BALKAN JOURNAL OF ELECTRICAL & COMPUTER ENGINEERING, Vol. 9, No. 3, July 2021

Comparisons of different Maximum Power Point Tracking Strategies with Zeta Converter

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Abstract—**Maximum power point tracking (MPPT) strategy is one of the major parameters affecting efficiency in photovoltaic (PV) systems. In this paper, distributed MPPT approaches are compared with central mode MPPT. Advantages and disadvantages of submodule level MPPT technique and module level MPPT approach are shown with simulation studies. Comparisons are made with incremental conductance (IC) algorithm. In this context, non-isolated zeta converter is used as a power-processing unit. Effect of the MPPT strategy on the collected energy performance is observed by simulation studies performed in MATLAB/Simulink. It is clear by these studies that energy capture is bigger in submodule level MPPT strategy and module level MPPT with respect to central mode which is seen by simulations. However, central mode MPPT offers cost effective solution because of the low hardware requirements.**

Index Terms— **Distributed MPPT, zeta converter, maximum power point tracking, central MPPT, module level MPPT, submodule level MPPT.**

I. INTRODUCTION

SINCE THE beginning of the 2000s, the use of renewable energy sources in electrical energy production has become increasingly widespread. Despite its intermittent and uncertain characteristics, solar energy has the highest potential among renewable energy sources [1].

The most important component of a solar energy system is the PV module. PV modules consist of solar cells with a voltage of about 0.6V and the efficiency of these cells is very low. In addition, due to the intermittent and uncertain nature of solar energy, PV modules can reach the highest efficiency value at a certain time of the day [2-3]. On the other hand, the current-voltage characteristics of PV modules have exponential function characteristics and they must be operated at specified current and voltage values in order to generate maximum power. Thus, high efficiency is obtained from the PV module.

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Manuscript received April 3, 2021; accepted July 5, 2021.
DOI: 10.17694/bajece.908875

In order for PV modules to operate at their maximum power point, they must not be connected directly to the load. Because it is very likely that there is impedance mismatch between module and load. In order to avoid this mismatch, a power converter is used between the module and the load. DC-DC converters are used for this purpose [4-5]. However, in order to obtain maximum power from a PV module, the converter must be controlled by a MPPT algorithm. In recent years, many algorithms have been proposed for this purpose [6-11].

When the literature is reviewed, it is seen that many MPPT studies with zeta converter have been conducted. In [12], variable step size based MPPT algorithm is used with discontinuous mode (DCM) zeta converter. Perturb and observe (P&O) algorithm, IC algorithm and modified P&O algorithm have been compared each other. In another study [13], the performances of buck-boost converter topologies using P&O algorithm were compared. According to this study, the zeta converter showed a lower oscillating performance in MPPT. In [14], MPPT application with IC algorithm based zeta converter is presented. A comparative study between synchronous zeta and synchronous SEPIC converter [15]. Analysis and design of a non-inverted zeta converter is investigated in [16]. The model of the zeta converter was designed in MATLAB/Simulink environment. In addition, MPPT application with zeta converter was carried out. In [17], performances of P&O algorithm and IC algorithm with zeta converter is analyzed. According to the result obtained in [17] that IC algorithm has superior performance with respect to P&O algorithm. Artificial neural network based optimization algorithm using zeta converter is studied in [18]. According to the findings obtained in this study, the ANN algorithm works better than the P&O algorithm. In another optimization-based study, human psychology algorithm is used for partial shading conditions (PSC) [19]. It is seen that FPGA-based MPPT studies have increased in recent years. Comparisons of two of the popular algorithms are made for different irradiation conditions [20].

In a PV system, the MPPT strategy can be implemented in different ways. While determining this strategy, issues such as system power, location, climate characteristics and cost are taken into account. It is also important whether MPPT is performed at the sub-module level, module level, array level, or centrally. In this study, the comparison of central MPPT with MPPT applications at sub-module and module level has been made. For this purpose, the zeta converter was used. The rest of the study can be summarized as follows. In the first part

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of the study, MPPT strategies are illustrated. In the second part, the basic mathematical model of the zeta converter is explained. Then, the simulation studies performed were explained and the results were evaluated. In the last section, the results of the study are shared.

II. MPPT STRATEGIES

MPPT strategy can be defined as how the MPPT process is performed. Generally, MPPT controlled from a single point is defined as centrally controlled MPPT. In this type of control, the system where a large number of solar panels are connected in series/parallel is considered as if there is a single maximum power point and situations that may cause incompatibility such as partial shading are not taken into account. The central mode MPPT circuit with two PV modules is given in Fig. 1. It is seen here that the PV modules are connected in series. In such an implementation, MPPT efficiency may be reduced if one of the modules is fully or partially shaded.

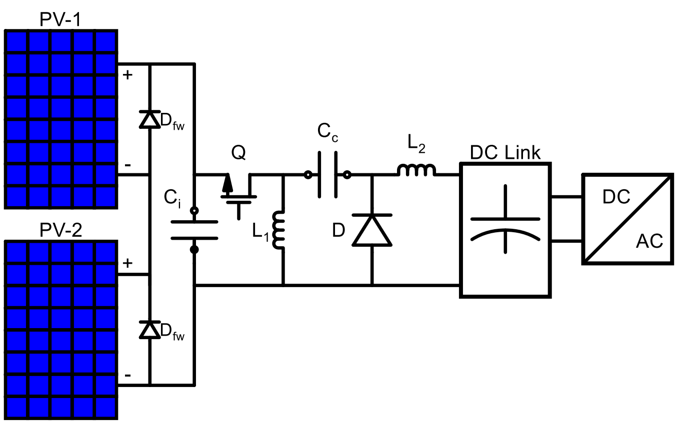

Fig. 1 Central MPPT configuration

In the module-based MPPT strategy, MPPT operation is performed independently in all modules. Thus, situations such as incompatibility between PV modules are less frequent [21]. MPPT efficiency is greater than centrally controlled MPPT. Module level MPPT configuration is presented in Fig. 2.

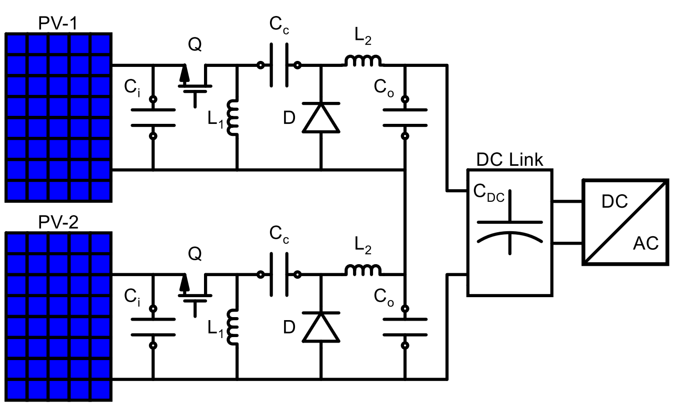

Fig. 2 Module level MPPT configuration

PV modules consist of 3-6 sub-modules. The number of sub-modules depends on the power of the PV module and the manufacturer's choice. Sub-module-based MPPT is a complex approach with high hardware requirements and less software needs. As shown in Fig. 3, each sub-module is connected to a converter and the converter output is connected in series or parallel to create a DC link for the inverter circuit. Higher efficiency values are achieved in sub-module based MPPT applications compared to the other two strategies. This strategy works especially well in shadowing situations [22].

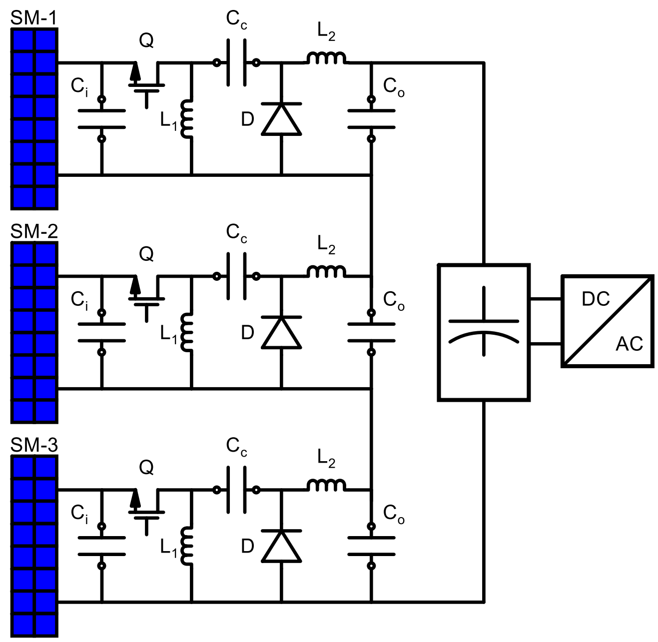

Fig. 3 Submodule level MPPT configuration

III. MPPT SYSTEM COMPONENTS

In order to compare MPPT strategies, it is useful to explain the components of the system first. System components can be listed as PV module, converter and algorithm.

Zeta converter is a circuit with the ability to decrease and increase the voltage. Although the zeta converter is similar to the single ended primary inductance converter (SEPIC) with this feature, the use of semiconductor switch is different from the SEPIC converter. High-side PMOS FET is used in the zeta converter. As seen in Fig. 4, this converter has two inductors, three capacitors, a diode and an active switch. [23].

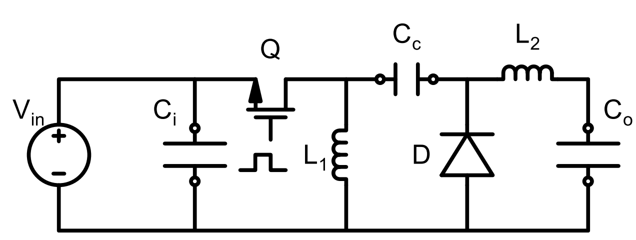

Fig.4. Electrical circuit of non-isolated zeta converter

A. *Operation Modes of Zeta Converters*

The operating principle of the zeta converter is explained based on the open and closed states of the PMOS FET switch. In order to determine the mathematical relationship between input and output in a zeta converter, it is necessary to determine the current variations on inductances. While the switch Q is turned on, the L_1 and L_2 are fed from the input voltage and the energies of the inductances increase. In this case, the voltages on the inductances are equal to the source voltage as presented in Fig. 5. Current variations on L_1 and L_2 are respectively;

$$v_{L1} = L_1 \frac{di_{L1}}{dt} \rightarrow \Delta i_{L1} = \frac{V_{in} D}{L_1 f} \quad (1)$$

$$v_{L2} = L_2 \frac{di_{L2}}{dt} \rightarrow \Delta i_{L2} = \frac{V_{in} D}{L_2 f} \quad (2)$$

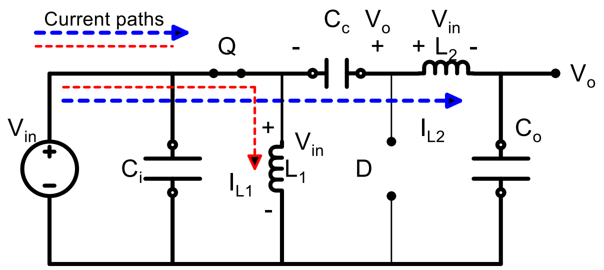

Fig. 5 Equivalent circuit when Q1 is turned on (red line: I_{L1}, blue line: I_{L2})

When Q is turned off, currents of L_1 and L_2 pass through the diode as shown in Fig. 6. Currents of L_1 and L_2 decrease. The voltage across inductances is equal to the output voltage. The amount of reduction of inductance current in this range is expressed in Eq. (3) and Eq. (4), respectively.

$$v_{L1} = L_1 \frac{di_{L1}}{dt} \rightarrow \Delta i_{L1} = \frac{V_o (1-D)}{L_1 f} \quad (3)$$

$$v_{L2} = L_2 \frac{di_{L2}}{dt} \rightarrow \Delta i_{L2} = \frac{V_o (1-D)}{L_2 f} \quad (4)$$

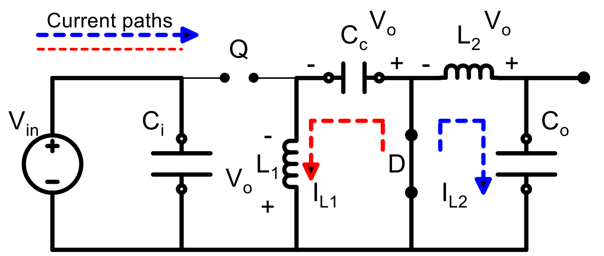

Fig. 6 Equivalent circuit when Q1 is turned off (red line: I_{L1}, blue line: I_{L2})

To prevent saturation; at steady state the current changes across inductances must be equal. According to this; if the current increase of the inductance L_1 and the current decrease of the inductance L_1 are equal to each other, the mathematical relationship between the input voltage and the output voltage is obtained as in Eq. (5).

$$V_o = V_{in} \frac{D}{1-D} \quad (5)$$

B. Zeta Converter for MPPT Application

Zeta converter is a suitable topology for MPPT application since its input and output voltage polarity is the same, and it has the characteristics of voltage reduction and increase.. In order to perform MPPT with a zeta converter, it is necessary to obtain the relationship between the input and output of the converter. Thanks to this relation, it is determined whether the maximum power point can be determined in the PV module current-voltage curve.

The input power of the converter is equal to the power of the PV system. This power can be expressed as in Eq. (6). PV system voltage can be expressed in Eq. (7).

$$P_{PV} = V_{PV} I_{PV} = I_{PV} R_{PV} \quad (6)$$

$$V_{PV} = I_{PV} R_{PV} \quad (7)$$

In Eq. (6) and Eq. (7), P_{PV} is the power of the PV system; V_{PV} and I_{PV} are the voltage of PV system and current of PV system, respectively. R_{PV} is the instantaneous equivalent impedance of PV system. Eq. (8) and Eq. (9) can be written for the output power and output voltage of the zeta converter, respectively.

$$P_o = V_o I_o = I_o^2 R_L \quad (8)$$

$$V_o = I_o R_L \quad (9)$$

In Eq. (8) and Eq. (9), P_O is the power of the zeta output, V_O and I_O are the output voltage of the zeta and output current of the zeta converter. R_L is the load resistance. By using Eq. (5-9), the relationship between R_L and R_{PV} can be formulated as in Eq. (10),

$$R_{PV} = R_L \frac{(1-D)^2}{D^2} \quad (10)$$

C. Incremental Conductance Algorithm

The IC algorithm is a hill climbing-based approach in which current and voltage changes are monitored. Although many of its properties are similar to the P&O algorithm, it is accepted that its dynamic response is better than P&O under suddenly changing irradiation conditions [9]. As can be seen from Fig. 7, the operation principle of the IC algorithm is based on the evaluation of the ratio of the PV system current change to the voltage change in general. Eq. (11) explains the algorithm.

$$\begin{cases} \frac{\Delta P}{\Delta V} = 0 \\ \frac{\Delta P}{\Delta V} > 0 \Rightarrow \\ \frac{\Delta P}{\Delta V} < 0 \end{cases} \begin{cases} \frac{\Delta I}{\Delta V} = \frac{-I}{V} \rightarrow MPP \\ \frac{\Delta I}{\Delta V} > \frac{-I}{V} \rightarrow left\ of\ MPP \\ \frac{\Delta I}{\Delta V} < \frac{-I}{V} \rightarrow right\ of\ MPP \end{cases} \quad (11)$$

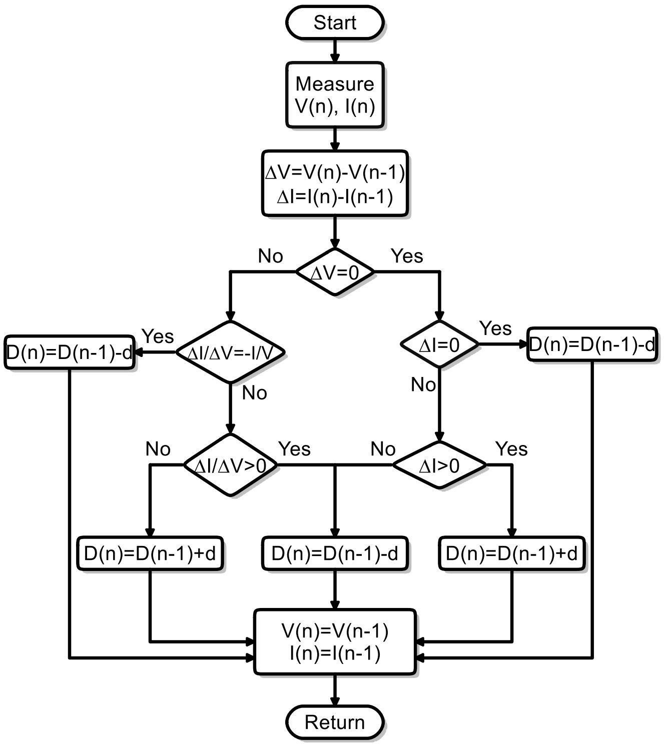

Fig. 7 Flowchart of the IC algorithm

IV. Simulation Results

The performance of three different MPPT strategies has been examined under different shading conditions with simulation studies. These strategies can be listed as central mode MPPT, module based MPPT, and submodule based MPPT. In these three approaches, a non-isolated zeta converter designed for a fixed power level and c-Si PV modules are used. Technical information of the module and submodule are listed in Table I. The basic parameters of the zeta converter are also listed in Table II.

TABLE I
SPECIFICATIONS OF THE PV MODULE [23]

Bosch PV Module c-Si M 48	**Value**
Short circuit current	8.5A
Open circuit voltage	28.9V
Maximum power voltage	23.4V
Maximum power current	7.9A
Maximum power	180W
Bypass diodes	3
Submodule - Bosch	**Value**
Maximum power voltage	7.8V
Maximum power current	7.9A
Maximum power	60W
Note: 1000W/m^2 25 °C AM: 1.5	

TABLE II
SPECIFICATIONS OF THE ZETA CONVERTER

Features	**Value**
Input / output capacitor	630µF / 100 µF
Primary/Secondary inductance	1mH/1mH
Switching frequency	20kHz

In central mode MPPT, two PV modules are connected in series. The modules whose technical specifications are given in Table I consist of three serially connected submodules. All submodules are connected to the diode in reverse parallel. The model for the simulation studies is shown in Fig. 8.

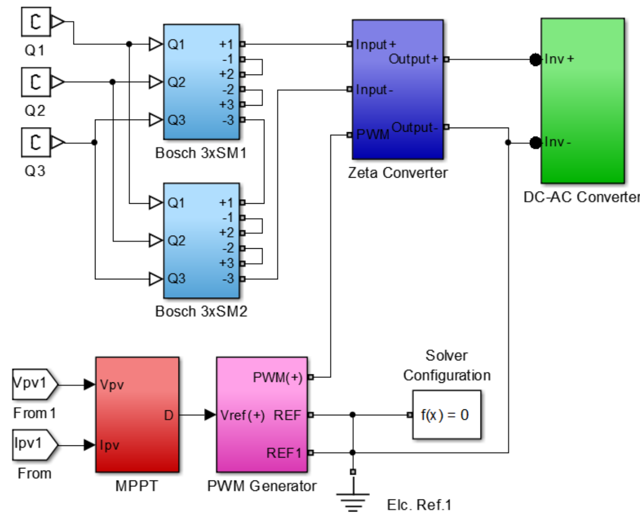

Fig. 8 Central mode MPPT

Simulation studies in three MPPT approaches were carried out for PSCs. In the first simulation study, the irradiation values of the shading situation are 200-500-1000W/m^2, in this case the global maximum power value of the PV system is around 127.5W. As can be seen from Fig. 9, there are three peaks in the PV system power-voltage (P-V) curve and the initial duty ratio value of the IC algorithm is determined as 80%. Under these conditions, it is possible to work at the global maximum power point (GMPP). Tracking efficiency is calculated as 96.24% within 0.3 seconds.

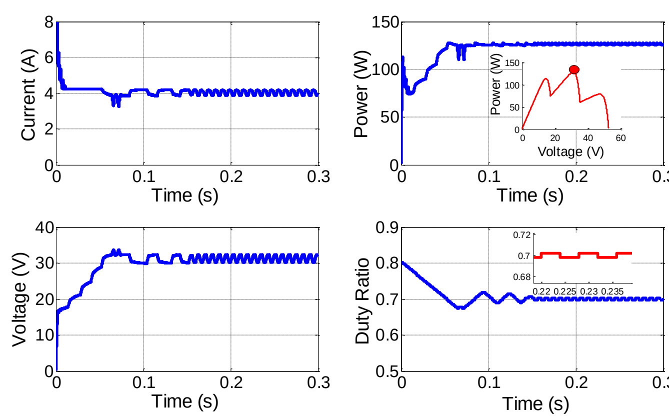

Fig. 9 Result of central mode MPPT for 200-500-1000W/m^2: Current, voltage, power and duty ratio variations.

In the second simulation study, an irradiation profile case with four different values was investigated. As can be seen in Fig. 10, there are four peaks in the P-V curve. Global maximum power value is around 150W. The initial duty ratio is 80%, and GMPP tracking (GMPPT) has been successfully implemented. However, since the IC algorithm is hill climbing based, the performance is directly related to the initial duty rate being randomly well determined.

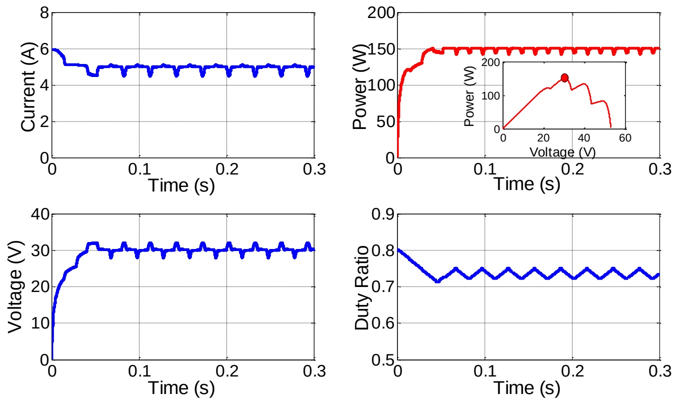

Fig. 10 Result of central mode MPPT for 200-400-600-700W/m^2: Current, voltage, power and duty ratio variations.

In the last simulation study for central mode MPPT, GMPPT could not be achieved. Although the GMPP is located at the far right of the P-V curve as given in Fig. 11, the IC algorithm remains stuck at the middle MPP. For this reason, tracking efficiency is calculated as 76.11%

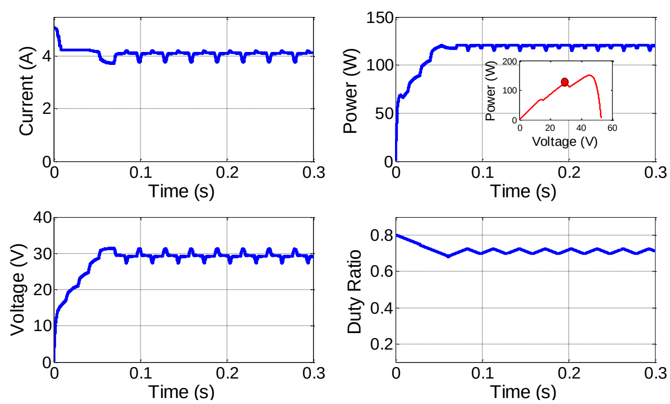

Fig. 11 Result of central mode MPPT for 400-500-600W/m^2: Current, voltage, power and duty ratio variations.

The same PV system is used in the module-based MPPT approach. The difference of module-based MPPT according to the central mode is that a zeta converter is used for each PV module and the MPPT operation is performed separately for each PV module, which is seen in Fig. 12. In the first simulation study, PV modules are exposed to three different irradiations and subjected to partial shading. Thanks to the bypass diodes in the PV module, the shadowed sub-modules are bypassed. The global maximum power value of the PV module in the P-V curve is 63.75W. Initial value of duty ratio is 80%. In Fig. 13, the result of the first simulation study for the first module-based MPPT approach is given. As can be seen from Fig. 13, GMPP is successfully monitored, within 0.3 seconds; the tracking efficiency is calculated as 97.59%. However, because of the multi-peak P-V curve condition, increased conductivity may not always give successful results. For example; if initial value of duty ratio is 20%, the tracking efficiency is 86.65%. Because, the IC algorithm fails in the first MPP which is located at the left side of the P-V curve.

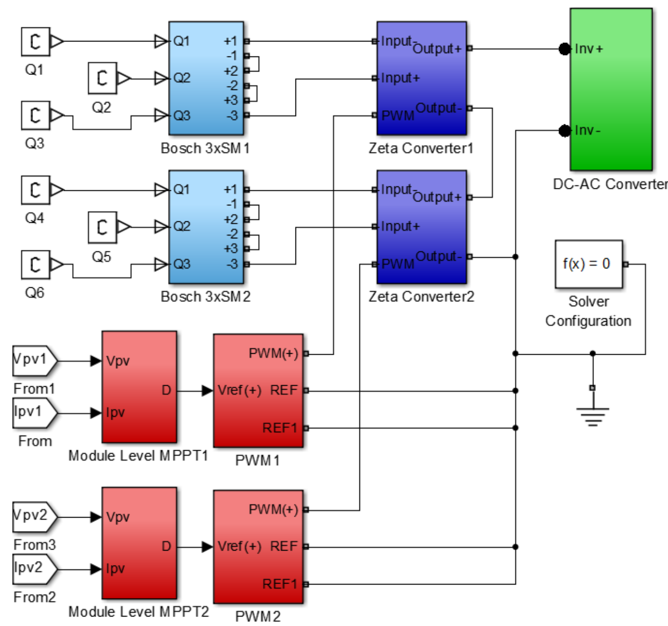

Fig. 12 Module level MPPT model

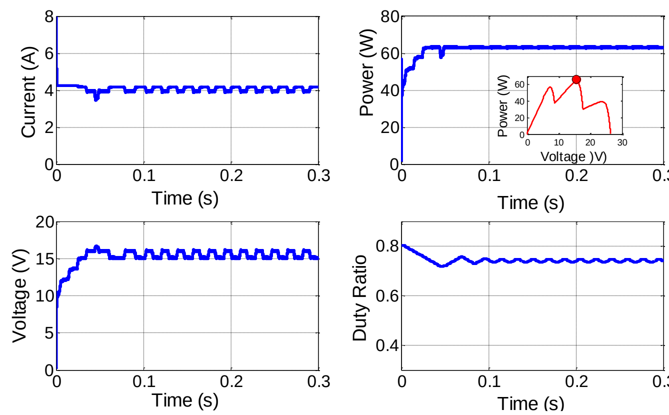

Fig. 13 Result of module level MPPT for 200-500-1000W/m^2: Current, voltage, power and duty ratio variations.

In the other simulation study, the PV modules receive 200-400-600W/m^2 and 700-700-700W/m^2, respectively. As it can be understood from here, one of the modules is partly shaded and the other is under uniform radiation. For this reason, the current and voltage changes of PV modules are different from each other. The PV module, which is subject to partial shading, has three peaks in the P-V curve, while the other module has a single MPP. The current, voltage and power changes of the two modules are given in Fig. 14. The modules operate continuously at the MPP with a power of 48.92W and 123.2W, respectively. Tracking efficiency is around 97% for both modules, respectively.

In the last module-based simulation study, the irradiance values are 400-500-600W/m^2. These irradiance values are applied to both modules. Since they have the same irradiance values, the MPPT of the PV modules is identical. The results of this simulation scenario are given in Fig. 15. Each module generates 75W of power.

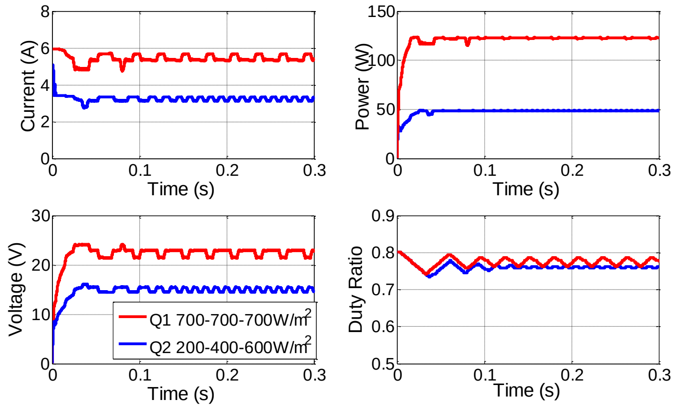

Fig. 14 Result of module level MPPT for 200-400-600-700W/m^2: Current, voltage, power and duty ratio variations.

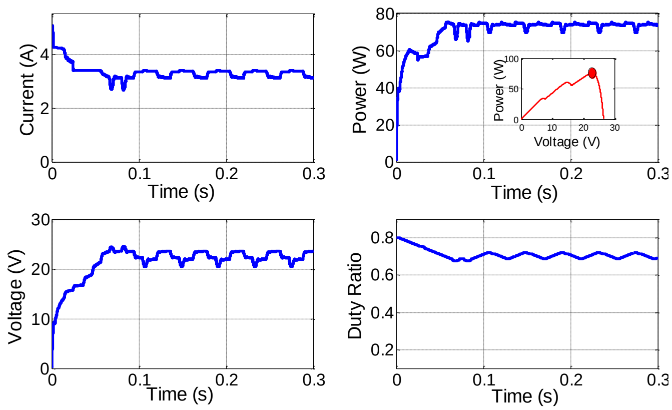

Fig. 15 Result of module level MPPT for 400-500-600W/m^2: Current, voltage, power and duty ratio variations.

In the submodule based MPPT approach, each submodule is connected to the zeta converter. Since PV two modules are used in this study, there is a PV system consisting of six sub-modules in total. All submodules are electrically independent from each other and there is no need to use a bypass diode. Because a multi-peak situation does not occur in the P-V curve. MPPT operation is performed separately in all submodules and outputs of the zeta converters are connected in series or parallel. Simulink model for submodule based MPPT approach is given in Fig. 16. Six different MPPT processes are applied to six submodules in this approach. In this way, it is ensured that the biggest possible powers are generated from submodules.

The first shading condition is the same as in the central mode MPPT and module-based MPPT approach. The irradiance values of the first module and the irradiance values of the second module are the same. Therefore, the changes in current, voltage, power and fill rate are the same in the two modules. When the changes given in Fig. 17 are evaluated; submodule exposed to 1000W/m^2 produces around 60W of power. Since the current and voltage values for this submodule are close to each other and the duty ratio converges to 100%, an unstable and oscillating operation has occurred. Although oscillating operation can be eliminated by changing the load value at the zeta converter output, this issue has been evaluated outside the scope of this study. On the other hand, stable operation has been realized for two submodules exposed to 200W/m^2 and 500W/m^2 irradiation. Tracking efficiency of around 97% has been achieved in these sub-modules. However, in the sub-module where high oscillation occurs due to unstable operation, the tracking efficiency is around 80%.

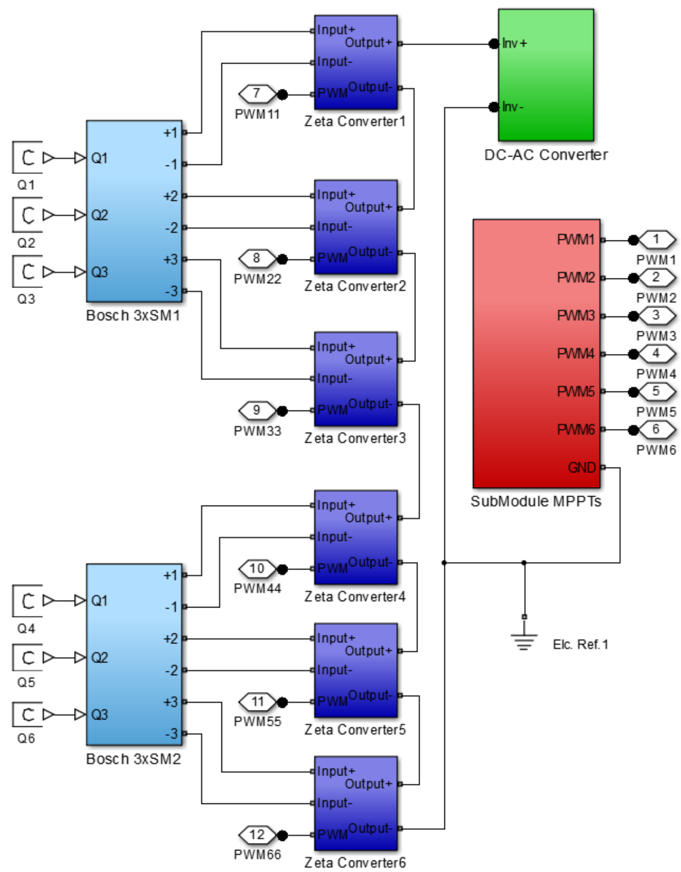

Fig. 16 Submodule level MPPT model

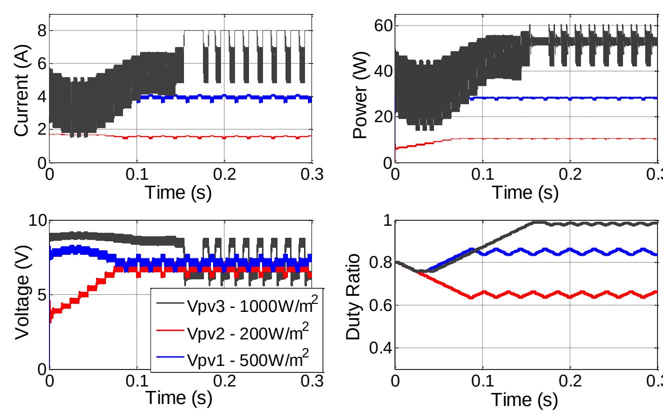

Fig. 17 Result of submodule level MPPT for 200-300-1000W/m^2: Current, voltage, power and duty ratio variations.

The results of the other two simulation studies related to the submodule based MPPT approach are given in Fig. 18 and Fig. 19. Since the P-V curve cannot be multi-peaked in a submodule, GMPPT has been successfully realized. As can be seen from Fig. 18, submodules produce different power values according to the irradiation they are exposed to. A similar comment can be made for Fig. 19.

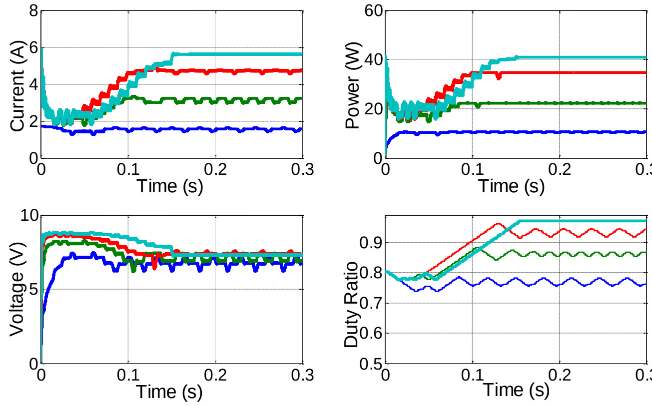

Fig. 18 Result of submodule level MPPT for 200-400-600-700W/m^2: Current, voltage, power and duty ratio variations.

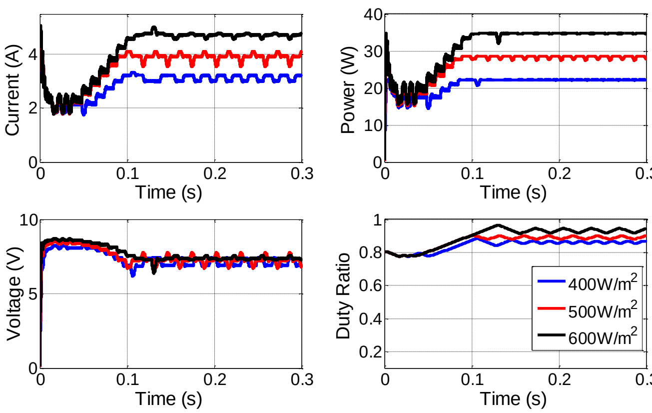

Fig. 19 Result of submodule level MPPT for 400-500-600W/m^2: Current, voltage, power and duty ratio variations.

V. Discussion

According to the simulation results, it is understood that the success of the MPPT depends on many parameters. These parameters can be listed as panel structure, algorithm used, approach type, load conditions, radiation, partial shading and some parameters in the algorithm. Table III shows the results for all MPPT approaches. Although these results may differ for different converters and conditions, they have had some outcomes. It is useful to explain one of these inferences with an example. Suppose the irradiance values are 400-500-600W/m^2. According to these irradiance values, when the initial value of duty ratio is taken as 80%, the efficiency of the central mode MPPT was calculated as 76% and the efficiency of the module-based MPPT approach was calculated as 93.98%. If the initial value of the duty ratio is taken as 35%, the efficiency values vary considerably. In this case, the efficiency is 58.67% for central mode MPPT, 54.9% for module based MPPT, and 80% for sub-module based MPPT application. In the central mode MPPT and module based MPPT approaches, the algorithm stuck at the wrong peak points in the P-V curve. On the other hand, in the submodule-based approach, it was able to catch the global power point. The reason for the small efficiency is related to the simulation time.

TABLE III
SIMULATON RESULTS

MPPT Approach	200-500-1000 W/m^2	200-400-600-700 W/m^2	400-500-600 W/m^2
Central	96.24%	96.58%	76.11%
Module	97.59%	97.18% 97.76%	93.98%
Submodule	97.5% 94.42% 76%	97.28% 93.87% 89.77% 83.19%	93.83% 92.25% 89.77%

VI. Conclusions

Performance evaluation of different MPPT strategies was made in this study. For this purpose, the zeta type buck-boost topology, which is a kind of DC-DC converter used in MPPT applications, has been chosen. The IC algorithm has been chosen as the algorithm in the comparisons. This performance evaluation has been conducted with many simulation studies and some of them are presented. It has been seen that MPPT performance depends on many parameters. However, MPPT precision increases from the central mode MPPT approach to the submodule-based MPPT approach. In this case, although the cost and hardware requirement increases, the need for complex algorithms disappears. On the other hand, hybrid and complex algorithms are required to ensure GMPPT in centralized mode and module-based approaches.

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