T-S Fuzzy Model Based Maximum Power Point Tracking Control of Photovoltaic System

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Outline

1. Introduction
2. System Modelling
   - Photovoltaic cell, array
   - Single Diode Model of a PV cell, array
3. T-S Fuzzy Control
   - T-S Fuzzy Model of the System
   - Stabilizing Controller
     - Fixed Gain Controller
     - Variable Gain Controller
   - Tracking Controller
   - Results

Introduction

- The early research in solar technologies started with an expectation that coal would soon become scarce.
- Development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits.
- Solar power is a renewable source, absolutely pollution free, generates no noise and is easy to install and maintain.

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Photovoltaic cell, array

- The factory standard rating of solar cell is 0.5 volts, 1.75 watts
- Efficiency can be anywhere from 1% to 14%
- Several cells are connected in series (for voltage buildup) and in parallel (for current buildup) to form an array.

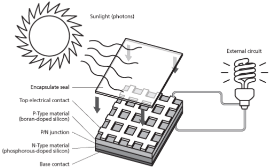

Figure: Construction and Working of PV / Solar Cell [5]

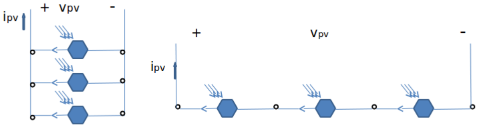

Figure: Series and Parallel connection of solar cells [5]

Photovoltaic cell, array

Typical rating of the PV panel is 42V 160W.

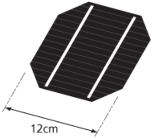

Figure: PV / Solar Cell [5]

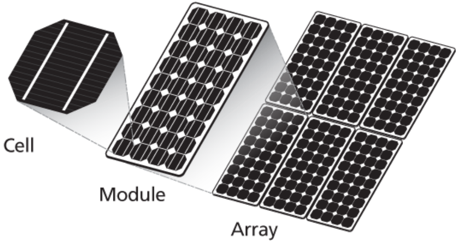

Figure: PV cell, Module and Array [5]

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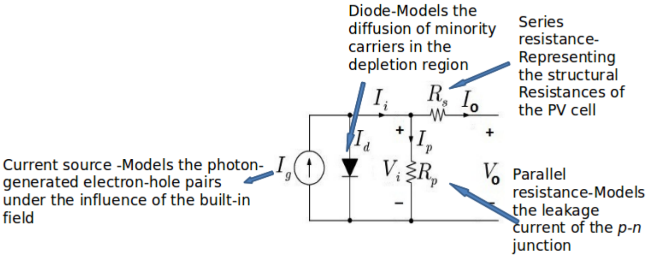
Single Diode Model of a PV cell

We assume an ideal PV cell and neglect R_s and R_p.

$$\begin{aligned} I_o(V_o) &= I_g - I_d \\ &= I_g - I_s(e^{\beta V_o} - 1) \end{aligned}$$

β is inverse thermal voltage given by,

$$\beta = \frac{q}{pKT}$$



I-V Characteristic of PV array

For a PV array with n_s cells connected in series and n_p cells connected in parallel

$$i_{pv} = n_p I_g - n_p I_s(e^{\beta v_{pv}/n_s} - 1)$$

where

$$I_g = (I_{sc} + k_I(T - T_r))\lambda/\lambda_r$$

$$I_s = I_r\left(\frac{T}{T_r}\right)^3 e^{qE_{gp}(\frac{1}{T_r} - \frac{1}{T})/pK}$$

Power output of a PV array is,

$$P_{pv} = n_p I_g v_{pv} - n_p I_s v_{pv}(e^{\frac{\beta v_{pv}}{n_s}} - 1)$$

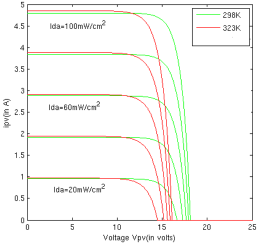


Figure: I-V characteristic of solar panel at different cell temperature and solar radiation

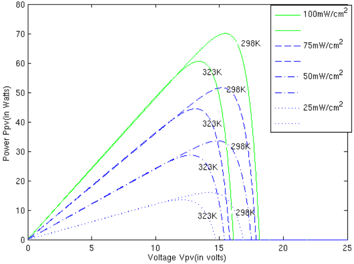


Figure: Dependence of PV power output on temperature and solar radiation

Maximum Power Point

Maximum power point occurs at a voltage where,

$$\frac{dP_{pv}}{dv_{pv}} = n_p I_g - n_p I_s[(e^{\frac{\beta v_{pv}}{n_s}} - 1) + \frac{\beta v_{pv}}{n_s} e^{\frac{\beta v_{pv}}{n_s}}] = 0$$

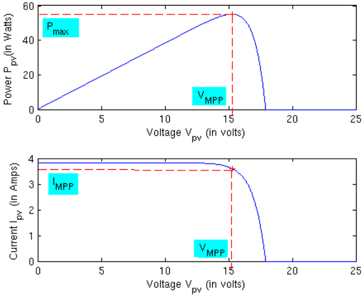


Figure: Maximum power point voltage and current

Circuit Operation at MPP

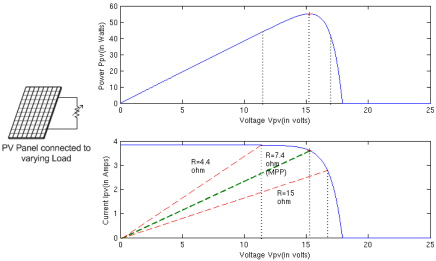


Figure: Circuit operation at MPP when panel is connected to varying load

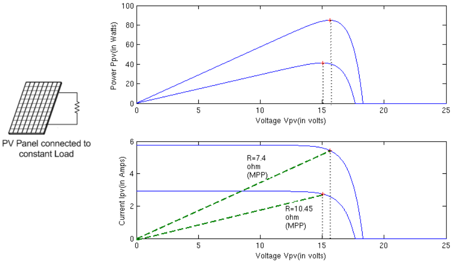


Figure: Circuit operation at MPP when panel is connected to a constant load

Power Converter

For a buck converter-

$$V_{in} = \frac{V_o}{D} \tag{1}$$

If, I_{in} : input current
I : average current flowing through the inductor

$$I_{in} = DI$$

$$R_{in} = \frac{R_o}{D^2}$$

Now, if $R_{in} = R_{th}$ maximum power transfer occurs and hence MPP is tracked.

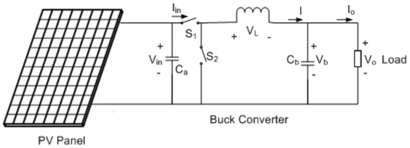


Figure: PV array + DC-DC converter system

Proposed Controller

- We dont need to calculate the MPPT.
- Both the stabilization and tracking problem are addressed. So, we wont be having any sustained oscillations in the output power in steady state.
- The system can be proved to be Lyapunov stable and convergence to the MPP has been achieved within few milliseconds.
- Performs well even in erratic weather conditions and guarantees asymptotic convergence to MPP.
- Measurement of solar radiation is not required.

Outline

Dynamic model of the System

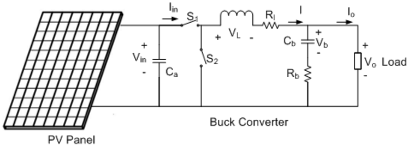


Figure: PV array + DC-DC converter system

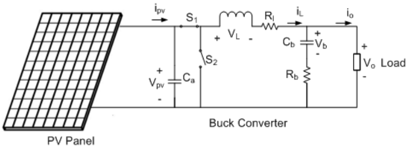


Figure: When switch S_1 is on and S_2 is off

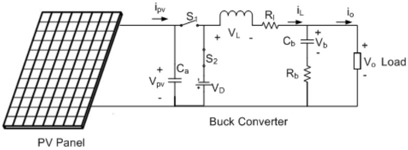


Figure: When switch S_1 is off and S_2 is on

State space model of the PV array + DC-DC converter

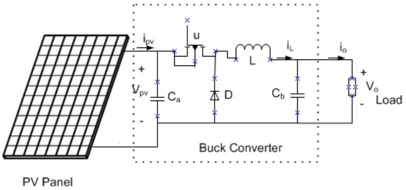


Figure: PV array + DC-DC converter system

$$\dot{i}_L = \frac{1}{L}(R_b i_o - (R_b + R_l)i_L - v_b + (V_D + v_{pv})u - V_D)$$

$$\dot{v}_{pv} = \frac{1}{C_a}(i_{pv} - i_L u)$$

$$\dot{v}_b = \frac{1}{C_b}(i_L - i_o)$$

State space model of the PV array + DC-DC converter

In addition,

$$i_{pv} = n_p I_g - n_p I_s \left(e^{\frac{\beta v_{pv}}{n_s}} - 1\right)$$
$$i_o = \frac{v_b}{R_L}$$

If $y(t) = \frac{dP_{pv}}{dv_{pv}}$ tracks $y_{ref} = 0 \implies$ MPP

T-S Fuzzy Model of the System

We can see that this system is a non-linear affine system of the form,

$$\dot{\mathbf{x}} = f(\mathbf{x}) + g(\mathbf{x})u$$

$f(\mathbf{x}) = [f_1(\mathbf{x}), f_2(\mathbf{x}), f_3(\mathbf{x})]^T$ and $g(\mathbf{x}) = [g_1(\mathbf{x}), g_2(\mathbf{x}), g_3(\mathbf{x})]^T$
$\mathbf{x}(t) = [i_L, v_{pv}, v_b]^T$ and u is the control signal.
where,

$$f_1(\mathbf{x}) = \frac{1}{L}\left[\left(\frac{R_b}{R_L} - 1\right)x_3 - (R_b + R_l)x_1 - V_D\right]$$

$$f_2(\mathbf{x}) = \frac{1}{C_a}\left[n_p I_g - n_p I_s(e^{(\beta x_2/n_s)} - 1)\right]$$

$$f_3(\mathbf{x}) = \frac{1}{C_b}\left(x_1 - \frac{x_3}{R_{ld}}\right)$$

$$g_1(\mathbf{x}) = \frac{(V_D + x_2)}{L}$$

$$g_2(\mathbf{x}) = -\frac{x_1}{C_a}$$

$$g_3(\mathbf{x}) = 0$$

Takagi-Sugeno Framework

The T-S model of this system is expressed in terms of 32 fuzzy rules where j^{th} rule is of form,

IF $z_1(t)$ is $F_1^j, z_2(t)$ is F_2^j ..... and $z_5(t)$ is F_5^j THEN,

$$\dot{\mathbf{x}}(t) = A_j\mathbf{x}(t) + B_j u(t)$$

where, F_i^j, $i = 1,2,....5$ is the membership function of i^{th} fuzzy term of j^{th} rule corresponding to variable z_i.

z_1, z_2, z_3, z_4, z_5 are chosen as i_L, v_{pv}, v_b, i_{pv} and $(n_p/n_s)I_s e^{\beta v_{pv}/n_s}$

Takagi-Sugeno Framework

For each rule there will be two matrices A_j and B_j such that,

$$f(\mathbf{x}) + g(\mathbf{x})u \approx A_j(\mathbf{x}) + B_j u \text{ and}$$
$$f(\mathbf{x}^c) + g(\mathbf{x}^c)u = A_j(\mathbf{x}^c) + B_j u$$

where, $\mathbf{x}^c$ is the fuzzy centre corresponding to j^{th} rule. According to [7],

$$a_i = \nabla^T f_i(\mathbf{x}^c) + \frac{f_i(\mathbf{x}^c) - (\mathbf{x}^c)^T \nabla f_i(\mathbf{x}^c)}{\|\mathbf{x}^c\|^2}(\mathbf{x}^c)^T$$
$$b_i = g_i(\mathbf{x}^c)$$

where, a_i and b_i are the i^{th} rows of A_j and B_j respectively

Takagi-Sugeno Framework

Where, $\bigtriangledown f_i(\mathbf{x}^c) = [\partial f_i/\partial x_1 \;\; \partial f_i/\partial x_2 \;\; \partial f_i/\partial x_3]^T$ at $\mathbf{x}^c$

For this solar power system we get,

$$\bigtriangledown f_1(\mathbf{x}^c) = \left[\frac{-(R_b + R_l)}{L} \; , \; 0 \; , \; \frac{\frac{R_b}{R_l} - 1}{L} \right]^T$$

$$\bigtriangledown f_2(\mathbf{x}^c) = \left[0 \; , \; \frac{-n_p \beta}{n_s C_a} I_s e^{\frac{\beta x_2^c}{ns}} \; , \; 0 \right]^T$$

$$\bigtriangledown f_3(\mathbf{x}^c) = \left[\frac{1}{C_b} \; , \; 0 \; , \; \frac{-1}{C_b R_L} \right]^T$$

Fuzzy membership function

Each fuzzy membership function F_i^j is either P_i (Positive) or N_i (Negative).

$$P_i = \begin{cases} 0 & \text{if } z_i < m_i \\ \frac{z_i - m}{M - m} & \text{if } m_i \leq z_i \leq M_i \\ 1 & \text{if } z_i > M_i. \end{cases}$$

$$\text{and, } N_i = 1 - P_i.$$

where,

i=1,2,3....5(Number of fuzzy variables)

j=1,2,3....32(Number of rules)

Takagi-Sugeno Framework

Given an input-output pair $(\mathbf{z}_0(t), u(t))$ the system can now be represented as,

$$\dot{\mathbf{x}}(t) = \frac{\sum_{j=1}^{32} \mu_j (A_j \mathbf{x}(t) + B_j u(t))}{\sum_{j=1}^{32} \mu_j} = \sum_{j=1}^{32} \sigma_j (A_j \mathbf{x}(t) + B_j u(t))$$

around this operating point.

Where, $\mu_j = \prod_{i=1}^{5} \mu_j^i(z_0(i))$ is the membership function of Fuzzy term F_i^j

Outline

Preliminary Feedback

- Pole placement technique

Problem : Let us have the SISO plant

$$\dot{\mathbf{x}} = A\mathbf{x} + Bu$$
$$y = C\mathbf{x}$$

Find the state feedback gains such that closed loop pole locations meet the desired performance requirements i.e. maximum overshoot(M_p), rise time(t_r), and settling time(t_s).

Preliminary Feedback : Steps

Solution :

ω_n : Natural frequency

ζ : Damping ratio

Step 1: The controllability matrix should have full rank.

$$M = [B \;\; AB \;\;]$$

Step 2: Find ζ, ω_n from

$$M_p = e^{\left(\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}\right)}, \quad t_r = \zeta \quad \mathit{and} \quad t_s = \frac{4}{\zeta\omega_n}$$

closed loop poles $= \left(-\zeta \pm \sqrt{1-\zeta^2}\right)\omega_n$

Step 3: The feedback gains can be calculated by comparing the like powers of $(s - pole1)(s - pole2)$ and $|sI - (A - BK)|$.

Preliminary Feedback : Example

Problem: $A = \begin{bmatrix} 0 & 1 \\ 20.6 & 0 \end{bmatrix}$,
$B = [0 \;\; 1]^T$ *and* $C = [1 \;\; 0]$
find K such that closed loop pole location is $-1.8 \pm j2.4$

Solution: $K = [29.6 \;\; 3.6]^T$.

- we have chosen the closed loop pole location at $-6000 \pm 1000i$.
- The settling time for our model is $4/6000 = 0.666$ msec

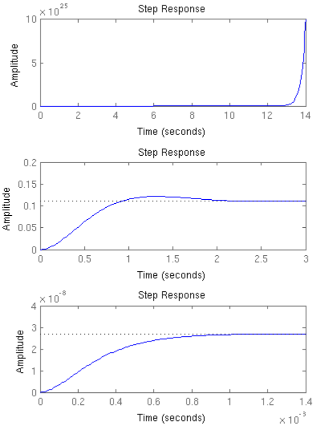


Figure: (a) Step response of open loop system (b) Step response of closed loop system and (c)

Preliminary Feedback : Example

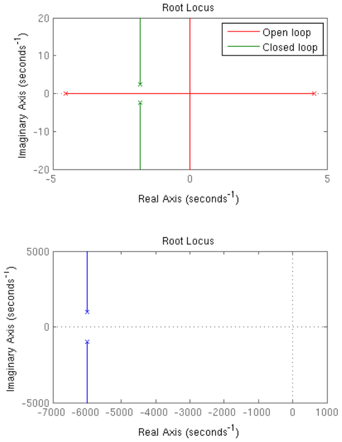


Figure: (a) Root locus of open and closed loop system (b) Root locus of the nominal model of our system

Fixed Gain Controller

- Fuzzy model is written as single nominal plant and the rest as the disturbance to it.
- The controller tries to stabilize the nominal plant in the presence of the disturbance terms.
- Overall control law is the summation of both preliminary feedback and fixed gain controller.

The fuzzy dynamics of the system can be represented as,

$$\begin{aligned}\dot{\mathbf{x}}(t) &= A\mathbf{x}(t) + Bu(t) + \sum_{j=1}^{32}\sigma_j(A_j - A)\mathbf{x}(t) + \sum_{j=1}^{32}\sigma_j(B_j - B)u(t) \\ &= A\mathbf{x}(t) + Bu(t) + F(\mathbf{x}(t), u(t))\end{aligned}$$

Fixed Gain Controller

Further, the disturbance term is expressed as,

$$F(\mathbf{x}(t), u(t)) = f(\mathbf{x}(t)) + Bh_1(\mathbf{x}(t)) + Bh_2(u(t))$$

Here $Bh_2(u(t))$ is the matched input disturbance term and $f(\mathbf{x}(t)) + Bh_1(\mathbf{x}(t))$ are the unmatched state disturbances.

$$\begin{aligned} Bh_2(u(t)) &= \sum_{j=1}^{32} \sigma_j (B_j - B) u(t). \\ &= B \sum_{j=1}^{32} \sigma_j \overline{B}_j u(t) \end{aligned}$$

where

$$B\overline{B}_j = (B_j - B)$$

Fixed Gain Controller

The unmatched and matched state disturbance can be written as

$$f(\mathbf{x}(t)) + Bh_1(\mathbf{x}(t)) = \sum_{j=1}^{32} \sigma_j (A_j - A)\mathbf{x}(t)$$
$$= \sum_{j=1}^{32} \sigma_j (A_{1_j} + BA_{2_j})\mathbf{x}(t)$$

If we can find $\bar{B}_j$, A_{1_j} and A_{2_j} for each rule j,
we have

$$h_2(u(t)) = \sum_{j=1}^{32} \sigma_j \bar{B}_j u(t)$$

$$f(\mathbf{x}(t)) = \sum_{j=1}^{32} \sigma_j A_{1_j} \mathbf{x}(t)$$

$$h_1(\mathbf{x}(t)) = \sum_{j=1}^{32} \sigma_j A_{2_j} \mathbf{x}(t)$$

Norm bounds of disturbance terms

The norm bound of matched state disturbance is given by

$$\begin{aligned} ||h_1(\mathbf{x}(t))|| &= ||\sum_{j=1}^{32} \sigma_j A_{2_j} \mathbf{x}(t)|| \\ &\leq \sum_{j=1}^{32} \sigma_j ||A_{2_j}|| ||\mathbf{x}(t)|| \\ &\leq \alpha_{hx} ||\mathbf{x}(t)|| \end{aligned}$$

where $\alpha_{hx_j} = \max_j ||A_{2_j}||$.

Norm bounds of disturbance terms

Similarly, the norm bound of matched input disturbance is

$$\begin{aligned} ||h_2 u(t)|| &= ||\sum_{j=1}^{32} \sigma_j \overline{B}_j u(t)|| \\ &\leq \left(\sum_{j=1}^{32} \sigma_j ||\overline{B}_j|| \right) ||u(t)|| \\ &= \alpha_u ||u(t)|| \end{aligned}$$

where $\alpha_u = \max_j ||\overline{B}_j||$. Next, the norm bound of the unmatched state disturbance is

$$\begin{aligned} ||f(\mathbf{x}(t))|| &= ||\sum_{j=1}^{32} \sigma_j A_{1_j} \mathbf{x}(t)|| \\ &\leq \max_j ||A_{1_j}|| ||\mathbf{x}(t)|| \\ &= \alpha_f ||\mathbf{x}(t)|| \end{aligned}$$

Here $\alpha_f = \max_j ||A_{1_j}||$.

Fixed Gain Controller : Theorem

Theorem

Suppose that A is asymptotically stable and P is a positive definite matrix satisfying $A^TP + PA = -2Q$ for some other symmetric positive definite matrix Q. Suppose also that, $\alpha_f < \frac{\lambda_{min}(Q)}{\lambda_{max}(P)}$ and $\alpha_u < 1$. Then the state feedback controller

$$u(t) = -\gamma B^T P\mathbf{x}(t)$$

where

$$\gamma > \frac{\alpha_{hx}^2}{4(1-\alpha_u)(\lambda_{min}(Q) - \alpha_f \lambda_{max}(P))}$$

asymptotically stabilizes the fuzzy model [8]

$$\dot{\mathbf{x}}(t) = A\mathbf{x}(t) + Bu(t) + F(\mathbf{x}(t), u(t))$$

$\lambda_{min}(A)$ and $\lambda_{min}(A)$ denote smallest and largest eigenvalues of A.

Variable Gain Controller

As the system states traverse through various fuzzy zones before reaching steady state, it seems appropriate to use variable gain instead of a fixed gain.

Norm bound of matched state disturbance is given by-

$$\begin{aligned} ||h_1(\mathbf{x}(t)) &= ||\sum_{j=1}^{32} \sigma_j A_{2_j} \mathbf{x}(t)|| \\ &\leq ||\sum_{j=1}^{32} \sigma_j A_{2_j}|| ||\mathbf{x}(t)|| \\ &= \sum_{j=1}^{32} \sigma_j \alpha_{hx_j} ||\mathbf{x}(t)|| \end{aligned}$$

where, $\alpha_{hx_j} = ||A_{2_j}||$.

Variable Gain Controller

The norm bound of match input disturbance is

$$\begin{aligned} ||h_2 u(t)|| &= ||\sum_{j=1}^{32} \sigma_j \overline{B}_j u(t)|| \\ &\leq \left(\sum_{j=1}^{32} \sigma_j ||\overline{B}_j|| \right) ||u(t)|| \\ &= \sum_{j=1}^{32} \sigma_j \alpha_{u_j} ||u(t)|| \end{aligned}$$

Here $\alpha_{u_j} = ||\overline{B}_j||$
and the norm bound of the unmatched state disturbance $\alpha_f = \max_j ||A_{1_j}||$.

Variable Gain Controller: Theorem

Theorem

Suppose that A is asymptotically stable and P is a positive definite matrix satisfying $A^T P + PA = -2Q$ for some other symmetric positive definite matrix Q. Suppose also that, $\alpha_f < \frac{\lambda_{min}(Q)}{\lambda_{max}(P)}$ and, $\sum_{j=1}^{32} \sigma_j \alpha_{u_j} < 1$. Then, the state feedback controller

$$u(t) = -\left(\sum_{k=1}^{32} \sigma_k \gamma_k\right) B^T P \mathbf{x}(t)$$

where,

$$\gamma_k > \frac{\alpha_{hx_k}\left(\sum_{j=1}^{32} \sigma_j \alpha_{hx_j}\right)}{4\left(1 - \sum_{j=1}^{32} \sigma_j \alpha_{u_j}\right)\left(\lambda_{min}(Q) - \alpha_f \lambda_{max}(P)\right)}$$

asymptotically stabilizes the fuzzy model [8]

$$\dot{\mathbf{x}}(t) = A\mathbf{x}(t) + Bu(t) + F(\mathbf{x}(t), u(t))$$

Outline

Maximum Power Point Tracking Controller

- A MPPT controller is needed in addition with stabilizing controller to track the maximum power point.
- The final controller is the summation of preliminary feedback controller, stabilizing controller and MPPT controller.

$$u(t) = -K_s\mathbf{x}(t) + v(t)$$

Our objective is to track $y(t) = dP_{pv}(t)/dv_{pv}$ at a reference level of $y_{ref} = 0$.

MPPT Controller Design

$$y(t) = dP_{pv}(t)/dv_{pv} = n_p I_g - n_p I_s \left[\left(e^{\frac{\beta x_2}{n_s}} - 1 \right) + \frac{\beta x_2}{n_s} e^{\frac{\beta x_2}{n_s}} \right]$$

$$\dot{y}(t) = \frac{dy(t)}{dt} = \frac{\partial y}{\partial x_2}\frac{\partial x_2}{\partial t} = \frac{-n_p I_s \beta}{n_s} e^{\frac{\beta x_2}{n_s}} \left[2 + \frac{\beta x_2}{n_s} \right] \dot{x}_2(t) \qquad (2)$$

We also have,

$$\dot{x}_2(t) = \sum_{j=1}^{32} \sigma_j \left(\left[\sum_{k=1}^{3} a_{j_{2,k}} x_k(t) \right] + b_{j_2} v(t) \right) \qquad (3)$$

where $A_j = \left[a_{j_{m,n}} \right]_{3\times 3}$ (i.e, $a_{j_{m,n}}$ is entry at m^{th} row, n^{th} column of matrix A_j) and $B_j = [b_{j_m}]_{3\times 1}$ (i.e, b_{j_m} is m^{th} entry of vector B_j).

MPPT Controller Design

From Equations 3 and 2,

$$\dot{y}(t) = \frac{-n_p I_s \beta}{n_s} e^{\frac{\beta x_2}{n_s}} \left[2 + \frac{\beta x_2}{n_s}\right] \times \left\{ \left[\sum_{j=1}^{32} \sigma_j \left(\sum_{k=1}^{3} a_{j_{2,k}} x_k(t)\right)\right] + \sum_{j=1}^{32} \sigma_j b_{j_2} v(t) \right\}$$

So, if we choose

$$v(t) = \frac{1}{\sum_{j=1}^{32} \sigma_j b_{j_2}} \times \left\{ \frac{\alpha e}{\frac{-n_p I_s \beta}{n_s} e^{\frac{\beta x_2}{n_s}} \left(2 + \frac{\beta x_2}{n_s}\right)} - \sum_{j=1}^{32} \sigma_j \left(\sum_{k=1}^{3} a_{j_{2,k}} x_k(t)\right) \right\}$$

The error dynamics of the system will now be $\dot{e} + \alpha e = 0$ which is Lyapunov stable for $\alpha > 0$. We have chosen $\alpha = 100$ which gave fairly good results.
where, $e = y_{ref} - y = -y = (z_4 - z_5 \times z_2)$, α is a positive quantity and $\mathbf{z}(t)$ is the input.

Outline

1. Introduction
2. System Modelling
   - Photovoltaic cell, array
   - Single Diode Model of a PV cell, array
   - System Design
   - Some Older techniques
3. T-S Fuzzy Control
   - T-S Fuzzy Model of the System
   - Stabilizing Controller
     - Fixed Gain Controller
     - Variable Gain Controller
   - Tracking Controller
   - Results

Transient Response at $25^0C(298K)$ and solar radiation of $100mW/cm^2$

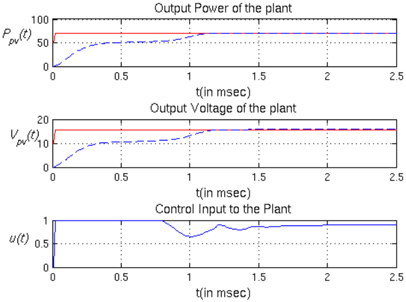


Figure: Transient response in (a)voltage, (b)power at temperature of $25^0C(298K)$ and solar radiation of $100mW/cm^2$ when the fixed gain controller is used. Dotted blue line represents actual response and continuous red line is the desired value. (c) is the control input

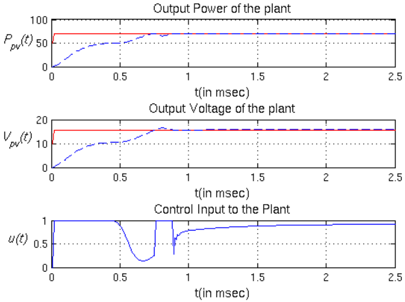


Figure: Transient response in (a)voltage, (b)power at temperature of $25^0C(298K)$ and solar radiation of $100mW/cm^2$ when the variable gain controller I is used. Dotted blue line represents actual response and continuous red line is the desired value. (c) is the control input

Transient Response at $25^0C(298K)$ and solar radiation of $100mW/cm^2$

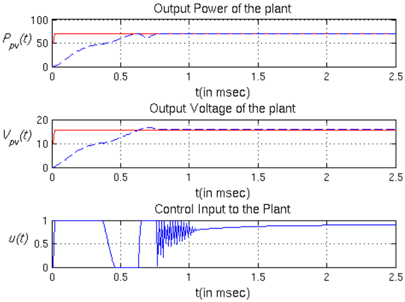


Figure: Transient response in (a)voltage, (b)power at temperature of $25^0C(298K)$ and solar radiation of $100\text{mW}/\text{cm}^2$ when the variable gain controller II is used. Dotted blue line represents actual response and continuous red line is the desired value. (c) is the control input

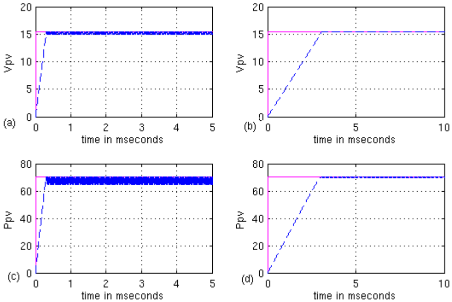


Figure: Transient response of perturb and observe algorithm (a)voltage, (c)power with $\Delta V = 0.5$volts, (b)voltage, (d)power with $\Delta V = 0.05$volts at temperature of $25^0C(298K)$ and solar radiation of $100mW/cm^2$

Controller performance comparison

The efficiency is calculated as

$$\eta = \frac{\int P_{actual} \ dt}{\int P_{max} \ dt}$$

Table: Controller performance comparison

	Efficiency %	Settling time in msec
Fixed gain controller	98.12	1.5
Variable gain controller I	98.72	1

Response with varied temperature and solar radiation in discrete steps

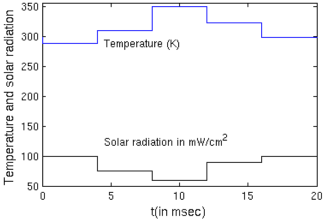


Figure: Variation in (a)temperature and (b)solar radiation

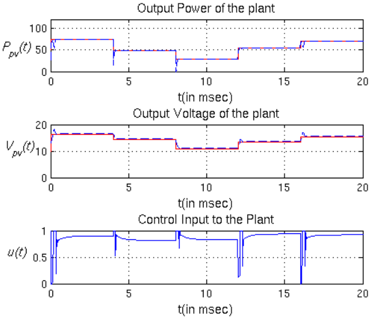


Figure: Output voltage(a), power(b) and control input(c) under varying climate conditions. Dotted blue line represents actual response and continuous red line is the desired value

Response with randomly varying solar radiation and at 298K

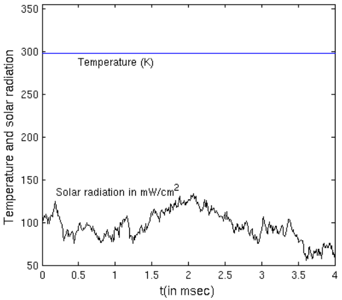


Figure: A more realistic variation of (a)temperature and (b)solar radiation

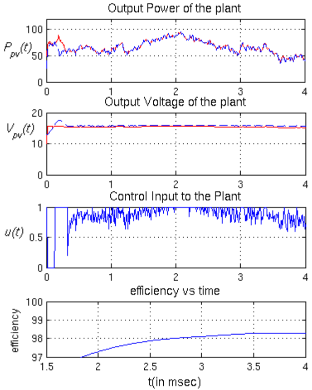


Figure: Output voltage(a), power(b), control input(c) and efficiency(d) in a more realistic simulation where temperature and solar radiation are varied randomly

Comparison with other controllers

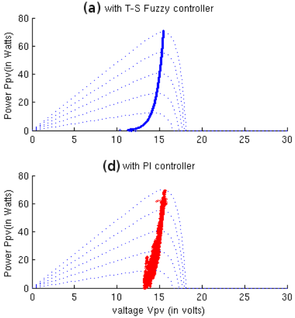
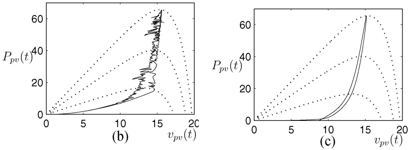


Figure: PV diagram under fixed temperature of 298K and varying radiation as $50 - 50\cos(100t)\text{mW/cm}^2$ for (a) Proposed T-S Fuzzy controller (b) Fuzzy Controller (c) Neural Network and (d) PI controller



The control input of PI controller is defined as

$$u(t) = K_p e(t) + K_i \int e(t)dt$$

where, $e(t) = v_{pv}(t) - v_{pvref}(t)$,
$K_p = 10$: Proportional gain
$K_i = 0.1$: Integral gain
$v_{pvref}(t)$ is determined from incremental conductance method.

Contributions

- A MPPT control strategy based on T-S Fuzzy model has been designed for a solar power generation system. A DC-DC buck converter is used as an interface to control the voltage so as to operate the system at MPP.
- A T-S Fuzzy framework was developed making the system locally linear. We then went on to compare fixed gain and variable gain state feedback controllers for stability. A fixed gain and a variable gain controllers were used and performances of above controllers are compared.
- A simple tracking controller was then designed which ensured stable error dynamics based on feedback linearization.
- The controller we proposed has shown improved tracking speed, efficiency and less chattering as compared with traditional PI controller. The system was also verified to be robust for sudden changes in atmospheric conditions.

Scope of Future work

- The next step could be to perform stabilization and tracking in one shot [9], [10].
- H_∞ decentralized fuzzy control could be used and a state feedback decentralized fuzzy control scheme can be developed for the same purpose. That will override the external disturbances such that the H_∞ disturbance attenuation performance is achieved.
- There can be one more approach for stability, D-stabilization of the uncertain Takagi-Sugeno fuzzy model with an H_∞ performance [11], [12].
- Setting desired speed could be the next performance characteristic.

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Thank You!

Questions and Suggestions

Nomenclature

I_g	Light generated current in A
I_d	Current through diode in A
I_s	Reverse saturation current of diode in A
β	Inverse thermal voltage in volts
q	1.6×10^{-19}C
K	1.3805×10^{-23}J/K
T	Cell temperature in K
p	Ideality factor
λ	Solar irradiance in milliwatts per square centimeter
i_{pv}	Output current of PV array in A
v_{pv}	Output voltage of PV array in volts
n_s	Number of cells connected in series
n_p	Number of cells connected in parallel
T_r	Reference temperature (298 K)
λ_r	Reference irradiation (100 milliwatts per square centimeter
E_{gp}	Bandgap energy of the semiconductor used in the cell (1.1eV)
k_I	Short-circuit current temperature coefficient in milliamperes per kelvin
P_{pv}	Power output of a PV array in Watts
C_a	Input capacitance in μF
C_b	Output capacitance in μF
v_b	Voltage across the capacitance in volts
i_L	Average Current through the inductance L in A
R_b	Internal resistances of the capacitance C_b in ohms
R_l	Internal resistances of the inductance L in ohms
R_{ld}	Load resistance in ohms
V_D	Forward bias voltage of the diode in volts
i_o	Load current in A
u	Duty ratio of buck converter

Dynamic model of the System

$$
\begin{aligned}
\dot{i}_L &= \frac{\delta V_L}{L} \\
&= \frac{1}{L}\left[v_{pv} - R_l i_L - v_b - R_b(i_L - i_o)\right] u + \left[-R_l i_L - v_b - R_b(i_L - i_o) - V_D\right](1-u) \\
&= \frac{1}{L}(R_b i_o - (R_b + R_l) i_L - v_b + (V_D + v_{pv})u - V_D)
\end{aligned}
$$

Similarly,

$$\dot{v}_{pv} = \frac{(i_{pv} - i_L)u + i_{pv}(1-u)}{C_a}$$

$$\dot{v}_{pv} = \frac{i_{pv} - i_L u}{C_a}$$

and

$$\dot{v}_b = \frac{(i_L - i_o)u + (i_L - i_o)(1-u)}{C_b}$$

$$\dot{v}_b = \frac{(i_L - i_o)}{C_b}$$

Power Converter

Using the capacitor charge balance for output capacitor

$$\left(I - \frac{V_o}{R}\right) DT_s + \left(I - \frac{V_o}{R}\right)(1 - D)T_s = 0$$

$$I = \frac{V_o}{R} = I_o$$

Finally, we have

$$I_{in} = DI_o \tag{4}$$

Now dividing eq. 1 by eq. 4 we have

$$R_{in} = \frac{R_o}{D^2}$$

Now, if $R_{in} = R_{th}$ maximum power transfer occurs and hence MPP is tracked.

Perturb and Observe (P&O)

- In this method, the terminal voltage is constantly perturbed.
- If the output power increases, its an indication that we are moving in the right direction and the voltage should be perturbed in the same direction next cycle.
- If the power decreases, that indicates that the MPP has passed and we should perturb in the opposite direction.

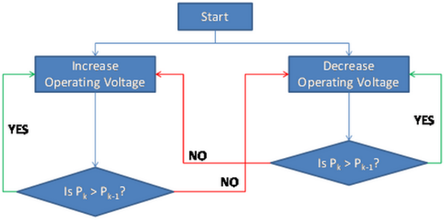


Figure: Flowchart for perturb and observe algorithm [6]

Perturb and Observe (P&O)

Advantages

- Results in top-level efficiency if a proper adaptive and predictive algorithm is adopted.
- Ease to implement

Disadvantages

- Oscillations in the output power around the MPP even in the steady state atmospheric conditions
- Fails to perform well under rapid atmospheric changes

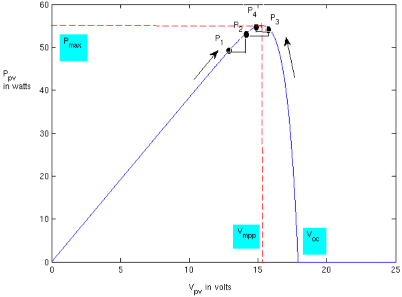


Figure: Perturb and observe algorithm

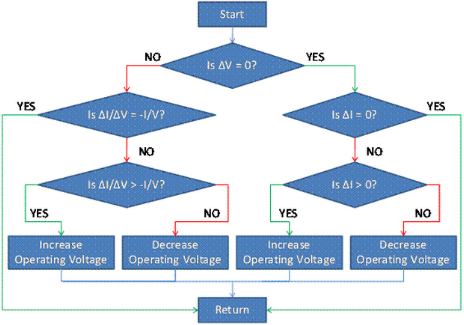
Incremental Conductance

Since, $\frac{dP}{dV} = I + V(\frac{dI}{dV})$, we have the following three cases:

i. $\frac{dP}{dV} > 0 : \frac{dI}{dV} > -\frac{I}{V}$

ii. $\frac{dP}{dV} < 0 : \frac{dI}{dV} < -\frac{I}{V}$

iii. $\frac{dP}{dV} = 0 : \frac{dI}{dV} = -\frac{I}{V}$ (MPP)



Incremental Conductance

Advantages

- Calculates the direction of the perturbation without constantly varying the voltage as in P&O method
- Tracking is fast, accurate and is efficient at fast changing weather conditions

Disadvantages

- Oscillations in the output power are observed
- More computations than the P&O method and hence a larger sampling period is required

Fuzzy rule base (1∼16)

Table: Fuzzy rule base (1∼16)

RULE NUMBER	Fuzzy membership function F_1^j	F_2^j	F_3^j	F_4^j	F_5^j	Fuzzy centre $(\mathbf{z}_0)$
1	N_1	N_2	N_3	N_4	N_5	$(m_1, m_2, m_3, m_4, m_5)$
2	P_1	N_2	N_3	N_4	N_5	$(M_1, m_2, m_3, m_4, m_5)$
3	N_1	P_2	N_3	N_4	N_5	$(m_1, M_2, m_3, m_4, m_5)$
4	P_1	P_2	N_3	N_4	N_5	$(M_1, M_2, m_3, m_4, m_5)$
5	N_1	N_2	P_3	N_4	N_5	$(m_1, m_2, M_3, m_4, m_5)$
6	P_1	N_2	P_3	N_4	N_5	$(M_1, m_2, M_3, m_4, m_5)$
7	N_1	P_2	P_3	N_4	N_5	$(m_1, M_2, M_3, m_4, m_5)$
8	P_1	P_2	P_3	N_4	N_5	$(M_1, M_2, M_3, m_4, m_5)$
9	N_1	N_2	N_3	P_4	N_5	$(m_1, m_2, m_3, M_4, m_5)$
10	P_1	N_2	N_3	P_4	N_5	$(M_1, m_2, m_3, M_4, m_5)$
11	N_1	P_2	N_3	P_4	N_5	$(m_1, M_2, m_3, M_4, m_5)$
12	P_1	P_2	N_3	P_4	N_5	$(M_1, M_2, m_3, M_4, m_5)$
13	N_1	N_2	P_3	P_4	N_5	$(m_1, m_2, M_3, M_4, m_5)$
14	P_1	N_2	P_3	P_4	N_5	$(M_1, m_2, M_3, M_4, m_5)$
15	N_1	P_2	P_3	P_4	N_5	$(m_1, M_2, M_3, M_4, m_5)$

Fuzzy rule base (17∼32)

Table: Fuzzy rule base (17∼32)

RULE NUMBER	Fuzzy membership function F_1^j	F_2^j	F_3^j	F_4^j	F_5^j	Fuzzy centre $(\mathbf{z}_0)$
17	N_1	N_2	N_3	N_4	P_5	$(m_1, m_2, m_3, m_4, M_5)$
18	P_1	N_2	N_3	N_4	P_5	$(M_1, m_2, m_3, m_4, M_5)$
19	N_1	P_2	N_3	N_4	P_5	$(m_1, M_2, m_3, m_4, M_5)$
20	P_1	P_2	N_3	N_4	P_5	$(M_1, M_2, m_3, m_4, M_5)$
21	N_1	N_2	P_3	N_4	P_5	$(m_1, m_2, M_3, m_4, M_5)$
22	P_1	N_2	P_3	N_4	P_5	$(M_1, m_2, M_3, m_4, M_5)$
23	N_1	P_2	P_3	N_4	P_5	$(m_1, M_2, M_3, m_4, M_5)$
24	P_1	P_2	P_3	N_4	P_5	$(M_1, M_2, M_3, m_4, M_5)$
25	N_1	N_2	N_3	P_4	P_5	$(m_1, m_2, m_3, M_4, M_5)$
26	P_1	N_2	N_3	P_4	P_5	$(M_1, m_2, m_3, M_4, M_5)$
27	N_1	P_2	N_3	P_4	P_5	$(m_1, M_2, m_3, M_4, M_5)$
28	P_1	P_2	N_3	P_4	P_5	$(M_1, M_2, m_3, M_4, M_5)$
29	N_1	N_2	P_3	P_4	P_5	$(m_1, m_2, M_3, M_4, M_5)$
30	P_1	N_2	P_3	P_4	P_5	$(M_1, m_2, M_3, M_4, M_5)$
31	N_1	P_2	P_3	P_4	P_5	$(m_1, M_2, M_3, M_4, M_5)$

Simulation Results : Specifications

The lower and upper bounds [m, M] on each variable are chosen as follows:
$-10 \leq z_1 \leq -6$, $10 \leq z_2 \leq 15$, $20 \leq z_3 \leq 30$, $0.8 \leq z_4 \leq 5.5$, $0.3 \leq z_5 \leq 4$.

Specifications of the Solar Panel :

$$\text{Number of cells in parallel, } n_p = 1$$
$$\text{Number of cells in series, } n_s = 36$$
$$\text{Short circuit current, } I_{sc} = 4.8A$$
$$\text{Short circuit current temperature coefficient, } k_I = 2.06mA/^0C$$

Specifications of the DC-DC converter :

$$\text{Storage Inductance, } L = 95\mu H$$
$$\text{Capacitance, } C_a = 200\mu F$$
$$\text{Capacitance, } C_b = 300\mu F$$
$$\text{The internal resistances of capacitance } C_b, \quad R_b = 162m\Omega$$
$$\text{The internal resistances of inductance } L, \quad R_l = 1\Omega$$
$$\text{The forward voltage of the power diode, } V_D = 0.7V$$
$$\text{Operational frequency, } f = 100KHz$$

Stabilizing Controller Specifications : Fixed Gain Controller

Plant corresponding to rule 1 is chosen as the nominal plant and the rest as disturbance. Therefore,

$$\text{nominal A} = 1 \times 10^4 \times \begin{bmatrix} -1.2109 & -0.0123 & -0.9919 \\ -0.0317 & -0.1183 & 0.0633 \\ 0.3333 & 0 & -0.1667 \end{bmatrix}$$

$$\text{nominal B} = 1 \times 10^5 \times \begin{bmatrix} 1.1263 \\ 0.5 \\ 0 \end{bmatrix}$$

The closed loop pole locations for preliminary feedback are chosen as [-6000 + 1000i, -6000 - 1000i, -3000].

The preliminary feedback gain was found to be K = [-0.0086, 0.0203, -0.0187].

Stabilizing Controller Specifications : Fixed Gain Controller

$A - BK$ is now asymptotically stable with

$$P = \begin{bmatrix} 0.1065 & 0.0137 & 0.0552 \\ 0.0137 & 0.4402 & 0.1166 \\ 0.0552 & 0.1166 & 0.4510 \end{bmatrix} \quad (\lambda_{max}(P) = 0.5677)$$

and $Q = 1000 \times I_{3\times3}$
The upper bound of norm of unmatched disturbance is $\alpha_f = 1631.4$.
The upper bound of norm of matched state disturbance is $\alpha_{hx} = 0.0159$.
The upper bound of norm of input disturbance is $\alpha_u = 0.3904$.
$\gamma = 1.4015 \times 10^{-6}$.
We can see that all the constraints have been satisfied.
The fixed gain state feedback controller,

$$u(t) = -K_s\mathbf{x}(t) = -(K + \gamma B^T P)\mathbf{x}(t) \text{ is found to be}$$

$$u(t) = [-0.0092, -0.0533, 0.0018]\ \mathbf{x}(t)$$

Stabilizing Controller Specifications : Variable Gain Controller I

The same nominal plant is chosen and is stabilized by feedback linearization.

The upper bound of norm of unmatched disturbance is $\alpha_f = 1631.4$.
The maximum of upper bound of norm of matched state disturbances is $\max_j(\alpha_{hx_j}) = 0.0159$.
The maximum of upper bound of norm of input disturbances is $\max_j(\alpha_{u_j}) = 0.3904$.
The variable gain controller,

$$u(t) = -K_s\mathbf{x}(t) = -\left[K + \left(\sum_{k=1}^{32} \sigma_k\gamma_k\right) B^T P\right] \mathbf{x}(t)$$

is found to be

$$u(t) = [0.0109, 0.0203, 0.0104]\ \mathbf{x}(t)$$

This is the control input in steady state as the controller parameter γ_k varies with time.