Improved Restricted Control Set Model Predictive Control (iRCS-MPC) Based Maximum Power Point Tracking of Photovoltaic Module

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ABSTRACT This paper presents a robust two stage maximum power point tracking (MPPT) system of the photovoltaic (PV) module using an improved restricted control set model predictive control (iRCS-MPC) technique. The suggested work is improved in two aspects; a revision in conventional P&O algorithm is made by employing three distinct step sizes for different conditions, and an improvement in conventional MPC algorithm. The improved MPC algorithm is based on the single step prediction horizon that provides less computational load and swift tracking of maximum power point (MPP) by applying the control pulses directly to the converter switch. The computer aided experimental results for various environmental scenarios revealed that compared with the conventional method (conventional P&O + MPC), for the PV power and inductor current, the undershoot and overshoot is decreased to 68% and 35% respectively under stiff environmental conditions. In addition, the settling time needed to reach a stable state is significantly reduced in the proposed system. The viability of the solution suggested is verified in MATLAB/Simulink and by hardware experimentation.

INDEX TERMS Boost converter, dc-dc power conversion, maximum power point tracking (MPPT), MPC, photovoltaic systems, model predictive control (RCS-MPC).

I. INTRODUCTION

The power harnessed by the PV unit is non-linear and dependent on the environmental conditions. Therefore, impedance matching is performed electronically to fetch maximum power from the PV module. Usually, load is matched with the PV module using a dedicated power electronic interface, for example a boost converter. A boost converter, matches the source impedance with the load impedance using software defined algorithms known as maximum power point tracking (MPPT) methods. Such algorithms record the reference variable in either current, voltage or the duty cycle and transfer to the controller the relevant output.

The most commonly used methods for MPPT are the hill climbing methods i.e., perturb and observe (P&O) and incremental conductance (InC) method [1]–[4]. Among these two, P&O is considered simple, flexible and more advantageous for commercial applications [5]. Conventional P&O methods, however, generate power oscillations under regular and volatile weather conditions. To solve these issues, researchers in [6], [7] recommended various strategies to follow the photovoltaic voltage using feedback system. Since the irradiation and photovoltaic current ($I_{pv}$) are linked together, in [8]–[10] the current is chosen as a control variable. However, under fast changing irradiation, the control system may lead the operating variable in the wrong direction, a phenomenon called drifting. The drifting phenomenon is mitigated in a revised sliding mode control (SMC) based P&O with voltage rectification loop [8]. In [11] an MPPT algorithm is presented that links the fractional short circuit current (FSCC) MPPT method to the conventional P&O. A model predictive controller (MPC) based MPPT is recommended in [10] wherein an MPC predicts the subsequent error. An appropriate control variable is applied to a dc-dc
TABLE 1. Comparison of different controllers used to track MPP.

| MPPT technique                      | Modulation   | Advantage                                      | Disadvantage                                      | Reference |
|-------------------------------------|--------------|------------------------------------------------|---------------------------------------------------|-----------|
| P&O technique                       | Pulse width modulation (PWM) | Easy implementation                            | Power oscillation under dynamic weather condition | [1], [15] |
| Incremental conductance technique  | PWM          | Control efficiency is better than P&O          | Not reliable                                      | [16], [17]|
| Fractional short circuit current    | PWM          | Perturbation is not required                    | Efficiency reduces                                 | [11], [18]|
| Fractional open circuit voltage     | PWM          | Perturbation is not required                    | Accuracy is reduced with respect to module parameters degradation | [19], [20]|
| Fuzzy logic based MPPT             | PWM          | Better tracks the MPP because of nonlinear control accuracy | Large computational load on controller and difficult to implement practically | [21], [22]|
| Sliding mode control based MPPT     | PWM          | High control efficiency than the previous techniques | Difficult to implement practically               | [8], [23] |
| MPC based MPPT                      | MPC pulses   | Fast Transient response                         | Small undershoot and overshoot under rapid change in irradiance | [24]      |
| Proposed modified MPC based MPPT    | MPC pulses   | No undershoot and overshoot under rapid change in irradiance | Not tested for grid connected application         | Proposed paper |

In the proposed work, an improved P&O algorithm based MPPT is combined with an improved restricted control set MPC (iRCS-MPC) controller. The proposed control technique reduces the implementation complexity for controller design and does not include inner control loops and infectors [25]. Moreover, use of restricted control set enjoys the modulator less operation and send the pulses directly to the boost converter. This uses a predictive limit to forecast the system’s future behavior by correctly modeling the practical system [26]. From the future behavior, the control algorithm decides the instantaneous input for which the instantaneous output is close to the desired output. In the proposed iRCS-MPC, only one step prediction limit is adopted to track the MPP. The paper presented makes an important contribution in minimizing the transients (% undershoot and overshoot) of the module current. Therefore, the power oscillations are significantly reduced without increasing the MPC workload. The remaining paper is organized according to the following scheme: Section II explains the PV system. Section III presents detailed modeling of the proposed system. Section IV explains the proposed approach. The concept validation of proposed and conventional method is exhibited under different simulation scenarios section V. In section VI, the validation of the proposed work is verified through hardware prototype.

II. PV SYSTEM DESCRIPTION

The proposed system is shown in Fig. 1. It includes a PV module, a dc-dc boost converter, resistive load and a control block. The inductor current \(I_L\), photovoltaic voltage \(V_{pv}\) and load voltage \(V_o\) are sensed using voltage and current sensors are used as input for the iRCS-MPC block. Note that the MPP tracker generates the reference current as output variable. The output of the iRCS-MPC block is used to gate the mosfet. \(\alpha\) and \(\beta\) in \(G_s = 0\) and \(G_s = 1\) are weighting factors that depends upon the priorities that are given to the different future errors in cost function (CF). \(V^*\) is the reference output voltage that is the numerical value provided by the user.

R.

III. PV SYSTEM MODELING

A. BOOST CONVERTER MODELING

Mathematical modeling in terms of state-space is desired for realizing the proposed iRCS-MPC system. The modeling is performed on the guidelines provided in [27]. Based on the gating signal of the switch \(Q\), a boost converter can have two equivalent circuits as shown in Fig. 2. Note that in Fig. 1, the control variables of the boost converter are \(I_L\) and \(V_{o}\).

During the switch off mode, the switch \(Q\) is open. The equivalent circuit shown in Fig. 2a can be mathematically expressed in terms of control variable as

\[
\frac{dI_L}{dt} = -\frac{1}{L} \cdot V_o + \frac{1}{L} \cdot V_{pv} \tag{1}
\]

\[
\frac{dV_o}{dt} = \frac{1}{C} \cdot I_L - \frac{1}{R_L \cdot C} \cdot V_o \tag{2}
\]

\(R_L\) represents the load resistance. To avoid mismatching condition and to improve the performance of the system, \(R_L\) should be calculated at each sampling instant. The calculation of \(R_L\) is given as follows:

\[
D = 1 - \left( \frac{V_{pv}}{V_c} \right) \tag{3}
\]

\[
i_o = i_L \cdot (1 - D) \tag{4}
\]

where \(i_o\) represents the output current

\[
R_L = \frac{V_c}{i_o} \tag{5}
\]
During the switch on mode, the switch Q is closed and therefore it can be modeled as a short circuit path. During this mode the control variables $I_L$ and $V_o$ are given as

\[
\frac{dI_L}{dt} = \frac{1}{L} V_{pv} \\
\frac{dV_o}{dt} = -\frac{1}{R_L C} V_o
\]

Equations (1)-(7) are transformed into a discrete domain for the practical use through the Euler equation as shown in eq.(8).

\[
\frac{dz(t)}{dt} \approx \frac{z(k+1) - z(k)}{T_s}
\]

where, $k$ is the sampling instant and $T_s$ is the sampling period.

Using eq.(8), eq. (1)- (7) can be discretized as follows:

\[
I_{L,s=0}(k+1) = I_L(k) - \frac{T_s}{L} V_o(k) + \frac{T_s}{L} V_{pv}(k) \\
V_{o,s=0}(k+1) = V_o(k) + \left(1 - \frac{T_s}{R_L C}\right) V_o(k) \\
I_{L,s=1}(k+1) = I_L(k) + \frac{T_s}{L} V_{pv}(k) \\
V_{o,s=1}(k+1) = (1 - \frac{T_s}{R_L C}) V_o(k)
\]

Note that the variable $C$ represents the output capacitor $C_o$, $L$ represents the inductor as shown in Fig.2. The eq.(9-12) can be rearranged as eq.(13).

\[
\begin{bmatrix}
I_{L}(k+1) \\
V_o(k+1)
\end{bmatrix} =
\begin{bmatrix}
1 & -(1-s) \frac{T_s}{L} \\
(1-s) & \frac{T_s}{C} (1 - \frac{T_s}{R_L C})
\end{bmatrix}
\begin{bmatrix}
I_L(k) \\
V_o(k)
\end{bmatrix} +
\begin{bmatrix}
\frac{T_s}{L} V_{pv}(k) \\
0
\end{bmatrix}
\]

where the switching condition of “$s$” is equivalent to 1 when switching on mode and 0 when switching off. Note that the performance of state variables $I_L$ and $V_o$ is projected to calculate the control sequence for the present and future sampling points.

**IV. PROPOSED SCHEME (REVISED P&O + iRCS-MPC)**

This section explains the proposed method (Revised P&O + iRCS-MPC) in contrast with the conventional method (conventional P&O + MPC). The proposed MPPT algorithm is a two stage scheme wherein, the first stage is the revised P&O and the second stage is the restricted control set MPC. The working of the stage I and II is explained below.

**A. STAGE I | THE REVISED P&O APPROACH**

The proposed MPPT method modifies the conventional P&O method in two aspects. First, it has two distinct step size values for various conditions. The $I_{inc1}$ is for normal P&O operation and $I_{inc2}$ is the step size for abrupt as well as for gradual change (Ramp shape) in irradiance. Secondly, the distinction between the gradual and sudden irradiance condition is made through a power limit that compares the power difference ($\Delta P$) with the predefined power band ($P_{set}$). The working of this stage is as follows.

The system starts by measuring the photovoltaic voltage ($V_{pv}$) and inductor current ($I_L$) and calculates the instantaneous power ($P_{pv}$). The algorithm then calculates the change in photovoltaic voltage ($\Delta V$), current ($\Delta I$), and power ($\Delta P$). The flowchart of the proposed system is shown in Fig.3. There are three different environmental conditions which is to be tackled by the proposed algorithm in stage I, the working of the proposed algorithm in stage I for three different environmental conditions are given as follows:

1) **NORMAL IRRADIANCE**

In this condition, the condition ($\Delta I >= I_{set}$) is violated because $I_{set}$ indicates the occurrence of gradual or abrupt change in irradiance, then ($I_{inc} = I_{inc1}$) is selected and then the second conditional block ($\Delta P > P_{set}$) is also violated because $P_{set}$ indicates the occurrence of abrupt change in irradiance. After that the conventional P&O is...
executed which provides $I^*$ for stage II. The working mechanism of proposed approach in normal irradiance condition is explained in Fig. 4.

2) GRADUALLY IRRADIANCE CHANGE (RAMP SHAPE)
In this condition, the condition ($\Delta I > I_{set}$) is fulfilled because $I_{set}$ indicates the occurrence of gradual or abrupt change in irradiance, then ($I_{inc} = I_{inc2}$) is selected and then the second conditional block ($\Delta P > P_{set}$) is violated because $P_{set}$ indicates the occurrence of abrupt change in irradiance. After that the conventional P&O is executed which provides $I^*$ for stage II. The working mechanism of proposed approach in gradual irradiance change condition is explained in Fig. 5.

3) ABRUPT IRRADIANCE CHANGE
In this condition, the conditional block ($\Delta I >= I_{set}$) is set true and ($I_{inc} = I_{inc2}$) is selected. In this case the second conditional block ($\Delta P > P_{set}$) is also fulfilled because $P_{set}$ indicates the occurrence of abrupt change in irradiance. In the first iteration, the stage I block provides the inductor current multiplied with $K_{opt}$ which is the optimum scaling factor as a reference current for stage II. This is done by turning on the MOSFET for somewhat extended period of time and it is synonymous to the concept of fractional short circuit current MPPT as expressed in eq. (14). The system is operated at this approximate MPPT and the reference is provided to stage 2. This is the instant when the ($I_L = I_{pv} = I_{scc}$), as evident from Fig. 2b. The working mechanism of proposed approach in abrupt irradiance change condition is explained in Fig. 6.

$$I_L \approx K_{opt} \cdot I_{scc}$$

where, $I_{scc}$ is the measured short circuit current, $K_{opt}$ is the optimum scaling factor with normal values between 0.80 to 0.92 [9], [28].
Stage 2 then receives the reference current as defined in eq. (14) until $\Delta P \leq P_{set}$ condition become fulfilled and then the algorithm jumps to the normal irradiation condition. After execution of stage I, the algorithm moves on to the stage II. The algorithm then moves on to the stage II (MPC block).

B. STAGE II | IMPROVED RESTRICTIVE CONTROL SET MODEL PREDICTIVE CONTROL

The reference current calculated in stage I is used in addition to the instantaneous photovoltaic current, voltage and output voltage. The future values of $I_{pv}$ and $V_o$ are predicted using eq.(10-13). The future values are then used to calculate $G_s=0$ and $G_s=1$ using the following procedure.

A general expression of CF for MPC algorithm which encompass the prediction step of M time steps is formulated as:

$$G_{cf} = \sum_{i=k}^{k+M-1} (||V_o(i)||^2 + u_{lim}(i))$$  \hspace{1cm} (15)

where $||V_o||^2$ is the predicted future error for the control variable in the form of Eucladian 2-norm, $u_{lim}$ is the constraint on current as defined below:

$$u_{lim}(i) = \begin{cases} 0 & \text{if } I \leq I_{min} \\ \inf & \text{if } I \geq I_{max} \end{cases}$$  \hspace{1cm} (16)

In the proposed iRCS-MPC, the time step used in (15) is limited to 1, consequently, Eq.(15) turns as follows:

$$G_s = \alpha \cdot |I_{LS}(k+1) - I^*| + \beta \cdot |V_{os}(k+1) - V^*|$$  \hspace{1cm} (17)

where, ‘s’ represents the switch status, either it is 0 or 1. Coefficients $\alpha$ and $\beta$ represents the weighting factors of current and voltage respectively. The working mechanism of iRCS-MPC is shown in Fig. 7 for inductor current and output voltage.

C. SELECTION OF $P_{set}$ FOR ABRUPT CHANGE IN THE IRRADIATION

The sudden change in irradiance greater than 100 W/m² is to be considered as abrupt irradiation change and in this case the modified part of P&O algorithm in Fig. 3 comes in action to quickly track the MPP. Selection of $P_{set}$ depends upon the sampling time that is used in the MPC based PV system. In simulations, it has to be checked as to how the value of $\Delta P$ changes at 100 W/m² of abrupt change in irradiance, note down the value of $\Delta P$ at the point of abrupt change and select the particular value of $\Delta P$ as $P_{set}$. Lower the sampling time, lower will be the value of $P_{set}$.

D. SELECTION CRITERIA FOR $I_{set}$

The slope of 3 W/m² is considered to be a gradual change in irradiance. Selection of $I_{set}$ depends upon the sampling time that is used in the MPC based PV system. In simulations it has to be check that during gradual change in irradiance, how the value of $\Delta I$ changes in one iteration. Note down the value of $\Delta I$ at that point and select the particular value as $I_{set}$. Lower the sampling time, lower will be the value of $I_{set}$.

E. SELECTION CRITERIA FOR WEIGHTING FACTOR $\alpha$ AND $\beta$

In simulations, $\alpha$ and $\beta$ is varied from 0 to 1 with the step of 0.1, then note down the average inductor current error and average output voltage error for each combination of $\alpha$ and $\beta$. Plot the graph of $\alpha$ vs $\beta$ vs absolute average inductor current error and $\alpha$ vs $\beta$ vs absolute average output voltage error as shown in the average inductor current increases the average output voltage as shown in Fig. 8. From Fig. 8, select the combination of $\alpha$ and $\beta$ so that the average inductor current error and average output voltage error is within the desired range for the particular application. In this work, inductor current is given more importance because it is involved in MPPT algorithm. The selected combination of $\alpha$ and $\beta$ are 0.89 and 0.14 respectively.
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V. CONCEPT VALIDATION

The proposed scheme is evaluated thoroughly using numerical simulations in MATLAB/Simulink and hardware prototype built in the laboratory. The results obtained through numerical simulations were benchmarked with the conventional P&O + MPC method. A boost converter with the specifications are presented in Table 2 is used to interface the PV source with the load. Notice that the weighting factor of current is more than the weighting factor of voltage. This indicates that the system is prioritized for the current control in particular. Note that from all the calculations of settling time, undershoot and overshoot for the respective testing condition, the minimum value of each is the best case scenario and maximum value is the worst case scenario.

The circuit shown in Fig.1 is tested and analyzed under six different environmental condition cases for 3s time. The obtained results for $P_{pv}$ and $I_L$ are plotted on the same graph for performance comparison. Moreover, the formula for percentage undershoot(US) and overshoot(OS) is based on the eq.(18) and eq.(19)

$$\%US = \frac{|Amp \ osc - std \ amp| \times 100}{std \ osc}$$

$$\%OS = \frac{|value \ after \ osc - peak \ osc| \times 100}{peak \ osc}$$

where, amp is amplitude, osc is oscillation, std represents steady.

A. CASE # 1

This case represents the standard testing conditions for PV panels i.e., 1000 $W/m^2$ irradiance and 25 °C temperature. The results for both conventional and proposed approach is shown in Fig.9.

The comparison between the conventional and proposed approach for testing condition # 1 is given in Table 3.

B. CASE # 2

Case two represents abrupt increase, decrease and gradual increase, decrease in irradiance while maintaining the temperature at 25 °C. The irradiation pattern is suddenly and gradually reduced from 1k $W/m^2$ to 0.7k $W/m^2$ and then from 0.7k $W/m^2$ to 1k $W/m^2$ as shown in Fig.10. The system outcome for proposed and conventional approach is shown in Fig. 11. The comparison between the conventional and proposed approach under case # 2 is given in Table 4.

| Specifications     | Conventional | Proposed |
|--------------------|--------------|----------|
| % of OS in PV power| 0%           | 0%       |
| Settling time      | 50 ms        | 66 ms    |

TABLE 2. Parameter summary.

| Specification | Variable | Value |
|---------------|----------|-------|
| PV module     | BIPV BIPV050-S11 | 49.68 W |
| Maximum voltage | $V_{oc}$ | 8.66 V |
| Maximum Current | $I_{sc}$ | 8.01 A |
| MPP voltage   | $V_{mpp}$ | 6.66 V |
| MPP current   | $I_{mpp}$ | 7.46 A |

TABLE 3. Comparison between conventional and proposed Approach for case # 1 (Note: O/S is overshoot).

![FIGURE 8. $\alpha$ vs $\beta$ vs [average inductor current error] and $\alpha$ vs $\beta$ vs [average output voltage error].](image1)

![FIGURE 9. System performance under case # 1.](image2)

![FIGURE 10. System performance under case # 2.](image3)
In case #3, the irradiation pattern simulates a step change in irradiance at the rate of 100 $W/m^2$ every 0.15s till zero. Afterwards it simulates an increment at the rate of 100 $W/m^2$ every 0.15s till 1000 $W/m^2$. Note that the temperature is fixed at 25 °C. The environmental conditions for case #3 is shown in Fig. 12. The system response for both the proposed and conventional approach under case #3 is shown in Fig. 13. The contrast between the two methods is shown in the Table 5.

### Table 4. Comparison of conventional method and proposed approach for case #2 (Note: U/S is undershoot and O/S is overshoot).

| Specifications                                      | Conventional | Proposed |
|-----------------------------------------------------|--------------|----------|
| % of U/S in PV power under abrupt change in irradiation | 43%          | 11%      |
| Settling time in case of sudden decrease in PV power | 26 ms        | 6 ms     |
| % of O/S in PV power under abrupt change in irradiation | 0%           | 0%       |
| Settling time in case of sudden increase in irradiation in PV power | 40 ms        | 1 ms     |
| % of U/S in $I_L$ in case of sudden irradiation change | 24%          | 4%       |
| Settling time of $I_L$ if irradiation unexpectedly reduces | 30 ms        | 5 ms     |
| % of O/S in $I_L$ in case of sudden irradiation change | 0%           | 0%       |
| Settling time of $I_L$ if irradiation unexpectedly increases | 35 ms        | 35 ms    |

### D. ROBUSTNESS OF THE PROPOSED SYSTEM

The robustness of the proposed system with respect to the conventional system is being determined from the phase portrait plot that is plotted under rapid step change in irradiance from 0 to 800 $W/m^2$ as shown in Fig. 14. From Fig. 14, it is analyzed that the derivative of output power is much smaller in proposed system as compared to conventional system which means that overshoot is larger in conventional system than proposed system. Moreover, the outer most circle rounds at 58W in conventional system while outermost circle rounds at 62.7W power which means that proposed system achieve stable condition having less oscillations than the conventional system.

The effect of change in output capacitance and inductor due to the effect of change in temperature or some non-linearities in the system on average inductor current is shown in Fig. 15. It is analyzed from Fig. 15 that average inductor current error have not much impact on distracting the MPP from its original point.

In conventional method, $R_L$ in the algorithm is constant throughout the operation while in proposed system $R_L$ is calculated in each sampling instant. The effect of change in $R_L$ due to the change in temperature or other non-linearities in the system on average inductor current error and average output voltage error is shown in Fig. 16 and it is analyzed that in conventional system, change in load resistance have much effect on distracting the system from original MPP.
TABLE 5. Comparison of conventional method and proposed approach for case # 3 (Note: U/S is undershoot and O/S is overshoot).

| Specifications                                | Conventional | Proposed |
|-----------------------------------------------|--------------|----------|
| % of U/S in PV power in case of sudden decrease in irradiation | 5%           | 0%       |
| % of U/S in PV power in case of sudden decrease in irradiation (Worst Case) | 44%          | 22%      |
| % of O/S in PV power in case of sudden increase in irradiation (Best Case) | 0%           | 0%       |
| % of O/S in PV power in case of sudden increase in irradiation (Worst Case) | 33%          | 18%      |
| Settling time in case of sudden decrease in PV power (Best Case) | 9 ms         | 5 ms     |
| Settling time in case of sudden decrease in PV power (Worst Case) | 83 ms        | 49 ms    |
| Settling time in case of sudden increase in PV power (Best Case) | 7 ms         | 4 ms     |
| Settling time in case of sudden increase in PV power (Worst Case) | 59 ms        | 33 ms    |
| % of U/S in $I_L$ in case of sudden irradiation change (Best Case) | 0%           | 0%       |
| % of U/S in $I_L$ in case of sudden irradiation change (Worst Case) | 35%          | 19%      |
| % of O/S in $I_L$ in case of sudden irradiation change (Best Case) | 0%           | 0%       |
| % of O/S in $I_L$ in case of sudden irradiation change (Worst Case) | 22%          | 17%      |
| Settling time of $I_L$ if irradiation unexpectedly reduces (Worst Case) | 82 ms        | 51 ms    |
| Settling time in case of sudden increase in irradiation in $I_L$ (Best Case) | 7 ms         | 4 ms     |
| Settling time in case of sudden increase in irradiation in $I_L$ (Worst Case) | 81 ms        | 47 ms    |

E. ANALYSIS OF COMPUTATIONAL TIME OF THE RECOMMENDED APPROACH

Figure 18 shows the pseudo code for calculating the computational time complexity. Here, N denotes the time step of MPC algorithm. In Fig. 18, cost of each executed command in a continuous loop is presented through which, the total time complexity function $W(n)$ of proposed scheme is calculated as follows:

$$W(n) = c_0 \ast 1 + c_1 \ast 1 + (c_2 \ast 2^N + 1)(c_3 \ast 1 + c_4 \ast 1 + c_5 \ast 1 + c_6 \ast 1 + c_7 \ast 1) + c_8 \ast 1 + c_9 \ast 1$$

(20)

where $c_0$-$c_9$ is the time utilized by the controller to undergo a given instruction with best, average and worst case scenario.

After solving, the (20) becomes

$$W(n) = c_0 + c_1 + c_8 + c_9 + c_2 \ast c_3 \ast 2^N + c_2 \ast c_4 \ast 2^N + c_2 \ast c_5 \ast 2^N + c_2 \ast c_6 \ast 2^N + c_2 \ast c_7 \ast 2^N + c_3 + c_4 + c_5 + c_6 + c_7$$

(21)
In the presented algorithm, to minimize the computational burden, the value of N is kept to 1 therefore (21) becomes

\[ W(n) = c_0 + c_1 + c_8 + c_9 + c_2 \times c_3 \times 2 + c_2 \times c_4 \times 2 + c_2 \times c_5 \times 2 + c_2 \times c_6 \times 2 + c_2 \times c_7 \times 2 + c_3 + c_4 + c_5 + c_6 + c_7 \]  

(22)

Note that larger the time step more is the value of W(n) and hence the computational load.

The comparison of the control efficiency among P&O in [15], Optimized P&O in [29], MPC based MPPT in [24] and proposed approach for different step change in irradiance is shown in Fig. 17. It is analyzed from Fig. 17 that upto absolute step change in irradiance of 200 W/m², control efficiency is almost equal to the control efficiency in MPC based MPPT, but it is significantly changed when step change in irradiance is increased and that is due to the modification in the flowchart of the proposed system that is shown in Fig. 3.

**VI. EXPERIMENTAL VALIDATION OF PROPOSED METHOD**

The experimental setup for the feasibility of the proposed method is shown in Fig. 19. The parameters used in the experimental setup is given in Table 6. Stm32F407-Discovery is used for the implementation of the proposed algorithm to generate the gating signal to drive the MOSFET in boost converter. Variable rheostat (0-100) Ω is used as a DC load in the experimental setup. The proposed system was tested for different reference current on normal sunny day as shown in Fig. 20 and 22, which shows tracking capability of the proposed system for different reference current. The result of conventional P&O system is expressed in Fig.21. It is visible that the conventional P&O method suffers from overshoot during change in reference current. In Fig.23, at t₀, the proposed system tracked the MPP at the practical environmental conditions at that time and at t₁, the PV module is artificially shaded as shown in Fig.24 and the tracking
VII. CONCLUSION

In this work, a revised P&O approach with modified MPC controller to track the MPP is proposed. It is verified under different practical testing conditions and compared with the conventional P&O algorithm. After analyzing the results from both of the methods under different testing conditions we conclude that:

- Overshoot in PV power under a sudden increase in irradiation is minimized up to 35% of its original value in the worst case when compared with the conventional method.
- Undershoot in PV power under a sudden increase in irradiation is minimized up to 68% of its original value in the worst when compared with the conventional method.
- Settling time in PV power is reduced to 145 ms in worst case environmental conditions in contrast with the benchmarked method.
- The computational load is reduced because application of iRCS-MPC algorithm in the MPC controller block.

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