CHAPTER 4

A NOVEL LOCV-VSS- INC STRATEGY BASED HYBRID MPPT CONTROLLER FOR PV - SSIFB SYSTEM

4.1 INTRODUCTION

In this chapter, a novel Hybrid Maximum Power Point Tracking (HMPPT) controller is introduced for harvesting maximum power from PV system with Soft Switched Interleaved Flyback (SSIFB) converter.

In medium and large PV systems, developing an efficient MPPT controller to make full utilization of PV array output power irrespective of solar irradiation, temperature and load characteristics forms the most essential part of the design. According to the complexity, convergence speed and effectiveness range, the MPPT techniques are categorized in to direct and indirect algorithms and most popular MPPT methods available in PV market were discussed in chapter 3.

The indirect MPPT algorithms generate the control signal depending on the prior evaluation of physical data model of PV panel and hence cannot track the MPP exactly as they operate under the assumption that any variations of PV panel temperature and irradiation have insignificant effect on MPP. So the indirect methods provide poor performance at higher irradiation as the MPPT efficiency depends on environmental conditions.
On other hand, the direct methods provide more accurate tracking as they employ the instantaneous values of PV current and PV voltage to generate control signals. In direct methods, the MPP is reached by periodically perturbing PV voltage ($V_{PV}$) or duty ratio (D) in steps based on the change in PV power (dP). However, these direct methods are less effective at lower irradiation as the dP becomes very small and the perturbation direction cannot be decided.

To track MPP effectively at all irradiations, the hybrid MPPT methods are developed as the combination of indirect and direct MPPT methods. The hybrid methods generate the control signal in two steps. First step is the estimation step which moves the reference point close to MPP using any simplified indirect method. The second step is a fine tuning step in which the exact MPP is reached using any direct MPPT method. Some hybrid methods employ Variable Step Size (VSS) MPPT methods to provide the faster dynamic response and good steady state performance. The choice of perturbation Step Size determines the MPPT performance such that the smaller Step Size exhibits slow response and larger Step Size makes the system oscillate around MPP. VSS MPPT methods seek MPP on a principle that a large Step Size is used when the reference voltage is far away from MPP and small perturbation step is used when the set point approach the region around the MPP.

In this chapter, a HMPPT controller is proposed and implemented on a 100W PV generation system with Soft Switched Interleaved Flyback (SSIFB) converter. The proposed HMPPT technique employs the modified OCV MPPT method viz., Linear Open Circuit Voltage (LOCV) based indirect method for lower irradiations and VSS INC based direct MPPT method for medium and higher irradiations. The steady state performance under various constant irradiations and transient characteristics for rapidly varying irradiations and changing load are investigated and conclusions drawn from the study are listed in the end of the chapter.
4.2 SYSTEM DESCRIPTION

Figure 4.1 shows the block diagram of PV-SSIFB system with proposed Hybrid MPPT controller. The HMPPT controller is designed to extract maximum power from PV panels. To implement the HMPPT technique effectively and to change the unregulated DC voltage from PV panel to desired, regulated DC voltage, a high efficiency SSIFB converter is connected between the PV source and DC loads. In chapter 2, the description of the SSIFB converter topology, its equivalent circuit, key diagrams, design equations were explained in detail. Single diode model is used to draw the equivalent circuit of the PV cell. The mathematical model derived from equivalent circuit of PV cell to simulate the PV characteristics was explained in detail in chapter 3. A lead acid battery is also included in the PV system to provide backup power during night times and low insolation conditions.
4.3 PRINCIPLE OF PROPOSED HMPPT ALGORITHM

The I-V and P-V characteristics of PV panel are non-linear and MPP varies with the changes in irradiance and temperature. When connected to load, the MPPT controller operates on the principle that MPP occurs at the equilibrium point of load line and PV characteristics. (ie) At MPP, the PV power \( P_{\text{MPP}} \) is equal to load power \( P_L \).

Figure 4.2 shows the load line and output characteristics of PV panel. When the load is connected directly to PV panel, the power available at load \( P_{L1} \) is lower than \( P_{\text{MPP}} \). Hence a DC–DC converter interface is included between PV source and load so that the load line is moved along the locus of the MPP and maximum power is extracted from PV panel at all climatic conditions. The function of the MPPT controller is to locate the MPP using an efficient tracking algorithm. The MPPT algorithm modifies the duty cycle \( D \) of the DC-DC converter till the load line intersects the MPP and maximum output power is obtained.
4.3.1 Step Change in Load

Figure 4.3 Load lines on I–V curve for the step variation of load

Figure 4.3 shows the load – I-V characteristics during load change. When load $R_L$ is varied, the load line is no longer intersects the MPP. As the irradiation remains constant, the PV voltage and PV current at MPP ($V_{MPP}$ and $I_{MPP}$) are maintained same. But the duty cycle $D$ of the converter varied by MPPT controller such that the load line passes through the MPP. When load is decreased (increased) from nominal value, the MPPT algorithm increase (decrease) the load current ($I_O$) and decrease (increase) the load voltage ($V_O$) till MPP is reached.

4.3.2 Rapid Change in Irradiation

Figure 4.4 shows the load – I-V characteristics during the rapid irradiation change. When irradiation is varied, the MPP is also changed and load line lies far away from new MPP. The MPPT controller changes duty cycle of converter such that all four parameters viz., $V_{MPP}$, $I_{MPP}$, $V_O$, $I_O$ have been modified to deliver maximum power. When the irradiation is increased
(decreased), the MPPT algorithm increase (decrease) the voltages ($V_{MPP}$, $V_O$) and currents ($I_{MPP}$, $I_O$) at both input and output side till MPP is reached.

![Graph showing load lines on I–V curves](image)

**Figure 4.4** Load lines on I–V curves for the rapid change of solar irradiation from 0.3 to 1.0 KW/m²

### 4.4 CHOICE OF ALGORITHMS FOR PROPOSED HMPPT METHOD

In general, the HMPPT is the combination of indirect and direct MPPT methods. The factors that have decided the choice of indirect and direct methods selected for the proposed HMPPT method are described in this section. In addition, Variable Step Size (VSS) update rule is followed in HMPPT method to increase the tracking speed and choice of VSS method used is also justified in this section.

#### 4.4.1 Selection of Direct Method for Medium and Higher Irradiations

Among the direct MPPT methods, INC and P&O provide the accurate tracking of MPP by perturbing the PV voltage ($V_{PV}$) in small steps. The direction of perturbation depends on the change in PV power (dP) or PV
current (dI). However, these methods are less effective at lower irradiation as the dP and dI become very small and the perturbation direction cannot be decided.

Though P&O algorithm is simpler than INC algorithm, it is not preferable for two reasons.

i. The PV power loss occurs as the P&O algorithm oscillates around MPP. The oscillations and resulting power loss is more pronounced in slowly varying atmosphere.

ii. In P&O algorithm, the perturbation in PV voltage (dV) is based on the change in PV power (dP). During the rapidly changing atmospheric conditions, the P&O algorithm could not differentiate between the change of power (dP) and change of irradiance.

Hence, in the proposed HMPPT algorithm, the INC MPPT method is opted for tracking MPP at medium and higher irradiations

4.4.2 Selection of Indirect Method For Low Irradiations

The indirect methods such as OCV, Short Circuit Current (SCC) techniques, track the MPP by matching the measured PV voltage (V_PV) with fixed reference voltage (V_{REF}) or measured PV current (I_PV) with fixed reference current (I_{REF}) respectively. In PV system, changing irradiations dramatically affects the MPP current (I_{MPP}) but slightly affects the MPP voltage (V_{MPP}) whereas the change in cell temperature affects V_{MPP} more than the I_{MPP}. Since cell temperature has the slow dynamics unlike irradiations, it is easy the bound the V_{MPP} within certain range. V_{MPP} is usually considered 70 to 82 % open circuit voltage (V_{OC}). Hence OCV technique is a better choice than SCC technique among the indirect methods. However, the indirect
methods present poor performance at higher irradiation as they use the linear relationship between $V_{OC}$ and $V_{MPP}$ or $I_{SC}$ and $I_{MPP}$ to reach MPP.

In the proposed HMPPT algorithm, a modified OCV method viz., Linear Open Circuit Voltage (LOCV) method is opted for tracking MPP at lower irrigations.

### 4.4.3 Choice of Variable Step Size (VSS) Operation.

For faster and smooth response, Variable Step Size (VSS) perturbation is preferred than Fixed Step Size (FSS) operation.

VSS is achieved as explained below

i. When $P_{PV}$ is far away from MPP, $V_{PV}$ is updated using large Step Size.

ii. When the $P_{PV}$ is reaching closer to MPP, $V_{PV}$ is updated with smaller Step Size.

There are two simple and popular methods available to implement the Variable Step Size efficiently.

i. Bisection method

ii. Multiplication factor method

#### 4.4.3.1 Bisection method

In this method, bisection principle is employed to reduce the Step Size when operating point is reached near the MPP and sign of the slope of PV curve determines the closeness of the reference point to MPP as shown in Figure 4.5.
Steps involved in bisection based VSS algorithm are listed below.

i. At any instant (n), PV voltage ($V_{PV}$) and current ($I_{PV}$) are measured.

ii. The PV power change (dP) and slope (dP/dV) are calculated for the instants (n) and (n-1).

iii. If slope is positive, voltage is incremented by large Step Size. However the negative slope implies that the operating point has crossed the MPP.

iv. Hence, when the negative slope is encountered, the Step Size is reduced by applying the bisection principle. In Figure 4.5, $V(n-1)$ shall not be changed but $V(n)$ is replaced by $V_{new}$ which is the average of $V(n)$ and $V(n-1)$. The difference between the values $V(n-1)$ and $V_{new}$ is calculated and the resulting smaller Step Size (d$V_{new}$) is used to increment the PV voltage. This process is continued until the power change (dP) comes within a very small range, say 0.1.

Figure 4.5 Principle of bisection method based VSS MPPT algorithm
4.4.3.2 Multiplication factor (M.F) method

In this method, the updating rule for the Step Size (SS) depends on the dP/dV and multiplication factor (M.F). (ie)

\[ \text{VSS} = M \cdot F \times \frac{dP}{dV} \tag{4.1} \]

where

\[ \frac{dP}{dV} = \frac{P_{\text{pv}}(n) - P_{\text{pv}}(n-1)}{V_{\text{pv}}(n) - V_{\text{pv}}(n-1)} \tag{4.2} \]

The performance of M.F based VSS MPPT system is determined by the optimum design of the multiplication factor (M.F). The smaller M.F affects the transient response and larger M.F may result in FSS operation.

\[ 0 < M \cdot F \leq dV_{\text{max}} \left/ \frac{dP}{dV}_{\text{Fixed step}=dV_{\text{max}}} \right. \tag{4.3} \]

where \( dV_{\text{max}} \) is the maximum allowed FSS perturbation in PV voltage that ensures a good transient response and the denominator represents the maximum steady state value of dP/dV measured at maximum FSS perturbation (dV_{max}).

Both bisection and MF methods calculate the VSS based on the change in PV power (dP) with respect to change in PV voltage (dV). In bisection method, the Step Size is calculated based on dP at each irradiation. It cannot perform effectively at lower irradiations as the dP become very small (<0.1) due to the flatness of the P-V characteristics. In MF method, MF is calculated based on maximum steady state value of dP/dV which usually occurs in higher irradiations and MF will not change with changing irradiations.
In the proposed HMPPT algorithm, MF based VSS perturbation is used for all irradiations.

4.5 PROPOSED HYBRID MPPT METHOD

The proposed HMPPT controller employs Linear Open Circuit Voltage indirect method for low Irradiation and Incremental Conductance MPPT algorithm for medium and high Irradiation. Both methods use the multiplication factor based VSS to update the $V_{REF}$. Thus the proposed HMPPT combines the advantages of indirect and direct MPPT techniques as well as VSS techniques.

Figure 4.6 describes the flow chart of the proposed HMPPT algorithm.

![Flow chart of proposed LOCV- VSS- INC method based HMPPT controller](image-url)
4.5.1 VSS - LOCV Method for Low Irradiations (G ≤ 350W/m²)

The flow chart and steps followed in OCV method is explained in chapter 3. In the Open Circuit Voltage (OCV) MPPT method, the $V_{MPP}$ is calculated from a fraction of the open circuit voltage ($V_{OC}$) as given in Equation (4.4).

$$V_{MPP} = K_V \times V_{OC}$$

where $K_V$ is an empirical constant and its value ranges from 0.73 to 0.8. In this work the value of $K_V$ is taken as 0.78.

The proposed LOCV MPPT algorithm uses the modified version of OCV method in which Equation (4.4) is generalized using linear fit. In LOCV method, $V_{MPP}$ is calculated by the Equation (4.5).

$$V_{MPP} = p V_{OC} + q$$

where $p$ and $q$ are empirical coefficients determined by applying least-squares regression method on ‘m’ samples of $V_{OC}$ and $V_{MPP}$. For 6 samples of $V_{OC}$ and $V_{MPP}$, $p$ and $q$ values are calculated as 0.825 and 1.53 respectively. MF based VSS is used to update the $V_{REF}$ in LOCV MPPT method.

The LOCV algorithm requires the periodic measurement of voltage at open circuit ($V_{OC}$). To eliminate the power loss during $V_{OC}$ measurements, an additional solar cell called pilot cell is introduced. The pilot cell has same characteristics as that of main PV module and measure the voltage in open circuit configuration.

4.5.2 VSS - INC MPPT Algorithm for Medium and High Irradiations (G > 350W/m²)

The INC algorithm perturbs the PV voltage ($V_{PV}$) according to the slope (dP/dV) of the PV characteristics. The value of slope dP/dV is positive at the left side of the MPP as the power is increasing with increase in PV
voltage, negative to the right side of the MPP and vanishes at MPP. The flowchart and steps involved in INC method are explained in chapter 3. The sign of $dP/dV$ is checked by measuring and comparing the instantaneous and incremental conductance ($I/V$ and $dI/dV$) of PV array. The rapid change in atmosphere is detected by the condition $(dV=0; dI\neq0)$. $V_{REF}$ is updated using MF based VSS method.

### 4.6 DISCUSSIONS ON SIMULATION AND EXPERIMENTAL RESULTS

To investigate the effectiveness of the proposed HMPPT algorithm, the performance characteristics at steady state and transient conditions were analyzed for different constant and rapidly changing irradiations and load changes. MATLAB/SIMULINK software was used to simulate the overall PV system and the results were verified experimentally on a 100W prototype. The detailed specification of the 100W SSIFB converter is given in Chapter 2 - Table 2.1. PV source was constructed by connecting 5 numbers of USL - KL020 model, polycrystalline type PV modules in series. The electrical parameters of each PV module at Standard Test Conditions (STC) are listed in Chapter 3- Table 3.1. The hardware setup of PV arrays with different positions to attain desired irradiations, series connection of PV modules to get desired voltage/power and sliding arrangement to change the irradiations are shown in Figure 4.7 and 4.8.

Figure 4.9 shows the experimental hardware setup of the proposed SSIFB PV system with HMPPT controller. A 16 bit dsPIC30F4011 controller was used to implement the HMPPT control scheme. The irradiation was measured by solar power meter (Model - KM-SPM-11) and a pilot solar cell was used for the $V_{OC}$ measurement required by LOCV technique. LEM voltage and current sensors were used to measure the $V_{PV}$, $I_{PV}$ and switch currents. The gate signals for the switches $S_a$ and $S_b$ should have $180^\circ$ phase difference and generated by the driver circuit IR2128.
Figure 4.7 Position of PV arrays for different irradiations (a) 0.9KW/m² (b) 0.6KW/m² (c) 0.3KW/m²
Figure 4.8  Series connection of PV modules and sliding arrangement of PV arrays

Figure 4.9  Hardware setup for PV-SSIFB system with HMPPT controller

Figure 4.10 illustrates the control scheme of PV – SSIFB system with HMPPT controller. It consists of 2 control loops viz, MPPT control and average current control. The proposed HMPPT algorithm calculates $v_{MPP}$ and compares it with sensed PV voltage $v_{pv}$. The error $v_e$ generated was given as input to PI voltage controller. The output $u_v$ was then divided into two current reference signals which were 180° phase apart. These current references $u_{a1}$ and $u_{a2}$ were compared with switch current in each phase and the difference was given as input to the PI current controllers. The output of the PI current
controller was compared with carrier signal to generate gate signals for switches $S_a$ and $S_b$. The PI loop update rate should be faster than the MPPT update rate so that PV voltage had enough time for stabilization. Reverse PI algorithm was applied as the decrease in PV voltage causes the increase in duty cycle ($D$) and vice versa. The optimum operating range of duty ratio was fixed between 0.3 and 0.7.

Figure 4.10 Block diagram of control scheme of PV- SSIFB system with HMPPT Controller
The temperature is maintained within certain range (NOCT) throughout the investigation as the dynamics of PV cell temperature is slower than that of solar irradiation. Figure 4.11 (a) and (b) show the I-V and P-V characteristics of PV array which were simulated by solving single diode model of PV cell as explained in Chapter 3 - section 3.2.1 for different solar irradiation values at NOCT. The simulation and experimental results of PV array characteristics obtained for different solar irradiations (G) at NOCT were compared and listed in Table 4.1 and 4.2.

Figure 4.12 presents the simulated and experimental waveforms of MOSFET switches $S_a$, $S_b$ and $L_r$ of SSIFB converter at irradiation $(G) = 0.9 \text{KW/m}^2$ and duty ratio $= 0.58$. It was noted that the gate signals were complementary to each other. Also it was verified that the switch voltage $(v_{DS})$ reached zero long before the switch current $(i_S)$ rises and thus a ‘Zero voltage turn On’ was achieved.

![Figure 4.11 Simulated waveforms of PV array (a) I-V characteristics (b) P-V characteristics](image-url)
Table 4.1 PV module characteristics at NOCT- Simulation results

<table>
<thead>
<tr>
<th>Irradiation G (KW/m²)</th>
<th>Simulation Results</th>
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<tr>
<td></td>
<td>V_{OC} (V)</td>
<td>I_{SC} (A)</td>
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<tr>
<td>0.90</td>
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<td>0.75</td>
<td>88.0</td>
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<td>0.60</td>
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<td>0.15</td>
<td>63.8</td>
<td>0.221</td>
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Table 4.2 PV module characteristics at NOCT- Hardware results and percentage error

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<tr>
<th>Irradiation G (KW/m²)</th>
<th>Experimental Results</th>
<th>Error (%)</th>
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<td>V_{MPP} (V)</td>
<td>I_{MPP} (A)</td>
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<td>0.90</td>
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<td>0.75</td>
<td>78</td>
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<td>64.6</td>
<td>0.369</td>
</tr>
<tr>
<td>0.15</td>
<td>55.8</td>
<td>0.174</td>
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</table>
The VSS was designed by calculating the multiplication factor. For the proposed system, the maximum Fixed Step Size (dV\text{max}) at which faster dynamic response obtained was 0.4. The steady state value dP/dV measured at dV\text{max} = 0.4 has been applied on equation (4.3) to calculate the M.F and was found to be 0.169. (ie) 0 < M.F \leq 1.169.

Figure 4.13 shows the MPP tacking procedure of VSS INC technique and FSS INC technique with Step Size 0.1 and 0.4. It was observed that the FSS always varies ±Step size (SS) to smooth the oscillations at steady state. In this case, FSS varies between ±0.4 for large Step Size and ±0.1 for small Step Size. But the VSS starts from large Step Size and continuously decreases the Step Size till MPP was reached. The maximum Step Size reached for irradiation 0.6KW/m\textsuperscript{2} was 0.49.
Figure 4.13 MPP tracking procedure for FSS INC and VSS INC algorithms at irradiation 0.6KW/m²

Figure 4.14 shows the simulation and hardware results of the steady state performance analysis of proposed system at irradiation $G = 0.6KW/m^2$ by employing VSS INC and FSS INC method with Step Size 0.4 and 0.1. For FSS INC of Step Size 0.1, the PV voltage ($V_{PV}$) was perturbed in steps of 0.1 and it reaches the MPP very slowly and smoothly. The FSS with step size 0.4 gave the faster response but has more oscillations at steady state. In VSS INC method, the MPP was reached faster and the steady state oscillations were completely removed. The hardware results clearly differentiate the settling time ($T_{set,PV}$) for VSS and FSS INC algorithms.
Figure 4.14 Simulation and experimental waveforms at irradiation 0.6KW/m² (a) FSS INC method with Step Size 0.1 (b) FSS INC method with Step Size 0.4 (c) Proposed VSS INC method
The FSS INC with Step Size 0.1 reached the MPP in 35 seconds while that with Step Size 0.4 reached in 10 seconds. VSS INC reached MPP in 9 seconds which was lesser than FSS INC with SS 0.4 and has smooth waveforms similar to FSS INC with Step Size 0.1.

Figure 4.15 Steady state performance of PV - SSIFB System at $R_L=125\Omega$; a(i) & a(ii) Simulation and experimental results at irradiation 0.9KW/m$^2$; b(i) & b(ii) Simulation and experimental results at irradiation 0.3KW/m$^2$
Figure 4.15 a(i) and b(i) show the simulation results of the steady state performance of SSIFB converter with proposed HMPPT controller at higher and lower irradiation. VSS INC MPPT algorithm was used to track the MPP at irradiation 0.9KW/m². MPP was reached at 0.045 seconds with maximum Step Size of 1.576. LOCV MPPT algorithm was selected for irradiation 0.3KW/m². The settling time (T_{set,PV}) was 0.07 seconds and maximum Step Size obtained was 0.118. The hardware results shown in Figure 4.15 a(ii) & b(ii) validate simulation results. In experimental setup, when G= 0.9KW/m², the MPP reached at 10 seconds with duty ratio D=0.58 and for G= 0.3KW/m², T_{set,PV} was 18 seconds with duty ratio D= 0.45.

The transient responses of the proposed PV-SSIFB system for a step change in load and rapid change of irradiation have been investigated. Figure 4.16 (a) shows that when the load R_L had changed from 150Ω to 100Ω, the load line was modified as explained Figure 4.3 and output smoothly settled in steady state within 0.02 seconds. MPP voltage (V_{MPP}) and current (I_{MPP}) on the PV side have not been changed as the irradiation maintained constant at 0.6KW/m² during load change. To analyze the effectiveness of proposed algorithm under rapidly changing environmental conditions, irradiation was varied from 0.3KW/m² to 0.9KW/m² as shown in Figure 4.16 (b). The MPP was reached as explained in Figure 4.4 and voltage and current at both PV and output sides have been modified. New MPP was reached within 0.015 seconds. It was noted that there was no significant overshoot during transition in both the cases and the output settles smoothly to steady state without oscillations. The settling time for the change of load and irradiation in experimental prototype were found to be 0.05 and 3 seconds respectively.
Figure 4.16 Transient response of PV-SSIFB system a(i) & a(ii)  
Simulation and experimental results for a step change in 
load from $R_L = 150\,\Omega$ to $100\,\Omega$ at irradiation $0.6\text{KW/m}^2$. b(i) & 
b(ii) Simulation and experimental results for a rapid 
changing of irradiation from $0.3\text{KW/m}^2$ to $0.9\text{KW/m}^2$.
Table 4.3  Comparison of MPPT efficiency with respect to different perturbation step sizes

<table>
<thead>
<tr>
<th>Irradiation (KW/m²)</th>
<th>MPPT Efficiency (η_{MPPT}) (%)</th>
<th>LOCV Method</th>
<th>FSS-INC Method (0.1 Step Size)</th>
<th>FSS-INC Method (0.4 Step Size)</th>
<th>VSS-INC Method</th>
<th>Proposed Hybrid Method (LOCV &amp; VSS-INC)</th>
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Table 4.4  Performance of PV- SSIFB system with proposed HMPPT algorithm for different irradiations

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<th>Irradiation (KW/m²)</th>
<th>MPP at PV Panel (P_{MPP}) (W)</th>
<th>Duty Ratio (D) (%)</th>
<th>Settling Time (T_{Set, PV}) (sec)</th>
<th>MPP tracked (P_{MPP,track}) (W)</th>
<th>Output Power (P_{O}) (W)</th>
<th>η_{MPPT} (%)</th>
<th>η_{OUT} (%)</th>
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<td>0.15</td>
<td>10.11</td>
<td>38.7</td>
<td>0.1</td>
<td>9.91</td>
<td>9.37</td>
<td>98.02</td>
</tr>
</tbody>
</table>
Table 4.3 lists the comparison results between other MPPT techniques and the proposed HMPPT algorithm and Table 4.4 tabulates the performance of proposed HMPPT controller for various irradiations.

Figure 4.17 to 4.19 show the performance evaluation of PV-SSIFB system with MPPT controller for various irradiations. Figure 4.17 shows the measured MPPT efficiency as a function of irradiation for various MPPT algorithms. It is clear that on comparison with indirect LOCV and FSS-INC methods, the proposed HMPPT algorithm was more efficient for low as well as high irradiations and its average efficiency was found to be 98.5%. Figure 4.18 shows the converter efficiency with respect to irradiations for various load conditions and it is found to be ranging from 91 to 96.5%. Figure 4.19 shows simulated and experimental efficiency of the PV-SSIFB system with respect to irradiation at steady state condition. There is a difference of 1.5 to 2% between simulation and hardware efficiency. However, the difference between converter efficiency and MPPT efficiency begins from 4.5% at $G=0.15\text{KW/m}^2$ and reduces to 2% as the irradiation gets increased.

![Figure 4.17 Irradiation vs $\eta_{\text{MPPT}}$ characteristics of PV-SSIFB system for different MPPT algorithms](image-url)
Figure 4.18 Irradiation vs $\eta_{\text{OUT}}$ characteristics of PV-SSIFB system for various loads

Figure 4.19 Irradiation vs simulated and experimental efficiency characteristics of HMPPT controller and SSIFB converter.

Table 4.5 compares proposed HMPPT technique with other Hybrid MPPT techniques mentioned in Yu et al (2004) and Moradi & Reisi (2011).
Table 4.5  Comparison of proposed HMPPT technique with other existing Hybrid MPPT techniques for different irradiations

<table>
<thead>
<tr>
<th>Irradiation (KW/m²)</th>
<th>MPP at PV Panel (P_{MPP}) (W)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>0.90  77.426</td>
<td>83.90</td>
</tr>
<tr>
<td></td>
<td>0.75  64.353</td>
<td>85.73</td>
</tr>
<tr>
<td>Medium</td>
<td>0.60  58.192</td>
<td>87.64</td>
</tr>
<tr>
<td></td>
<td>0.45  43.323</td>
<td>81.21</td>
</tr>
<tr>
<td>Low</td>
<td>0.30  24.643</td>
<td>73.04</td>
</tr>
<tr>
<td></td>
<td>0.15  10.11</td>
<td>69.15</td>
</tr>
</tbody>
</table>

4.7 CONCLUSION

A novel LOCV-VSS-INC method based HMPPT controller has been proposed in this chapter for a PV-SSIFB system used for remote power electronic applications. The performance of the system has been verified by simulation results and validated by experimental results. The steady state performance has been analyzed for low and high irradiations ranging from 0.15 KW/m² to 0.9KW/m². The dynamic performance has been evaluated by rapidly varying the irradiation from 0.3 KW/m² to 0.9KW/m² and load from 150Ω to 100 Ω. It is observed that, on comparison with the conventional FSS-INC and OCV MPPT methods, the proposed HMPPT algorithm exhibits the performance enhancement in terms of tracking time, steady state oscillations, accuracy and efficiency. Tracking speed varies from 0.045 sec to 0.07 sec for constant irradiations and settles within 0.02 sec when a rapid change in irradiation and load occurred. The HMPPT controller provides an efficiency of 98.02 % even at the lowest irradiation of 0.15KW/m². The SSIFB converter, designed to have low current stress on active switches, shows an efficiency of 92 to 97% for different irradiation levels.