIPS [1] [9].

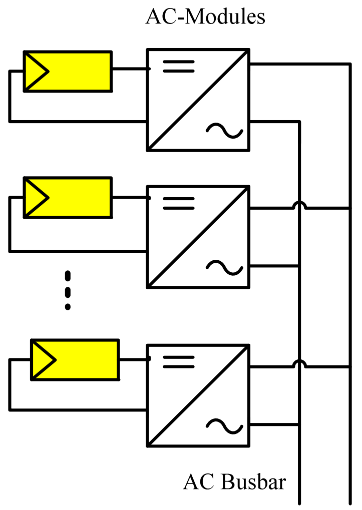


Fig. 13 AC Modules

4.3 DMPPT/ Power Optimizers

In DMPPT, power electronic circuit (fig. 14) is provided for each module so that input and output voltage of each module are independent and MPP voltage can be set individually for each module[12] [15] . A new product called SolarMagic® power optimizers are being launched this year (2009) from National Semiconductor. They claim that this technology monitors and maximizes the energy harvest of each individual solar panel and reclaims up to 57% of energy lost to real world mismatch conditions [11]. In this technology, the modules which have potential of predictable shading because of existing trees, chimneys etc are provided with SolarMagic® optimizers. They consist of dc-dc converters and hence, MPP tracking unit to make sure that output current of underperforming module is equal to that of string and module is always operated in its MPP. This configuration helps to reduce mismatch losses in string because of predictable shading sources. Fig. 14 shows the cascading of the several MPP trackers which in turn are connected to grid via conventional inverters. MPP trackers can also be parallel working on a common dc bus [16].

The performance of DMPPT will be similar to AC-modules as each module can operate in its MPP. If a lot of shading is expected, DMPPT can be beneficial as shading losses can be reduced. Mismatch losses are eliminated but power conversion and cabling losses are increased because of additional electronic circuit [15]. Further, DMPPT are beneficial to reduce module level shading losses only. If only the part of the module is shaded, the power of the concerning part across bypass diodes will be lost and DMPPT would not help. The losses in the converters should also be considered.

Hence, it may not be economical to provide such optimizer for each module. Further, the rate of return and payback period of such investment should be investigated

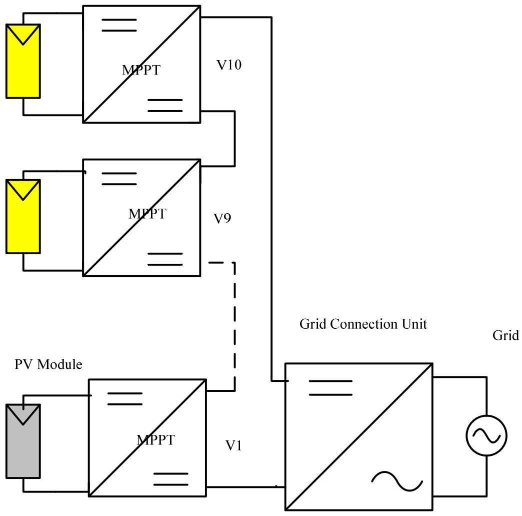


Fig.14 Distributed maximum power point tracking units

5 CONCLUSIONS

In this paper the mismatch effect and the performance decrease of PV strings due to non-optimal operating conditions in terms of mismatch losses and partial shading were studied. The objective was to give a performance comparison between a conventional PV string inverter configuration and module based MPP tracking units, such as AC-modules or DMPPT.

Especially in locations where substantial shading losses are expected, such as building integrated PV, module based MPPT concepts may yield significantly more energy than PV systems incorporating traditional string or central inverters. Module based MPPT decouples the power generation of each module so that mismatch losses are restricted to the shaded modules only.

AC-modules for example could yield more than 4-12% energy in certain situations. Active bypass used in string configurations may also increase the energy output slightly because conduction losses are minimised.

The investigation here was limited to a single string inverter configuration. However, in case more strings operate in parallel on the same inverter the yield might be even more considering the whole array could be operated in a single maximum power point only.

6. ACKNOWLEDGEMENTS

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