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Assessment of Membership Functions for Fuzzy Controlled Solar Photovoltaic System

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Abstract
This article figure out the performance of distinctive membership functions (MFs) with fuzzy MPPT controller applied to solar PV panels under insolation variations in climate. The generic MFs under examination are triangular, bell type, trapezoidal, Gaussian, Gaussian-2 and Sigmoidal types. The effect of each type of MFs for solar PV panels under climatic changes is examined through MATLAB simulation. The out turn of the fuzzy controller is assessed in terms of voltage ripple, conversion efficiency and steady state error for various MFs with triangular MF as the base.

***Keywords:** MPPT algorithms; Membership Functions (MFs); Fuzzy Controller: Photo voltaic (PV) panel; MATLAB/SIMULINK*

I. INTRODUCTION

The renewable power division in India is the fourth most interesting sustainable energy market in the world [1]. In fact, India has moved to clean energy after it approved the Paris agreement. The Renewable Energy ministry has set 100GW solar energy target by 2022.

At present, the efficiency of PV system ranges from 20-40% and several researchers are aiming to attain maximum energy transfer from source to load [2, 3]. This is achieved by Maximum Power Point Tracking (MPPT) approaches in association with regulators of DC and DC-DC converters [4,5]. In the past decade, Fuzzy control that belongs to the family of intelligent control [6] is applied to identify MPP in partial shading environment, in addition to constant and variable insolation conditions for PV arrays. One main benefit of fuzzy control is, it does not need plant modeling. Fuzzy control truly embeds the prior knowledge of plant engineer, and frequently those of an investigator of process. Custom developed MFs are available in few fuzzy logic simulation tools

In literature MFs of various forms have been recommended for fuzzy controllers [7]. In modern PSO-fuzzy control method, particularly where particle swarm optimization techniques are applied to tune and develop a fuzzy system, MFs of sigmoidal have been used [8]. In fuzzy control processes, triangular type MFs and trapezoidal shaped MFs are most commonly used for all the inputs and outputs. Sometimes, hybrid MFs are also implemented for the fuzzy input and outputs However, in the earlier articles, no decent analysis is present to found the upper hand of MF of particular type.

The intention of this article is to investigate and correlate the effect of various MFs in the fuzzy MPPT controlled solar PV panels. A rapid change in insolation has been expressed to examine soundness of the PV array. The performance index, such as accuracy, conversion efficiency and voltage and power ripples have been examined for PV control system bench mark. This article is grouped into five divisions. The first division gives an introduction and second division describes the depiction of MFs. Third division devotes the PV array and boost converter models. Fuzzy controlled PV system with various MFs is assessed in division four. Finally, conclusions are mentioned in fifth division.

II. MEMBERSHIP FUNCTIONS DEPICTION[9]

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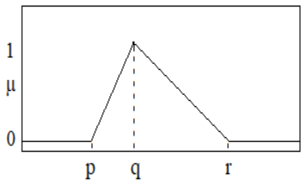
Fig.1 shows distinct patterns of MFs. The broad division of MFs is given below:

1. Piecewise Linear Functions

Triangular or trapezoidal type MFs are generally piecewise linear functions. The truncated triangle shape is used for trapezoidal MF and may be symmetrical or asymmetrical in shape. The formula for triangular MF with parameters ‘p’ , ‘q’ and ‘r’ is

$$f(x;p,q,r) = \mathrm{Max}\left\{\mathrm{Min}\left(\frac{(x-p)}{(q-p)},\frac{(r-x)}{(r-q)}\right),\ 0\right\} \qquad (1)$$

where the parameter ‘q’ locates the peak, ‘p’ and ‘r’ locate the "feet" of the triangle , as shown in Fig. 1(a).



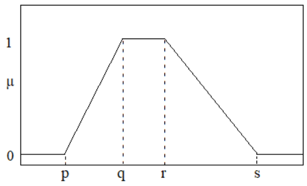


Fig. 1(a) Fig. 1(b)

The expression for trapezoidal MF with parameters ‘p’, ’q’, ’r’ and ‘s’ is

$$f(x;p,q,r,s) = \mathrm{Max}\left\{\mathrm{Min}\left(\frac{(x-p)}{(q-p)},\ 1\ ,\frac{(s-x)}{(s-r)}\right),\ 0\right\}$$

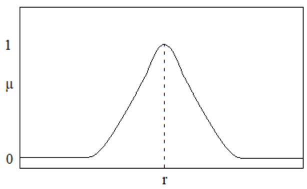
(2)

where ‘p’, ‘s’ indicates the “feet” of the trapezoid and ‘q’ and ‘r’ depicts the “shoulder”, as shown in Fig. 1(b).

2. Gaussian Functions

The formula for a Gaussian MF with symmetry, depicted in Fig. 1(c), is

$$f(x;\ \sigma,\ \mathrm{r}) = e^{\frac{-[x-r]^2}{2\sigma^2}} \qquad (3)$$



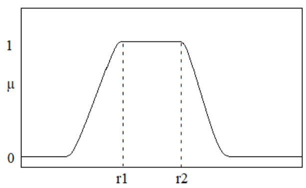


Fig. 1(c) Fig. 1(d)

where c shows the length from the base and 0 depicts width of the MF. In a Gaussian MF of two-sided, shown in Fig. l(d), the parameters ‘r1’, ‘r2’, describe the pattern of the left-side and right side curves.

3. Bell-Shaped Function

The equation of a symmetrical bell-shaped MF is

$$f(x;\ \mathrm{p},\ \mathrm{q},\ \mathrm{r}) = \frac{1}{\left[1+\left|\frac{x-r}{p}\right|^{2q}\right]}$$

(4)

where ‘q’ is generally positive, ‘r’ locates the curve center point and a indicates curve width. This MF is shown in fig. 1(e).

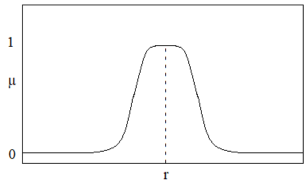


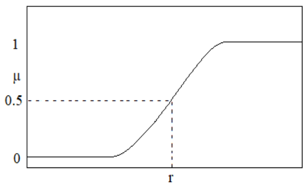
Fig. 1(e)

4. Sigmoidal Function

Figs. l(f) and l(g) show a MF of sigmoidal type, that is with left or right open. The general formula of this MF is expressed as

$$f(x;p,r) = \frac{1}{1+e^{-p(x-r)}}$$

(5)



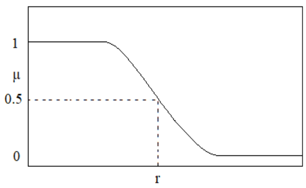


Fig. 1(f) Fig. 1(g)

where ‘r’ indicates the length from the base and ‘p’ gives function steepness. The MF with right open for positive ‘p’ and vice versa. The MF formed by the difference between the two sigmoidal MFs is referred as difference and product of two is referred as product of the two sigmoidal MFs and shown respectively in Figs. 1(h) and l(i).

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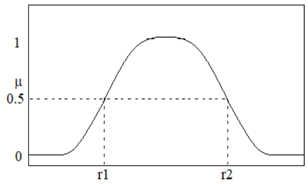

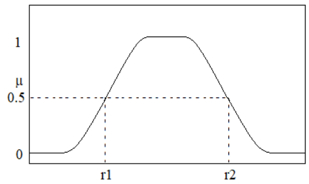

Fig. 1(h) Fig. 1(i)

III. MODELLING OF OVERALL SYSTEM

The leading system main parts are

- PV panels
- Fuzzy MPPT controller and
- Boost converter

A PV arrays model

In the total system, the vital part is PV panel also called as PV array. Fig.2 elucidates the diode - PV array model. Fig.3 reports the P - V and V-I tendency of the system. Modeling of PV array [10] is cited in equations (6) to (9).

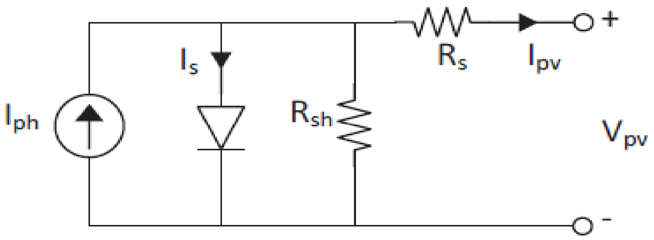

Fig. 2 .PV panel model with one diode

$$I_{PV} = I_{ph} - I_s\left(\exp\left(\frac{(V_{PV} - R_s I_{PV})}{AV_T}\right) - 1\right) - \frac{(V_{PV} - I_{PV} R_s)}{R_{sh}} \quad (6)$$

$$V_T = \frac{kT}{Q} \quad (7)$$

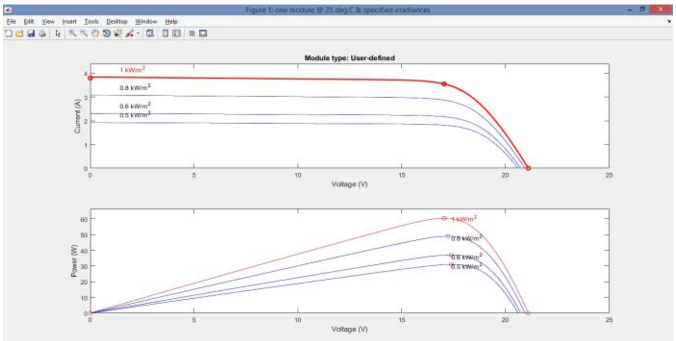

Fig. 3. PV panel characeristics

$$I_{ph} = \frac{G}{G_{stc}}\left(I_{sc} + K_i\left(T - T_{stc}\right)\right)$$

(8)

$$I_s = \frac{I_{sc} + K_i\left(T - T_{stc}\right)}{e^{\left(\frac{V_{oc} + K_v\left(T - T_{stc}\right)}{AV_t}\right)} - 1}$$

(9)

Terminology

I_{ph}	~ Photon Current
I_s	~ Saturated dark Current
V_{pv}	~ Panel Voltage
R_s	~ Series Resistance
A	~ Ideality Quality
VT	~ Thermal Emf
k	~ Boltzmann's constant
T	~ Temperature at p - n junction
Q	~ Electron Charge
R_{sh}	~ Shunt Resistance
PV	~ Photo-Voltaic
MPP	~ Maximum Power Point
MPPT	~ Maximum Power Point Tracking
STC	~ Std Test Conditions
P & O	~ Perturb & Observe
InC	~ Incremental Conductance
R_{mp}	~ MPP Resistance of Solar Cell
Ro	~ Output (load) Resistance
D	~ Duty Cycle
V_s	~ PV array voltage
Δi_L	~ Inductor current ripple
F	~ Switching frequency
L	~ Inductor
Ci	~ Input Capacitor
Co	~ Output Capacitor.

B. Boost Converter:

Greater than or equal DC input is the output of the boost converter shown in fig.4. Modelling equations of this converter [11] are cited in equations (10) to (17).

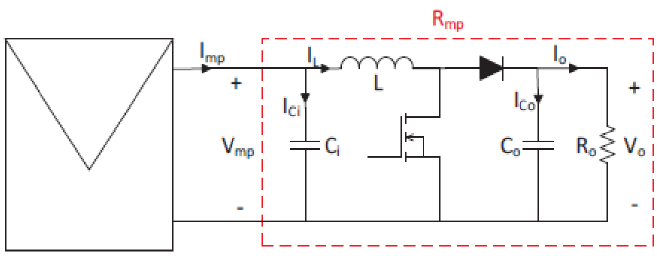

Fig. 4. Boost converter electric circuit.

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$$R_{mp} = \frac{V_{mp}}{I_{mp}} \quad (10)$$

$$R_o = \frac{1}{(1\text{-}D)^2} R_{mp} \quad (11)$$

$$D = 1 - Sqrt\left(\frac{R_{mp}}{R_o}\right) \quad (12)$$

$$V_o = V_{mp}\ Sqrt\left(\frac{R_o}{R_{mp}}\right) \quad (13)$$

$$V_{o\,Max} = \frac{1}{(1\text{-}D_{Max})} V_{mpG} \quad (14)$$

$$L = \frac{D}{f\,\Delta\, i_L} V_s \quad (15)$$

$$C_i = \frac{1}{8L\gamma_{V_{mp}}\, f^2} D \quad (16)$$

$$C_o = \frac{D}{R_{mp}\ f\ \gamma_{V_o}} [1\text{-}D]^2 \quad (17)$$

C. Fuzzy MPPT Controlled PV System

In this sub section, PV system with fuzzy controller is depicted using triangular MFs. With this MF as the reference, the behaviour of the PV system with remaining MFs will be analysed in the further sections.

Fig. 5 depicts the Simulink diagram of the fuzzy controlled PV system with various MFs. For the applied insolation, PV system induces voltage and current signals. With suitable manipulations the error (E = dP/dV) and change in error (CE) are applied as inputs for fuzzy controller. The MPPT fuzzy system, as shown, fuzzifies the inputs and produces the control output by control rules estimation with defuzzification. The inputs and outputs (ce, e and dD) use reference MFs, as mentioned in Fig.3. The linguistic variables of the MFs are ‘NB’ (negative big), ‘NS’ (negative small), ‘Z’ (zero), ‘PS’ (positive small) and ‘PB’ (positive big), as indicated. Table 1 shows the matrix rules for fuzzy system. The defuzzification method is implemented on Centre Of Area method. The behaviour of fuzzy MPPT controller is the desired duty cycle fed to boost converter to shift PV maximum power to load [12].

IV. SIMULATION RESULTS

The intension of the article is to examine the fuzzy-controlled PV array behavior for variety of optimum MFs.

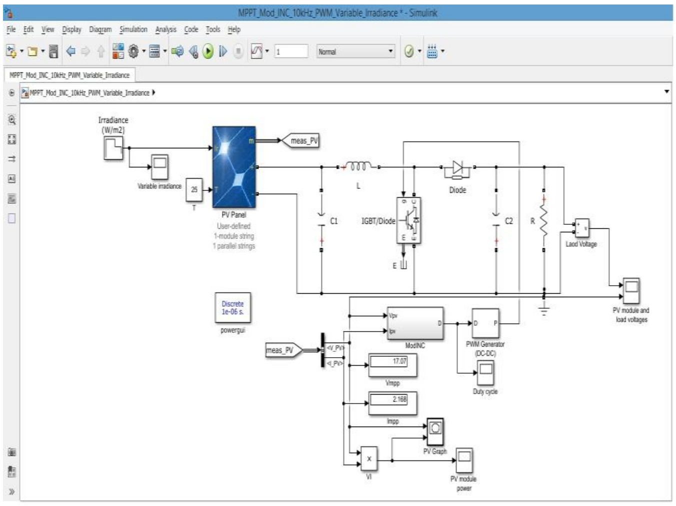

Fig. 5. PV system Simulink diagram.

With the reference of triangular MF, the behavior of the overall system with remaining MFs with optimum MFs will be compared and analyzed.

A. Description of model

The user outlined overall system will offer Impp = 3.55A, Vmpp = 17.04V and Pmpp = 60.53W at STC. The selected converter with 10KHz operating frequency and elements of R =30Ω, L = 13mH and $C_{in} = C_o$ = 1000μF.

B. Simulation Results

Fuzzy controlled PV system Simulated results are analyzed with six MFs under dynamic environmental conditions as presented in fig. 6

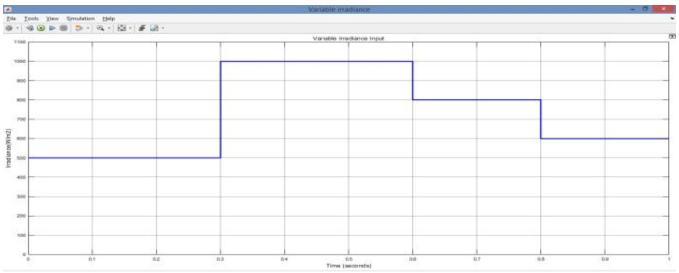

Fig.6 Varying irradiance input.

Case1: Fig. 7 and 8 exhibit the power of PV panel, voltages of simulated system at input and output with triangular MF.

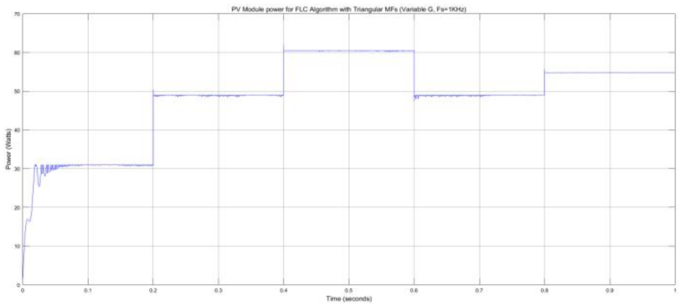

Fig. 7. Power waveform of PV panel with triangular MF.

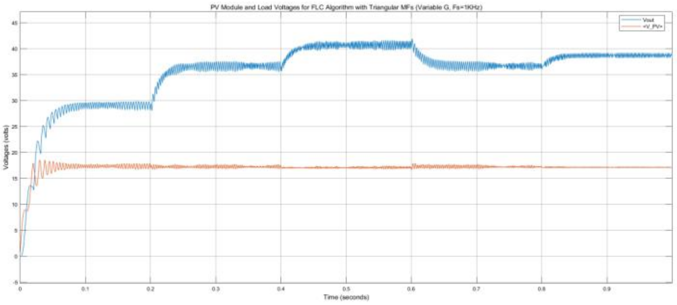

Fig. 8. Voltage waveform at converter input and output stages.

Performance indices of the simulated system with triangular MF are listed in table I.

Case2: Figures 9 and 10 exhibit the power of PV panel, voltages of simulated system at input and output with bell type MF.

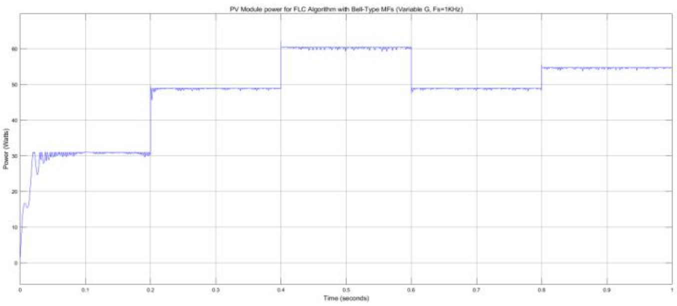

Fig. 9. Power waveform of PV panel with bell type MF.

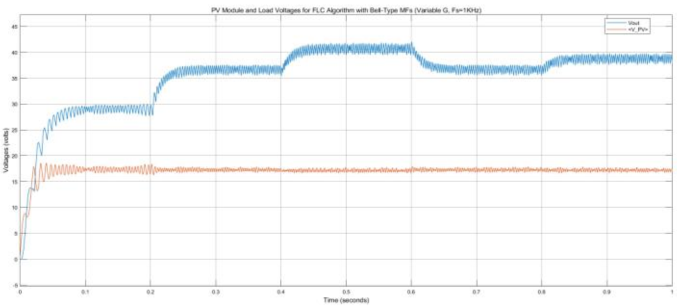

Fig. 10. Voltage waveform at converter input and output stages.

Performance indices of the simulated system with bell type MF are listed in table I.

Case3: Figures 11 and 12 exhibit the power of PV panel, voltages of simulated system at input and output with trapezoidal MF.

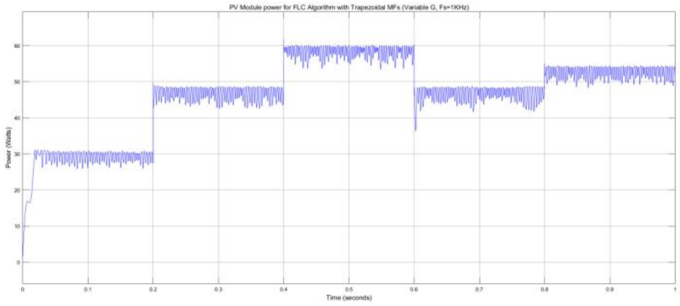

Fig. 11. Power waveform of PV panel with trapezoidal MF.

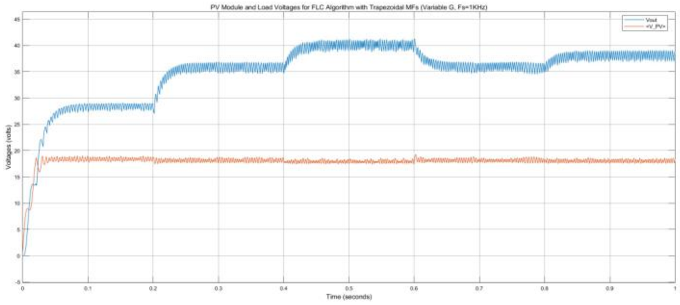

Fig. 12. Voltages of Boost converter at input and output.

Performance indices of the simulated system with trapezoidal MF are listed in table I.

Case4: Figures 13 and 14 exhibit the power of PV panel, voltages of simulated system at input and output with gaussian MF.

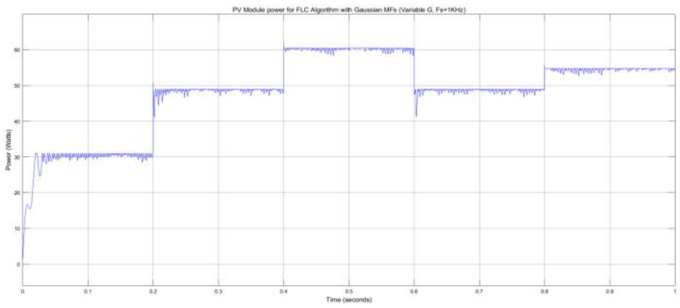

Fig. 13. Power waveform of PV panel with gaussian MF.

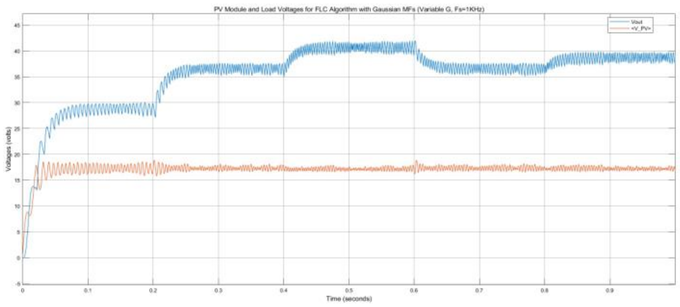

Fig. 14. Voltages of Boost converter at input and output.

Performance indices of the simulated system with gaussian MF are listed in table I.

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Case5: Figures 15 and 16 exhibit the power of PV panel, voltages of simulated system at input and output with gaussian -2 MF.

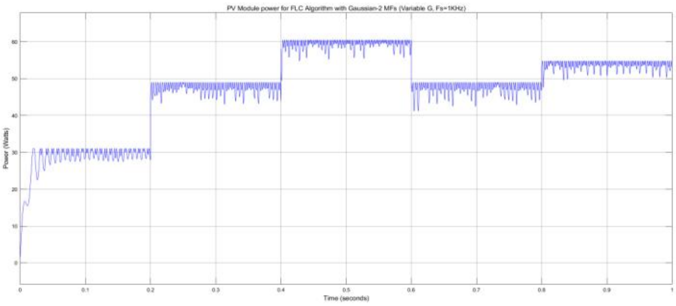

Fig. 15. Power waveform of PV panel with gaussian-2 MF.

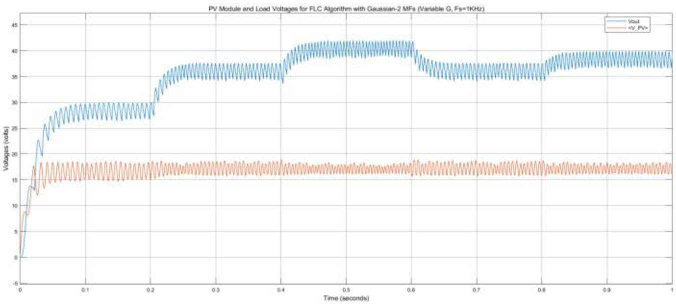

Fig. 16. Input and output voltages of Boost converter.

Performance indices of the simulated system with gaussian -2 MF are listed in table I.

Case6: Figures 17 and 18 exhibit the power of PV panel, voltages of simulated system at input and output with P-sigmoidal MF.

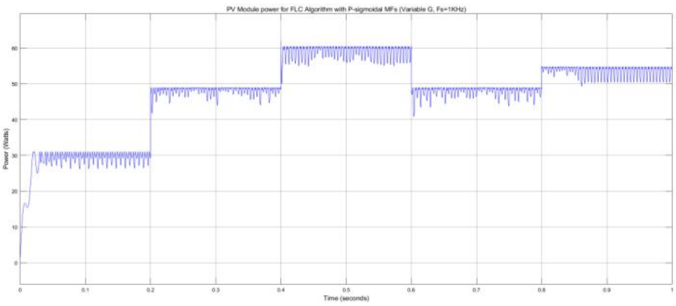

Fig. 17. Power waveform of PV panel with P-sigmoidal MF.

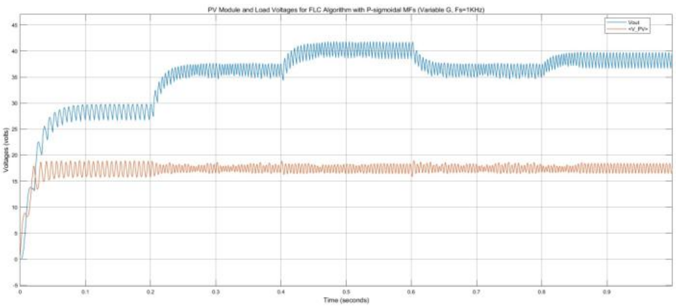

Fig. 18. Input and output voltages of Boost converter.

Performance indices of the simulated system with P-sigmoidal MF are listed in table I.

Observations

The dynamic climate change plays a key role on the operation of PV system. The system ability valuation conditions are similar in each MF, so, analysis can be done with the triangular MF as the reference. Figures 7 to 18 show the PV system behavior with six varieties of MFs. The performance criteria are percentage error in maximum power delivered by PV system, ripple in load voltage, response time and steady state accuracy at various irradiance levels.

Gaussian, trapezoidal and sigmoidal MFs exhibit common characteristic; the MF is not zero value in the entire pattern. This will have an effect on the controlled system accuracy and output voltage ripple when compared to triangular and bell type MFs where the percentage error and voltage ripple are minimum.

Analyzing the PV system response graphs in detail, it can be observed that reference i.e. triangular MF provide the best behavior, i.e., negligible error in power at MPP, fast response, minimum output voltage ripple and better accuracy at steady state. The output behavior for bell type MFs are almost identical. The performances with remaining MFs are somewhat degraded. The desired features are summed up and analyzed in Table 1.

V. CONCLUSION

In this article, various membership functions are applied to fuzzy MPPT controlled PV system. The MFs under examination are triangular, bell-shaped, trapezoidal, Gaussian, Gaussian–2 and sigmoidal. Fuzzy MPPT control is carried out with distinct MFs of symmetrical type and the similar shape of MF is applied for two inputs and one output. A complete fuzzy MPPT controlled PV system setup is then examined with the fuzzy MPPT controller using distinct MFs. The outcome of the simulation results reveal that triangular shaped MF provides the best performance of PV system in terms of voltage ripple, conversion efficiency and accuracy.

The bell type MF response is almost same as the triangular MF. Trapezoidal and Gaussian MFs responses are moderately acceptable but sigmoidal and Gaussian-2 responses are unacceptable to the PV system. Triangular MF, involving of straight line segments, is simple to carry out in fuzzy control. Although the analysis relates only PV system, the similar results will be mostly valid for remaining control applications.

TABLE I. Comparison of performance indices of PV system

Triangular MFs						Gaussian MFs					
Irradiance	Vout (V)	Voltage Ripple	Pmpp (W)	Pout (W)	% Error	Irradiance	Vout (V)	Voltage Ripple	Pmpp (W)	Pout (W)	% Error
500	29.1	3.9%	31.03	30.96	0.23	500	28.7	7.8%	31.03	30.49	1.74
800	36.4	3.0%	49.00	48.96	0.08	800	36.5	6.2%	49.00	48.53	0.96
900	38.7	2.4%	54.78	54.78	0.00	900	38.8	5.3%	54.78	54.53	0.46
1000	40.7	2.4%	60.53	60.48	0.08	1000	40.7	4.9%	60.53	59.87	1.09
Bell-Type MFs						**Gaussian-2 MFs**					
Irradiance	Vout (V)	Voltage Ripple	Pmpp (W)	Pout (W)	% Error	Irradiance	Vout (V)	Voltage Ripple	Pmpp (W)	Pout (W)	% Error
500	29.0	4.9%	31.03	30.79	0.77	500	28.3	10.6%	31.03	29.36	5.38
800	36.7	4.4%	49.00	48.84	0.33	800	36.1	8.3%	49.00	47.84	2.37
900	38.7	4.6%	54.78	54.60	0.33	900	38.4	7.6%	54.78	53.69	1.99
1000	40.7	4.6%	60.53	60.24	0.48	1000	40.4	7.4%	60.53	59.31	2.02
Trapezoidal MFs						**P-Sigmoidal MFs**					
Irradiance	Vout (V)	Voltage Ripple	Pmpp (W)	Pout (W)	% Error	Irradiance	Vout (V)	Voltage Ripple	Pmpp (W)	Pout (W)	% Error
500	28.3	4.5%	31.03	28.76	7.32	500	28.2	10.7%	31.03	28.75	7.35
800	35.8	4.8%	49.00	46.90	4.29	800	36.4	6.6%	49.00	48.02	2.00
900	38.0	4.9%	54.78	52.27	4.58	900	38.2	8.1%	54.78	52.64	3.91
1000	40.0	4.5%	60.53	58.79	2.87	1000	40.3	7.5%	60.53	58.25	3.77

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