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Comparative Study of Photovoltaic Array Maximum Power Point Tracking Techniques

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***Abstract*—This paper provides a comprehensive review of the maximum power point tracking (MPPT) techniques applied to photovoltaic (PV) power system available until March, 2014. A good number of publications report on different MPPT techniques for a PV system together with implementation. But, confusion lies while selecting a MPPT as every technique has its own merits and demerits. Hence, a proper review of these techniques is essential. Since, MPPT is an essential part of a PV system, extensive research has been revealed in recent years in this field and many new techniques have been reported to the list since then. In this paper, a detailed description and then classification of the MPPT techniques have made based on features, such as number of control variables involved, types of control strategies employed, types of circuitry used suitably for PV system, transient responce and practical/ commercial applications. This paper is intended to serve as a convenient reference for future MPPT users in PV systems.**

Keywords— Maximum Power Point Tracking (MPPT), photovoltaic (PV).

I. INTRODUCTION

Increasing demand of solar PV energy is due the rising prices and limited stock of conventional energy sources like coal, petroleum, etc. Solar PV energy has many advantages like clean-green energy, free and abundant, environment friendly, low operation and maintenance cost, etc. and hence the demand is increased. Therefore, maximizing the efficiency has also become necessary. To maximize the efficiency means to develop efficient technique for maximum power point tracking. Many MPPT techniques are reported in the literature [2]-[33]. Selection of MPPT technique is very difficult and confusing for a particular application. Only few papers are available on the comparative study of various MPPT techniques [3]-[9]-[9] till 2012. Many new MPPT technique such as model Reference Adaptive Control (MRAC), Model Predictive Control (MPC), improved distributed MPPT, Support vector regression control, Adaptive control etc. have been reported since then. Hence it is necessary to prepare a new review including this techniques. In this review paper MPPT techniques are compared on the basis of advantages, disadvantages, control variables, circuitry use, complexity, cost, parameter tuning, parameter used, speed of convergence and transient response. In this paper attempt is made to provide a comparative review on most of the reported MPPT techniques excluding any unintentionally omitted papers because of space limitations.

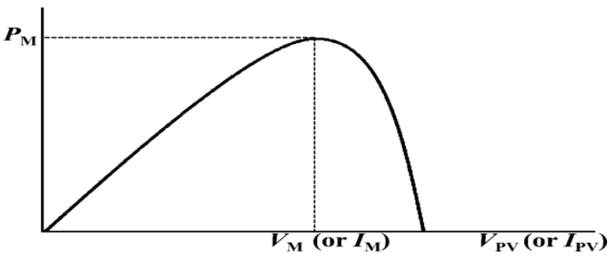

Fig 1: power voltage characteristics of PV system.

II. CONTROL ALGORITHMS

The following are the mostly used MPPT techniques used in various PV applications.

A. *Short circuit method*

It is observed that I_{mpp} is linearly proportional to I_{sc} of a photo voltaic array [1].

$$I_{mpp} \alpha I_{sc}$$

$$I_{mpp} = K_{sc}. I_{sc} \quad (1)$$

Where $K_{sc.}$ Is constant of proportionality. In this method maximum power point is achieved through a close loop control system as shown in fig (2). For comparison of I_{mpp} and I_{sc} it is required to calculate I_{sc}. I_{sc} is a short circuit current which can be calculated by introducing a static switch in parallel with the PV array in order to create the short circuit condition for each solar irradiation level change. But this can cause large oscillations of power output. And also calculation of I_{mpp} is very sensitive to K_{sc} parameter and relation between I_{mpp} and I_{sc} is not 100% linear.

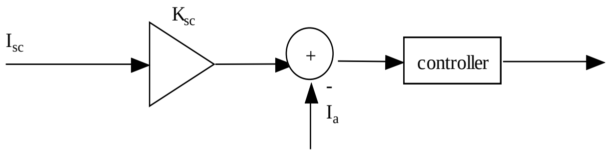

Fig 2: Block diagram short circuit method.

B. *Open circuit method*

It is observed that V_{mpp} is about linearly proportional to V_{oc} of PV array [2].

$$V_{mpp} \alpha V_{oc}$$

$$V_{mpp} = K_{oc} .V_{oc} \quad (2)$$

K_{oc} is constant of proportionality. Circuitry and working is same as short circuit current method. Fig (3) shows the control system for open circuit voltage method. Here also it is necessary

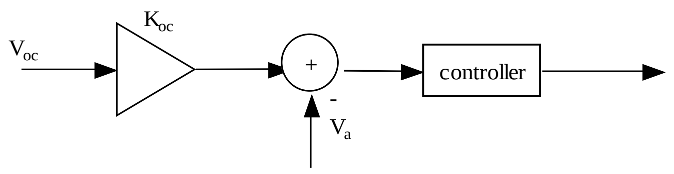

Fig 3: Block diagram of open circuit method.

to insert the static switch in series with the Pv array in order to create open circuit for various irradiation and temperature change. This will cause large oscillation of output power. Also, relation between open circuit voltage and V_{mpp} is not 100% linear.

C. Perturb and observe method

This is the most commonly used MPPT technique for PV array. In this method measurement of short circuit current or open circuit voltage is not required. Here array terminal voltage or current is periodically perturb and output power is observed. If increase in voltage causes increase in power, control system moves the PV array operating point in that same direction otherwise perturbation is changed to the opposite direction. This procedure is continues until MPP is reached. In this way pick point and corresponding voltage at MPP is calculated [2]-[4]. Fig (4) shows the flow chart of Perturb and Observe technique.

D. Incremental conductance method

This method is based on the fact that the slope of the PV array power curve as shown in fig (1) is zero at the MPP, positive on the left of the MPP, and negative on the right [3],

$$dP/dV = 0,$$
$$dP/dV > 0,$$
$$dP/dV < 0, \quad (3)$$

Since

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = I + V\frac{\Delta I}{\Delta V} \quad (4)$$

Thus, by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$) MPP can be tracked as shown in flowchart in the fig(5).

Speed of convergence depends on the increment size. Fast convergence can be achieved with big increments. But there are chances of oscillations about the MPP instead of operating at MPP. In [31] and [35],the algorithm is proposed in which, first operating point is bring close to MPP and then Inc Cond is used to exactly track the MPP in the second stage. In [37] by using linear function, I/V curve is divided into two areas, one containing all the possible MPPs under changing atmospheric conditions. The operating point is brought into this area and then IncCond is used to reach the MPP.

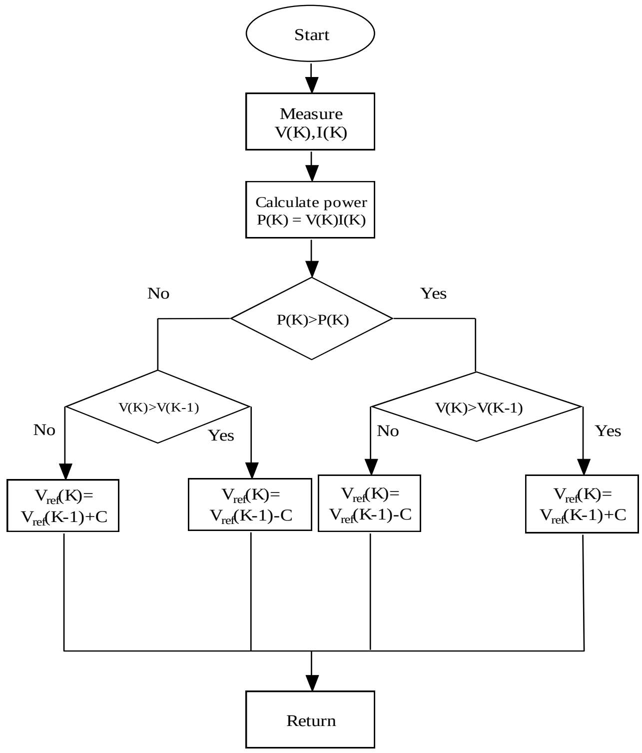

Fig 4: Flow chart of Perturb and Observe technique.

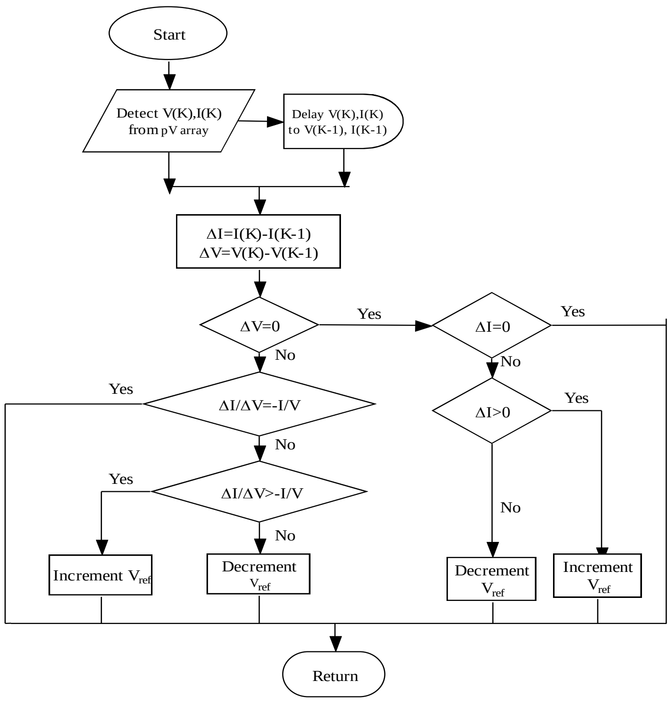

Fig 5: Flow chart of Incremental conductance method.

E. Ripple corelation control

The ripple correlation control (RCC) is nothing but improved version of perturbed and observed method. Difference between this two methods is, RCC uses the switching ripple of the converter for the perturbation. Therefor external circuitry is not required in this method. In addition, RCC has proven to converge asymptotically to the MPP. Also it has less complexity and straightforward circuit implementation.

RCC is based on the observation that time base derivative of array voltage V_{pv} and power P_{pv} will be greater than zero to the left of the MPP, less than zero to the right of the MPP and zero at the MPP. See fig (1)

$$\frac{dPpv}{dt}\frac{dVpv}{dt} > o \qquad \text{When } V_{pv} < V_M$$
$$\frac{dPpv}{dt}\frac{dVpv}{dt} < o \qquad \text{When } V_{pv} > V_M$$
$$\frac{dPpv}{dt}\frac{dVpv}{dt} = o \qquad \text{When } V_{pv} = V_M \qquad (5)$$

These observation lead to the control law derived in [5]

$$\frac{d\,d(t)}{dt} = k\frac{dPpv}{dt}\frac{dVpv}{dt} \quad (6)$$

Where k is constant of negative gain. The above control law says that for maximum power, aim is to derive the time base derivative of *d* to zero [5]-[7].

F. Adaptive maximum power point tracking

In this method, adaptive MPPT algorithm is use for tracking. As stated in [8] array voltage and array power both has natural fluctuations. This natural fluctuations are used for reaching the MPP. Fig (1) shows the voltage-power curve for PV system.
The PV curve is divided into three regions, as shown in fig (6).

Region A:
In this region MPP is to the right of the operating point. The ratio of dP/dV > 0, which means voltage and power has same trends. Therefore, local minimum voltage corresponds to local minimum power. V_A is the instruction voltage. In this region maximum power point voltage is V_{A1} (shown by dotted line). Here $V_{A1} > V_A$ so V_{A1} is set as new instruction voltage. PV array voltage will move to the right until the MPP voltage V_C is reached.
Region B:
When operating voltage has reached to the MPP, maximum power will be located at mid-point of the voltage pulse at that time. Therefore, by the control strategy bus voltage will not be moved. In case of temperature and intensity of sunlight change, MPP will shift causing voltage corresponding to MPP also shifts and hence bus voltage instruction also changes.
Region C:
In this region dP/dV < 0, which means voltage and power has opposite trends. Therefore local minimum voltage corresponds to local maximum power. Now $V_{B1} < V_B$ and hence V_{B1} is set as new instruction voltage. PV array voltage will move in left direction until MPP voltage V_C is reached.

The relative merit of the method is no effect to the grid power, and it tracks the maximum power point quickly without any parameters setting. It can be applied to single-phase or three-phase photovoltaic grid-connected inverter system.

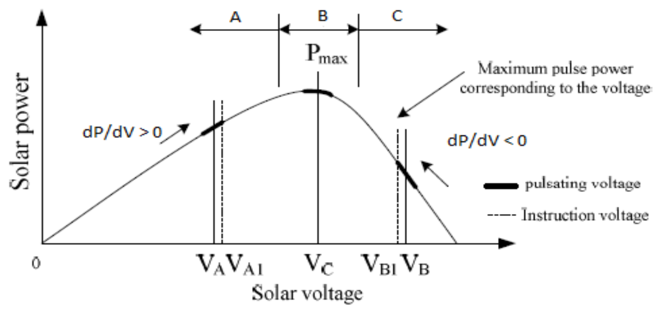

Fig 6: P-V curve for adaptive MPPT.

G. DC link capacitor droop voltage

DC link capacitor droop control [10] is specifically designed MPPT technique which work with the PV system that is connected in parallel with an AC system line as shown in fig(7).
The duty ratio d of an ideal boost converter is formulated as

$$D = 1 - \frac{V}{Vlink} \qquad (7)$$

Where V is the PV array voltage and V_{link} is the dc link voltage. By keeping V_{link} constant, power coming out from the boost converter and the power coming out from the PV array can be increased by increasing the current going in the inverter. V_{link} can be kept constant till powerrequired by the inverter does not exceeds the maximum power available from the PV array. Otherwise V_{link} starts drooping. Exactly before this point, current control command of the inverter is at its maximum and PV array operates at MPP [9].

H. Current sweep method

In this method, using a sweep waveform for the PV array current such that the characteristic of the PV array is obtained and updated at fixed time intervals.
From [3], we have

$$\frac{dP(t)}{di(t)} = V(t) + K\frac{dV(t)}{dt} = 0 \qquad (8)$$

Where K is the constant of proportionality.

After the current sweep, V_{mpp} is computed and it is double check by equation (8) whether the MPP has been reached. In [11], it is mention that this technique is only feasible if the power consumption of the tracking unit is lower than the increase in the power that it can bring to the entire PV system.

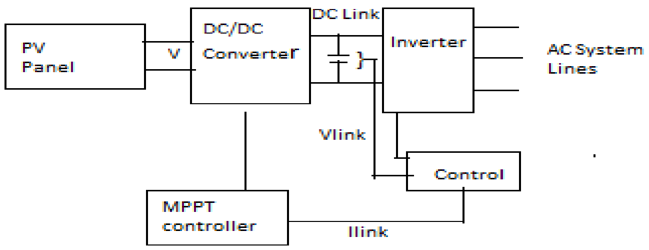

Fig 7: Block diagram of dc-link capacitor droop method.

I. Support vector regression (SVR)

As mention in [12], the output power of the PV system depends on temperature and solar irradiation. Fig (8) shows I-v curves for the various irradiation and temperature levels. This fig is divided into two parts as part A and part B. In part A curves do not intersect with each other and in part B curves intersects with each other at several points. At the intersecting point i.e. on the right side of fig, if we use SVR to estimate the irradiation and temperature, the performance of estimator will deteriorated. Therefore here multistage SVR is proposed. The proposed method consist of three levels: the first level estimates the initial value of temperature and irradiation; the second level estimates the irradiation assuming that the temperature is constant within a one hour time span; and the third level updates the estimated temperature once every one hour. Fig (9) shows the flow chart of the proposed multistage algorithm MSA.

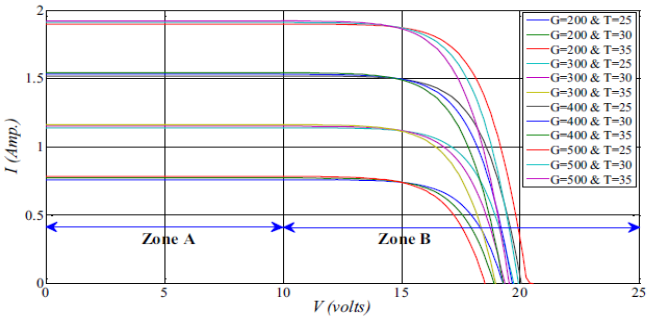

Fig 8: I-v curves for the various irradiation and temperature levels.

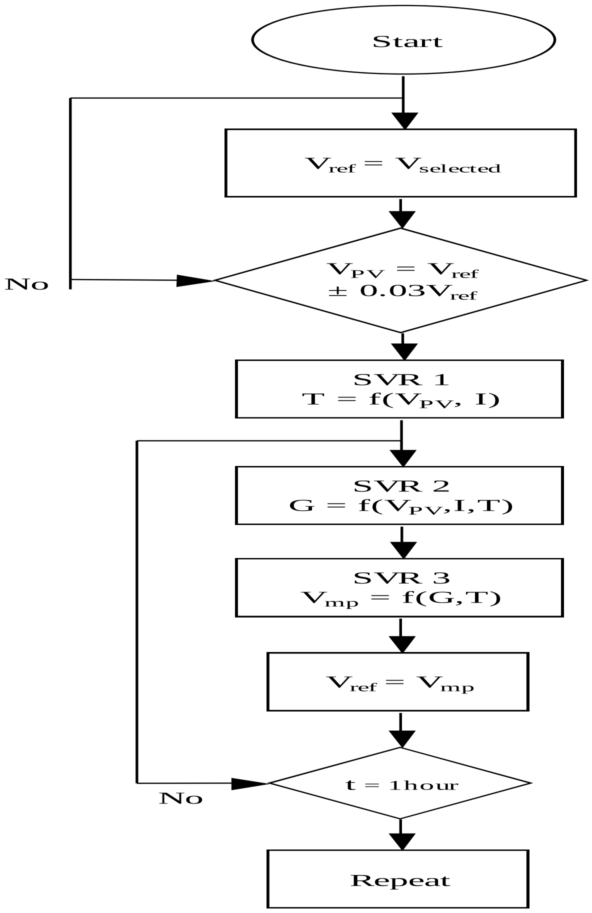

Fig 9: Proposed multistage algorithm MSA

J. One cycle control

One cycle control is a nonlinear MPPT method. In this method single stage inverter is used where the output current of the inverter can be adjusted according to the voltage of the PV array so as to get maximum power from it [14]-[15]. The one cycle control system is shown in fig (10). The parameter L and C are required to be tuned properly as accuracy is affected by this parameters [9]. Both MPPT control and DC to AC conversion are carried out in single stage.

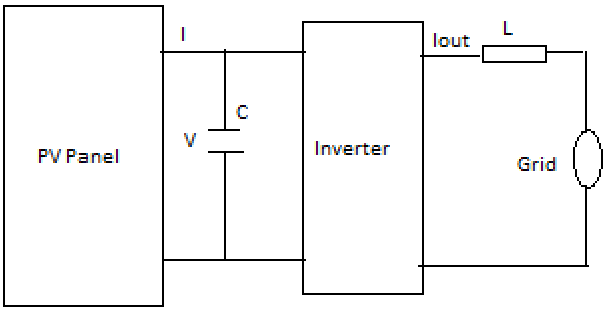

Fig 10: Block diagram of OCC technique.

K. Estimated perturb and observe

This is an extended P & O method. In this method there is one estimate process between two perturb process [17]. Perturb process searches the maximum power over a highly nonlinear characteristics of PV array and estimate process compensate for the perturb process for continuously changing irradiation conditions. This method is more accurate and has more tracking speed as compare to P & O method at the expense of complexity [16].

L. Fuzzy logic based MPPT method

This method of tracking maximum power point has achieved very good performances, fast response without overshoot, and has less fluctuations in the steady state for continuous variations of temperature and irradiation level. Also this technique do not requires the knowledge of the exact plant [20], [21]. Generally fuzzy logic based MPPT have two input and one output. The two input variable can be error E and change in error DE as shown in fig (11) while the output is duty cycle. K is sample time.

$$E(K) = \frac{P(K) - P(K-1)}{V(K) - V(K-1)} \quad (9)$$

$$DE = E(K) - E(K-1) \quad (10)$$

Fuzzy logic control is mainly dived into four stages which includes fuzzification, inference, rule base, and defuzzification as shown. In fuzzification, the input in numerical form is converted into linguistic variable based on the membership function. Inference is use to determine the output of fuzzy logic. Then control tracks the MPP based on rule base table [19]. Among the many methods for inference, mamdani is very popular one. The fuzzy output is then converted into numerical value during defuzzification. Centroid is very popular method for defuzzification as it produces more accurate results.

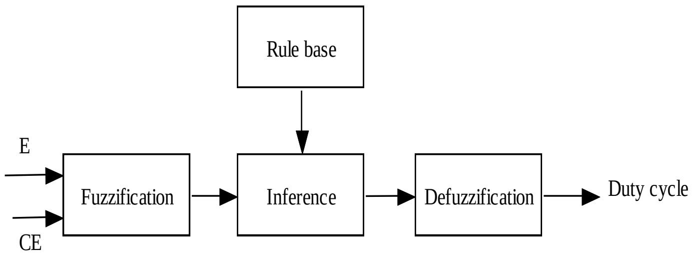

Fig 11: Block diagram of conventional FLC MPPT algorithm

M. Artificial Neural Network (ANN) based MPPT method

The operation of ANN control is like black box model, do not requires detail information about the PV system. Input for ANN can be parameter like PV array voltage, currents, environmental data like irradiance and temperature, or any combination of these. Output is identified maximum power or the duty cycle signal given to the converter to operate at MPP. ANN can track MPP online after learning relation of V_{MPP} with temperature and irradiance [22]-[23]

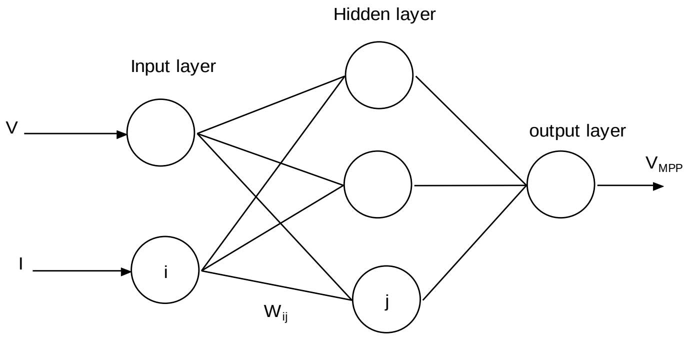

Fig (12): ANN-based MPPT [24].

N. Model Reference Adaptive Control method (MRAC)

In this method, for improving the performance of MPPT a two level adaptive control architecture is developed. The first level of control is ripple correlation control and the second level of control is MRAC. This architecture has proven to reduce complexity in the control system and effectively handle the uncertainties and perturbations in the PV system and environment [6].

Along with steady-state analysis, transient response of the converter should also be considered. Due to the rapidly changing duty cycle according to rapidly changing environment conditions, oscillations in the output are produce. Fast convergence to the MPP with minimum oscillations is required. For this MRAC algorithm is proposed to prevent the array voltage from exhibiting an underdamped response.

Fig (13) shows the proposed MPPT control architecture. As shown in fig (13), V_{PV} and P_{PV} are the input to the RCC, RCC calculates the duty cycle as discuss earlier in RCC technique. In second level, this new duty cycle calculated from the RCC unit and is routed into MRAC unit, where the dynamics of the entire PV power conversion system or plan are improved to eliminate the transient oscillations in the system. C_b and C_f are feedback and feed forward controller respectively. This parameters are tune by error between the plan and model. Properly tuning this parameters leads to exact matching of plant with reference model. At some point error will be zero and maximum power is obtained.

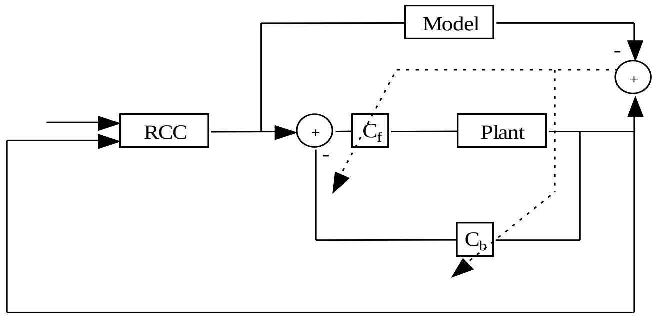

Fig (13): proposed MPPT architecture.

O. Distributed maximum power point tracking

Due to partial shading or manufacturing inequalities there are mismatches in the PV array module characteristics and hence conventional MPPT scheme becomes insufficient and ineffective. There are some techniques to maximize power output under partially shaded or mismatch condition. In this techniques, maximum power is tracked either by using full power dedicated dc-dc converter (FPDC) with each module or by compensation power-dedicated dc-dc converter (CPDC).

Here, a new distributed MPPT technique based on current compensation (CPDC_DMPPT) is given. In this technique each PV module is regulated at its exact MPP voltage by injecting appropriate current. A control scheme is implemented to determine the exact MPP for each PV module. This is achieved by using a special arrangement of a controller, a resonant pulse is generated on the secondary side of the fly back converter. The converter operated in two modes one is resonant MPPT mode and the normal fly back mode.

Implementation of proposed CPDC_DMPPT scheme is as shown in fig (12) [25]. In this scheme intelligent module controller IMC (I, j) is assigned to each module and one overall intelligent array controller (IAC) is assigned to array. There are three functions of IMC; to initiate MPPT mode for each PV module, to determine and store the MPP voltage during resonant mode and to regulate the voltage of the fly back converter at reference MPP voltage of PV module. $V_{PV(out)}$ i.e. the desired output voltage of PV array and it is sum of MPP voltage of the individual modules in a string. According to [25], PV system adopting DMPPT and operating under mismatching condition, it is not always possible to obtain the working of each PV module in its own MPP.

P. Model predictive control

In this method of MPPT combination of incremental conductance algorithm (IC) and finite site model productive control (MPC) is applied. MPC is one of the best controller due to its simple implementation [28]-[29]. Addition of MPC to IC algorithm gives advantages such as fast response and ability to extract maximum power under different conditions. Also it reaches steady state faster.

This is a two stage technique in which first stage is modified IC (MIC) use to generate the maximum power reference and the second stage is MPC which is used to control the PV module and achives the maximum power [26]. This method has the ability to track the MPP under changing environmental condition and reaches steady state in very small time. Fig (14) shows the flow chart of INC-MPC algorithm.

The important parameter of MPC is cost function. Cost function determines the required control function. Here our control function is to control the PV output current and voltage. Two cost functions are calculated; one with the consideration that the switch of the converter is off.

$$G_0 = A^* \left| V_{PV,0}(K+1) = V_{ref} \right| + B^* \left| I_{PV,0}(K+1) - I_{ref} \right| \quad (11)$$

And the second one with consideration that switch of converter is on.

$$G_1 = A^* \left| V_{PV,1}(K+1) = V_{ref} \right| + B^* \left| I_{PV,1}(K+1) - I_{ref} \right| \quad (12)$$

Where A and B are the weighting factors and the selection of A and B depends on try and error method [27]. Operation of the INC-MPC method is as follows; current and voltage of the PV module and the output voltage is measured. Then MPC predicts value of PV voltage and current in two stages i.e. one at on state and other at off state. Using current values PV voltage and current, MPC generate the reference current. From this data cost functions G_0 and G_1 are calculated. At the end cost function optimization [26].

III. DISCUSSION

Above discussed and many more MPPT techniques are presently available to PV system user, it might not be obvious for the latter to choose which one better suits there application needs. In this paper classification based on features like number of control variable required, sensors used, circuitry used, cost, and transient response is done.

1.According to number of control variables

There are different MPPT method which uses different number of control variables like voltage, current, temperature, irradiance, etc. MPPT Techniques can be classified according the number of control variable used. The classification is one variable technique and two variable technique. Taking only one control variable as voltage is suitable and efficient.

A. Sensors used

Decision of choosing MPPT technique also depends on number of sensors required and type of sensor required. Measurement of voltage is much easier than that of current measurement. Also current sensors are expensive and bulky. System that consist of several PV arrays with separate MPP trackers, use of current sensors might be inconvenient. In such cases, MPPT technique which uses only one sensor is convenient.

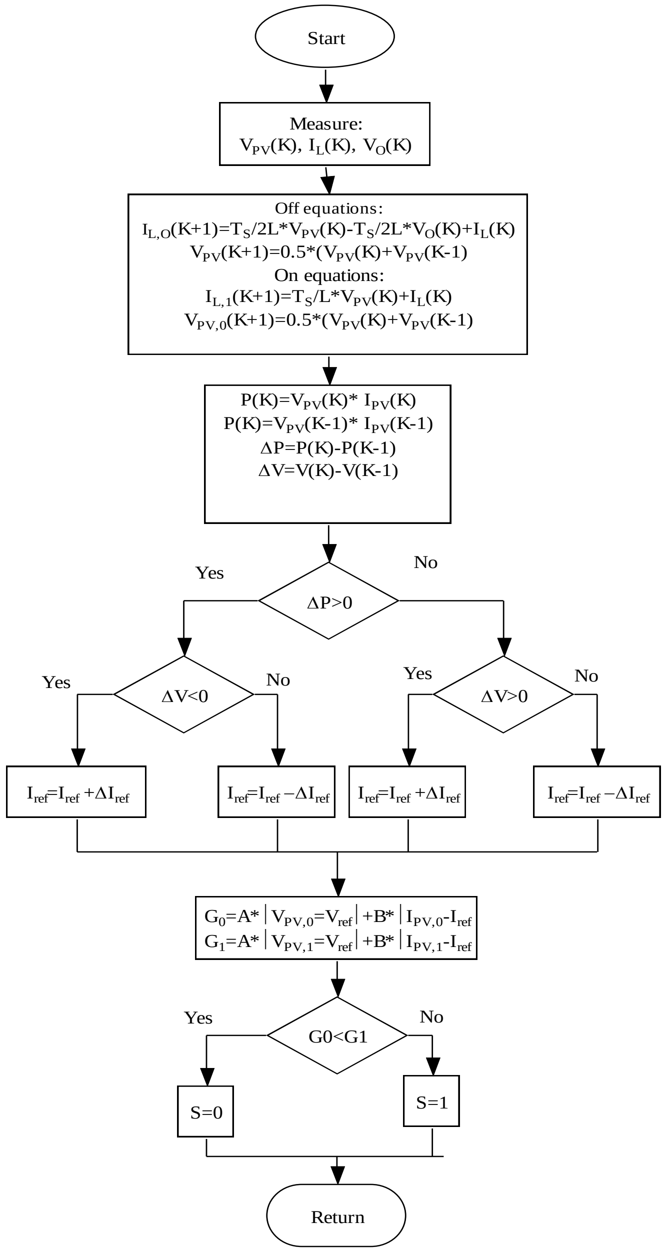

Fig 14: Flow chart of INC-MPC algorithm

B. According to types of circuitry used

There are two types of circuitry involve in MPPT technique such as analog and digital. The ease of implementation is an important factor for deciding which MPPT technique to select. Many user are comfortable with analog technique, so they can select short circuit, open circuit, or RCC technique. If others are willing to work with digital circuitry which requires the knowledge of software and programming. Then there selection should include P&O, incremental conductance, MRAC, etc.

TABLE I. Comparison of different MPPT techniques according to their classified types.

MPPT method	A/D	Parameter tuning	Converter used	Control variable	True MPPT	Convergence speed	Complexity	Cost	Transient response
A) S.C	Both	Yes	DC/DC	I	No	Medium	Medium	INEX	Poor
B) O.C	Both	Yes	DC/DC	V	No	Medium	Low	INEX	Poor
C) P&O	Both	No	DC/DC	V,I	Yes	Varies	Low	EX	Poor
D) INC	D	No	DC/DC	V,I	Yes	Varies	Medium	EX	Medium
E) RCC	A	Yes	DC/DC	V/I	Yes	Fast	Low	EX	Poor
F) A MPPT	D	Yes	DC/AC	V	Yes	Fast	High	EX	Good
G) DC link capacitor droop voltage	Both	No	DC/DC +DC/AC	V	No	Medium	Low	EX	Poor
H) Current sweep	D	Yes	DC/AC	I	Yes	Slow	High	EX	Poor
I) SVR	D	Yes	DC/DC +DC/AC	V,I	Yes	Fast	High	INEX	Medium
J) One cycle control	Both	Yes	DC/AC	I	No	Fast	Medium	INEX	Poor
K) E P&O	Both	No	DC/DC	V,I	Yes	Medium	Medium	EX	Poor
L) FLC	D	Yes	Both	V/I	Yes	Fast	High	EX	Medium
M) ANN	D	Yes	Both	V/I	Yes	Fast	High	EX	Medium
N) MRAC	D	Yes	DC/DC	V/I	Yes	Fast	Medium	EX	Good
O) DMPPT	D	Yes	DC/DC	I	Yes	Medium	High	EX	Poor
P) MPC	D	Yes	DC/DC	V,I	Yes	Fast	High	EX	Good

NOTE: V= voltage, I= current, A= analog, D= digital, EX= expensive, INEX = inexpensive.

C. According to cost

In some cases cost is not an issue but accuracy is needed fo example solar vehicles, industry, large scale residential. But some sys like water pumping for irrigation, small residency, etc. need simple and cheap MPPT technique. It is very hard to mention the exact cost of every single MPPT technique unless it is built and implemented. In this paper rough idea of expenses are describe in the table1.

D. According to cost

In some cases cost is not an issue but accuracy is needed fo example solar vehicles, industry, large scale residential. But some sys like water pumping for irrigation, small residency, etc. need simple and cheap MPPT technique. It is very hard to mention the exact cost of every single MPPT technique unless it is built and implemented. In this paper rough idea of expenses are describe in the table1.

E. Transient response

Many of the MPPT techniques discuss above gives true MPP at steady state due to the rapidly changing environmental conditions duty cycle also changes rapidly in order to track MPP. Hence transient oscillations occur at the output voltage. Sometime good transient response is needed. From the above discussed techniques, MRAC, MPC, AP&O, gives good transient response compare to single stage techniques like P&O, SC, OC, etc.

CONCLUSION

Several MPPT techniques taken from the literature are discussed and analyzed herein, with their advantage and disadvantages. The concluding discussion and the table should serve as useful guide for selection of proper MPPT technique. .

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