Solar powered Single Stage boost inverter with ANN based MPPT algorithm

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Presentation By

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Objectives of This Paper

• Design and development of solar powered single stage boost inverter for RL load

• Design of accurate PV module and improved MPPT algorithm using Neural Networks

• Comparison of closed loop controlling of boost inverter using-
  – PI controller
  – Sliding mode controller
  – MPPT algorithm
Contents of Presentation

• Simulation of accurate PV panel

• Simulation of improved maximum power point tracking algorithm using Neural Networks

• Analysis and simulation of open loop single stage PV fed boost dc-ac converter

• Developing sliding mode control and PI control for PV fed boost inverter

• Comparison of the results and conclusion
PHOTOVOLTAIC CELL WORKING PRINCIPLE

Inside a Photovoltaic Cell
- Glass
- Transparent Negative Terminal
- n-Type Layer (Semiconductor)
- Junction
- p-Type Layer (Semiconductor)
- Positive Terminal
- Electrical Transmission System
- Energy From Light
- Solar Arrays
- Freed Electrons
- Holes Filled by Freed Electrons
- Electron Flow (Current)


Workshop the creator not his creation - Edmond Becquerel, 1889 Electricity From Sun

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From the figure

\[ I = I_L - I_D \]  \hspace{1cm} (1)

Where
- \( I \) = Output Current In Amps
- \( I_L \) = light Current Or Photo Generated Current In Amps
- \( I_D \) = Diode Current In Amps
By Shockley equation, current diverted through diode is

\[ I_D = I_o \left[ \exp \left( \frac{U + IR_s}{n k T / q} \right) - 1 \right] \]

Where
- \( I_o \) = Reverse Saturation Current
- \( n \) = Diode Ideality Factor
- \( K \) = Boltzmann’s Constant
- \( T \) = Absolute Temperature
- \( q \) = Elementary Charge

For silicon of 25°C, \( n k T / q = 0.0259 \) volts = \( \alpha \)

\[ I_D = I_o \left[ \exp \left( \frac{U + IR_s}{\alpha} \right) - 1 \right] \]
Substituting above equation in equation (1) we get

\[ I = I_L - I_o \left[ \exp \left( \frac{U + IR_s}{\alpha} \right) - 1 \right] \]

Where \( \alpha = nkT/q \) is known as Thermal Voltage Timing Completion Factor

The four Parameters \( I_L, I_o, R_s \) and \( \alpha \) need to be determined to Study the I-U characteristics of PV cells
PHOTOVOLTAIC CELL MODELING Cont…

LIGHT CURRENT $I_L$ determination

$$I_L = \frac{\phi}{\phi_{ref}} \left[ I_{L,ref} + \mu_{I,SC} (T_{c} - T_{c,ref}) \right]$$

Where

- $\phi = \text{irradiance (W/m}^2\text{)}$
- $\phi_{ref} = \text{reference irradiance (1000 W/m}^2\text{ is used in this study)}$
- $I_{L,ref} = \text{Light current at reference condition (1000 W/m}^2\text{ and 25 °C)}$
- $T_c = \text{PV cell temperature}$
- $T_{c,ref} = \text{Reference Temperature (25°C is used here)}$
- $\mu_{I,SC} = \text{Temperature coefficient of the short circuit current (A/°C)}$

Both $I_{L,ref}$ and $\mu_{I,SC}$ can be obtained from manufacturer data sheet.
PHOTOVOLTAIC CELL MODELING Cont...

SATURATION CURRENT $I_o$ determination

$$I_o = I_{o,ref} \left( \frac{T_{c,ref} + 273}{T_c + 273} \right)^3 \exp \left[ \frac{e_{\text{gap}}N_s}{q\alpha_{\text{ref}}} \left( 1 - \frac{T_{c,ref} + 273}{T_c + 273} \right) \right]$$

*Where* $I_{o,ref}$ = Saturation current at the reference condition (A)

- $e_{\text{gap}}$ = Band gap of the material (1.17 eV for Si materials)
- $N_s$ = Number of cells in series of the PV module
- $q$ = Charge of the electron ($1.60217733 \times 10^{-19}$ C)
- $\alpha_{\text{ref}}$ = The value of $\alpha$ at the reference condition

$$I_{o,ref} = I_{L,ref} \exp \left( - \frac{U_{oc,ref}}{\alpha_{\text{ref}}} \right)$$

$U_{oc,ref}$ = The open circuit voltage of the PV module

at the reference condition (V) (Will be provided by manufacturers)
PHOTOVOLTAIC CELL MODELING Cont…

Calculation of α

\[
\alpha_{\text{ref}} = \frac{2U_{\text{mp, ref}} - U_{\text{oc, ref}}}{I_{\text{sc, ref}}} + \ln \left(1 - \frac{I_{\text{mp, ref}}}{I_{\text{sc, ref}}}\right)
\]

Where

\[U_{\text{mp, ref}} = \text{Maximum power point voltage at the reference condition (V)}\]
\[I_{\text{mp, ref}} = \text{Maximum power point current at the reference condition (A)}\]
\[I_{\text{sc, ref}} = \text{Short circuit current at the reference condition (A)}\]

\(\alpha\) is a function of temperature, which is expressed as

\[
\alpha = \frac{T_c + 273}{T_{c, \text{ref}} + 273} \alpha_{\text{ref}}
\]
PHOTOVOLTAIC CELL MODELING Cont...

Calculation of Series Resistance $R_s$

Some manufactures provide value of $R_s$, if they do not provide
It can be calculated as follows

$$R_s = \frac{\alpha_{ref} \ln \left(1 - \frac{I_{mp,ref}}{I_{sc,ref}}\right) + U_{oc,ref} - U_{mp,ref}}{I_{mp,ref}}$$

$R_s$ is taken as constant here

Thermal Model of Photovoltaic cell

$$C_{pv} \frac{dT_c}{dt} = k_{in, pv} \phi - \frac{U \times I}{A} - K_{loss} (T_c - T_a)$$

$C_{pv}$ = The overall heat capacity per unit area of the PV cell/Module (J/(°C m^2))

$K_{in, pv}$ = Transmittance absorption product of PV cells

$k_{loss}$ = Overall heat loss coefficient (W/(°C m^2))

$T_a$ = Ambient temperature (°C)

$A$ = Effective area of the PV cell/Module (m^2)
PHOTOVOLTAIC CELL MODEL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{L,ref}$</td>
<td>2.664 A</td>
</tr>
<tr>
<td>$I_{SC,ref}$</td>
<td></td>
</tr>
<tr>
<td>$\alpha_{ref}$</td>
<td>5.472 V</td>
</tr>
<tr>
<td>$R_s$</td>
<td>1.324 $\Omega$</td>
</tr>
<tr>
<td>$U_{oc,ref}$</td>
<td>87.72 V</td>
</tr>
<tr>
<td>$U_{mp,ref}$</td>
<td>70.731 V</td>
</tr>
<tr>
<td>$I_{mp,ref}$</td>
<td>2.448 A</td>
</tr>
<tr>
<td>$\Phi_{ref}$</td>
<td>1000 W/m²</td>
</tr>
<tr>
<td>$T_{c,ref}$</td>
<td>25°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{PV}$</td>
<td>$5 \times 10^4$ J/((0c.m²))</td>
</tr>
<tr>
<td>$A$</td>
<td>1.5 m²</td>
</tr>
<tr>
<td>$K_{in,pv}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$K_{loss}$</td>
<td>30 W/((0c.m²))</td>
</tr>
</tbody>
</table>

Be willing to accept temporary inconvenience for permanent improvement – Dynamo-Michael Faraday-1832
Distance lends enchantment to the view –CRO- Karl Ferdinand Braun- 1897
CHARACTERISTICS OF PV CELL AT CONSTANT CELL TEMPERATURE

Voltage Vs Power Characteristics

- 1400 W/Sq.M
- 1600 W/Sq.M
- 1200 W/Sq.M
- 1000 W/Sq.M
- 800 W/Sq.M

Constant Cell Temperature 25 deg Centigrade

Voltage Vs Current Characteristics

- 1600 W/Sq.M
- 1400 W/Sq.M
- 1200 W/Sq.M
- 1000 W/Sq.M
- 800 W/Sq.M

Constant Cell Temperature of 25 deg Cent

Everyone wants to go to heaven but nobody wants to die - Megger – Evershed - 1905

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CHARACTERISTICS OF PV CELL AT CONSTANT IRRADIANCE

Voltage Vs Current Characteristics

Voltage Vs Power Characteristics

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Maximum Power Point Tracking of PV cell Using Neural Networks

Transfer Function in the Input Layer : Linear
Transfer Function in the Hidden Layer : Tan Sigmoid
Transfer Function in the output Layer : Linear
Training Algorithm : Back Propagation
# Maximum Power Point Tracking of PV cell Using Neural Networks

- **Electrolytic capacitor - Julius Edgar-1928**

<table>
<thead>
<tr>
<th>$T_C$</th>
<th>$G$</th>
<th>$I_{mp}$ (A)</th>
<th>$V_{mp}$ (V)</th>
<th>$P$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>200W/m²</td>
<td>0.477</td>
<td>56.5</td>
<td>27.3</td>
</tr>
<tr>
<td>400W/m²</td>
<td></td>
<td>0.956</td>
<td>59</td>
<td>57.4</td>
</tr>
<tr>
<td>600W/m²</td>
<td></td>
<td>1.437</td>
<td>62.2</td>
<td>88.4</td>
</tr>
<tr>
<td>800W/m²</td>
<td></td>
<td>1.913</td>
<td>61</td>
<td>118.5</td>
</tr>
<tr>
<td>1000W/m²</td>
<td></td>
<td>2.394</td>
<td>61.2</td>
<td>149.5</td>
</tr>
<tr>
<td>1200W/m²</td>
<td></td>
<td>2.875</td>
<td>64.4</td>
<td>182</td>
</tr>
<tr>
<td>1400W/m²</td>
<td></td>
<td>3.346</td>
<td>62.8</td>
<td>212</td>
</tr>
<tr>
<td>1600W/m²</td>
<td></td>
<td>3.827</td>
<td>62</td>
<td>241</td>
</tr>
<tr>
<td>1800W/m²</td>
<td></td>
<td>4.298</td>
<td>61.8</td>
<td>270</td>
</tr>
</tbody>
</table>
Maximum Power Point Tracking of PV cell Using Neural Networks

One can never consent to creep when one feels an impulse to soar – Electromagnetism – Maxwell-1865

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Single Stage Boost Inverter

Circuit implementation

Modes of operation

Don’t sit like a rock work like a clock- Fluorescent Lamp –Edmund Germer - 1926
Modeling of Single Stage Boost Inverter

\[
\begin{bmatrix}
\frac{d i_{L1}}{dt} \\
\frac{d V_1}{dt}
\end{bmatrix} = \begin{bmatrix}
- \frac{R_a}{L_1} & - \frac{1}{L_1} \\
\frac{1}{C_1} & - \frac{1}{C_1 R_1}
\end{bmatrix} \begin{bmatrix}
i_{L1} \\
V_1
\end{bmatrix} + \begin{bmatrix}
\frac{V_1}{L_1} \\
\frac{i_{L1}}{C_1}
\end{bmatrix} \gamma + \begin{bmatrix}
\frac{V_{in}}{L_1} \\
\frac{V_2}{C_1 R_1}
\end{bmatrix}
\]

The above equation is of the form

\[\dot{V} = AV + B \gamma + C\]
Similarly we can write the state space equations when switches $S_3$ and $S_4$ are switched and the total state space equation is given by

\[
\begin{bmatrix}
\frac{di_{L1}}{dt} \\
\frac{dV_1}{dt} \\
\frac{di_{L2}}{dt} \\
\frac{dV_2}{dt}
\end{bmatrix}
= \begin{bmatrix}
\frac{1}{L_1} & 0 & 0 & 0 \\
\frac{1}{C_1} & \frac{1}{C_1R_1} & 0 & 0 \\
0 & 0 & \frac{1}{L_2} & \frac{1}{L_2} \\
0 & 0 & \frac{1}{C_2} & \frac{1}{C_2R_1}
\end{bmatrix}
\begin{bmatrix}
i_{L1} \\
V_1 \\
i_{L2} \\
V_2
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{L_1} & 0 & 0 & 0 \\
\frac{1}{C_1} & \frac{1}{C_1R_1} & 0 & 0 \\
0 & 0 & \frac{1}{L_2} & \frac{1}{L_2} \\
0 & 0 & \frac{1}{C_2} & \frac{1}{C_2R_1}
\end{bmatrix}
\begin{bmatrix}
V_{in} \\
L_1 \\
V_{in} \\
L_2
\end{bmatrix}
\gamma + \begin{bmatrix}
\frac{1}{L_1} & 0 & 0 & 0 \\
\frac{1}{C_1} & \frac{1}{C_1R_1} & 0 & 0 \\
0 & 0 & \frac{1}{L_2} & \frac{1}{L_2} \\
0 & 0 & \frac{1}{C_2} & \frac{1}{C_2R_1}
\end{bmatrix}
\begin{bmatrix}
i_{L1} \\
V_1 \\
i_{L2} \\
V_2
\end{bmatrix}
\]

Where $\gamma$ is the status of switches.

A great talker is a great liar - Hall Effect - Edwin Hall - 1879
A man is as old as he feels - Hybrid Vehicle –Ferdinand Porsche-1899

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Simulation Results
With Constant Irradiance and Temperature Continues….

Be willing to accept temporary inconvenience for permanent improvement- Logic gates-Charles Babbage -1837
Simulation Results
With Variable Irradiance and Constant Temperature

PV panel voltage

PV cell output voltage for Different values of Irradiance

Voltage in Volts

G=500 W/sq.M
G=700 W/sq.M
G=1000 W/sq.M

Time in Secs

G=500 W/sq.M
G=700 W/sq.M
G=1000 W/sq.M

Output voltage

Time (sec)

Believing in yourself is the first step to success- Neon Lamp –Georges Claude-1910

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Simulation Results
With Variable Irradiance and Constant Temperature Continues…

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0</td>
</tr>
<tr>
<td>140</td>
<td>1</td>
</tr>
<tr>
<td>130</td>
<td>2</td>
</tr>
<tr>
<td>120</td>
<td>3</td>
</tr>
<tr>
<td>110</td>
<td>4</td>
</tr>
<tr>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>90</td>
<td>6</td>
</tr>
<tr>
<td>80</td>
<td>7</td>
</tr>
<tr>
<td>70</td>
<td>8</td>
</tr>
<tr>
<td>60</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>9</td>
</tr>
</tbody>
</table>

A hungry man is an angry man - Pager-Al Gross-1949

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PI Controller Fed Single Stage Boost Inverter

Discretion is the better part of valor

Piezoelectricity-Pierre Curie-1880

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Simulation of PI Controller
With Constant Irradiance and Temperature

![Graph showing input and output voltage over time.]

Lightning never strikes twice in the same place  -Relay-Joseph Henry-1835

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Simulation Results
With Variable Irradiance and Constant Temperature

Money makes the world go round - Thermo Electricity –Thomson Johann Seebeck-1821

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When good transient response of the output voltage is needed, a sliding surface equation in the state space, expressed by a linear combination of state-variable errors $\varepsilon_I$ (defined by difference to the references variables), can be given by

$$S(i_{L1}, V_1) = K_1\varepsilon_1 + K_2\varepsilon_2 = 0$$

where coefficients $K_1$ and $K_2$ are proper gains, $\varepsilon_1$ is the feedback current error, $\varepsilon_2$ and is the feedback voltage error, or

$$\varepsilon_1 = i_{L1} - i_{Lref}$$
$$\varepsilon_2 = V_1 - V_{ref}$$

$$S(i_{L1}, V_1) = K_1(i_{L1} - i_{Lref}) + K_2(V_1 - V_{ref}) = 0$$

The system response is determined by the circuit parameters and coefficients $K_1$ and $K_2$. With a proper selection of these coefficients in any operating condition, high control robustness, stability, and fast response can be achieved.
Sliding Mode Controller Continued….

Sliding mode controller scheme

Never put off until tomorrow what you can do today - Remote Control –Nikola Tesla-1898
Simulation Results for Sliding Mode Controller With Variable Irradiance

PV Output Voltage For different irradiance

- G=500W/sq.M
- G=1000W/sq.M

Output Voltage (PV) Sliding Mode Control

No one can make you feel inferior without your consent – Regenerative Circuit-Edwin Armstrong-1914

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Simulation Results for Sliding Mode Controller With Variable Irradiance continues....

Output voltage across capacitors

Inductor Currents in Amps

Simulation Results for Sliding Mode Controller With Variable Irradiance continues....

Selected signal: 18 cycles. FFT window (in red): 1 cycles

Fundamental (60Hz) = 185.4 , THD= 1.20%

Practice makes perfect - Fax Machine-Alexander Bain-1842
Simulation Results for
Sliding Mode Controller With Variable Temperature
continues....

PV output Voltage For different Temperatures (Sliding Mode Control)

PV output for different Cell Temperatures

Seeing is believing - Electro Magnet - William Sturgeon - 1825

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Simulation Results for Sliding Mode Controller With Variable Temperature continues....

- Transistor-Brattain Walter-1947

Set a thief to catch a thief

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### Comparisons

<table>
<thead>
<tr>
<th>Controller</th>
<th>Output</th>
<th>THD</th>
<th>Settling time</th>
<th>Input condition</th>
<th>Atmospheric condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open loop</td>
<td>AC with constant RMS</td>
<td>≈ 5</td>
<td>≈0.01 s</td>
<td>Constant $V_{ph}$ and $I_{ph}$</td>
<td>Constant irradiation ($G$) and temperature ($T$)</td>
</tr>
<tr>
<td>Open loop</td>
<td>AC with changing RMS</td>
<td>≈9</td>
<td>≈0.01 s</td>
<td>Varying $V_{ph}$ and $I_{ph}$</td>
<td>Varying $G / T$</td>
</tr>
<tr>
<td>PI</td>
<td>AC with almost constant RMS</td>
<td>≈2</td>
<td>≈0.005s</td>
<td>Varying $V_{ph}$ and $I_{ph}$</td>
<td>Varying $G / T$</td>
</tr>
<tr>
<td>SMC</td>
<td>AC with constant RMS</td>
<td>≈1.5</td>
<td>≈0.002s</td>
<td>Varying $V_{ph}$ and $I_{ph}$</td>
<td>Varying $G / T$</td>
</tr>
</tbody>
</table>

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*Attack is the best form of defence - Darlington Pair - Darlington Sidney - 1953*
Conclusions

• Simple and reliable operation

• The cost of this inverter is relatively low as minimum number of power devices are used

• Closed loop controlling improves the reliability and dynamic stability

• Closed loop controlling using MPPT is simple and more reliable compared to all other controllers

Ask no questions and hear no lies – Hysterisis- Ewing James Alferd-1890
Success is a journey, Which has no Destination