DC to DC Bidirectional Converter by using TS-Fuzzy Controller for PV System

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Abstract— Photovoltaic Systems (PVSs) are commonly used to produce electricity for various applications. The solar irradiances will not be constant on every time, it will be always fluctuating and changing. Many PV modules need to be managed in the combination of parallel and series to meet load requirement at rated voltage. In order to harvest maximum energy from PV modules, it must be worked at particular voltage which is related to maximum power location. Generally a boost converter is associated to work as a maximum power point tracker (MPPT) device with help of perturb and observe (P&O) mechanism. A battery bank is incorporated to form a dc-link to store the energy from PV to be utilized whenever it is required. Therefore, a dc to dc bidirectional device is placed to regulate the discharging and charging process of batteries. Compared to PI and conventional Fuzzy controllers, Takagi Sugeno-Fuzzy (TS-Fuzzy) controllers are able to generate accurate response quickly under rapid changes of solar irradiance. Therefore, TS-Fuzzy controller based control method for the dc to dc circuit is implemented in this paper. The P&O algorithm is also integrated to control mechanism of a dc to dc bidirectional circuit. Hence no need of an extra circuit for working as MPPT circuit. Hardware – in the – Loop (HIL) is developed by using OPAL-RT units to analyze various results in this paper.

Keywords— MPPT, HIL, TS-Fuzzy, Renewable Energy Sources, PV.

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1. INTRODUCTION

Applications of Photovoltaic Systems (PVSs) are increasing day by day and generating electrical power is one of the bet among them. Global warming can be reduced by using PVS for generating electrical power. However, the cost of PV modules are very high, hence they must be operated for best utilization. Due to nonlinear characteristics of PV modules or panels, maximum power point tracker (MPPT) circuits must be incorporate to generate maximum power from solar energy.

Due to fluctuations in a generated power through PV modules, a storage device may be required depends on applications. Most famous storage device for PV systems is batteries. The dc-link voltage also can be maintained constant by integrating battery bank through an efficient converter. There are many converters to work as MPPT circuits including buck, boost, buck boost, cuk, inverters etc. at the same time a dc to dc converter which can allow power flow on both the directions (i.e., bidirectional power flow) must be used to regulate charging and discharging actions of the battery bank. Therefore, the bidirectional dc to dc converter should be used to regulate dc-link voltage. The solar irradiance is depends on weather conditions [1-7]. Further, the load which is operating at dc-link is also changing rapidly by time to time. Hence, an efficient algorithm must be developed to give the proper directions to MPPT converter for operating PV panels at maximum power level.

Using one converter for MPPT and other for bidirectional power flow converter for battery will be increasing the overall system cost and decrease the efficiency for low and medium power applications. Therefore, using bidirectional converter as a MPPT circuit for PV system by regulating the voltage to deliver the maximum power from PV panels can be a better idea to solve many issues. To achieve this operation, the MPPT algorithm is integrated with control of bidirectional dc to dc circuit. Due to fixed gains of conventional PI controller, it cannot produce accurate output quickly as like TS-Fuzzy controllers. Hence, TS-Fuzzy controller is used in the control method of the bidirectional converter. There is no guarantee on results presented through MATLAB, hence a hardware – in the – loop (HIL) is implemented in this paper to collect various results under various operating conditions.

Many scholars are presented various MPPT techniques but the proposed technique is a hybrid method where integrated conventional P&O algorithm with TS-Fuzzy based control method of a dc to dc bidirectional converter. In order to protect the battery from over discharging and charging, the state of charge (SoC) commend is incorporated into the proposed method to restrict the charging and discharging of the battery. This research work further divided into following sections. Overall system description is carryout by Section-II. The process of MPPT and modeling of PV system is presented in Section-III. A detailed modeling with mathematical equations of a battery model is given in Section-IV. Details and designing of a TS-Fuzzy method is presented in Section-V. Results collected through HIL of the system are provided in Section-VI. Conclusion is given at the end of the work in Section-VII.

2. OVERVIEW OF THE MODEL

A model diagram of PV-Battery based dc-standalone system is show in Fig. 1. There is no extra converter incorporated to PV system for the purpose of MPPT. The converter used to manage bidirectional power flow for battery is also used as MPPT of the PV system by integrating P&O technique with the proposed control method of the bidirectional dc to dc converter. Therefore, dc to dc bidirectional circuit not only helps to regulate the voltage, but also working as a MPPT circuit of the PV system during uniform irradiance. This configuration can be able to reduce an extra circuit to work as MPPT of the PV system. Bidirectional circuit consists of two power electronic devices. One switch (Q_1) is used to work as buck converter which can allow current from dc-link to battery for charging. Another switch (Q_2) is working like a boost converter for discharging current into dc-link from battery bank. Various loads including dc to dc and dc to AC will be operated at dc-link. The voltage at dc-link is regulated according to voltage with respect to maximum power location of the PV modules.

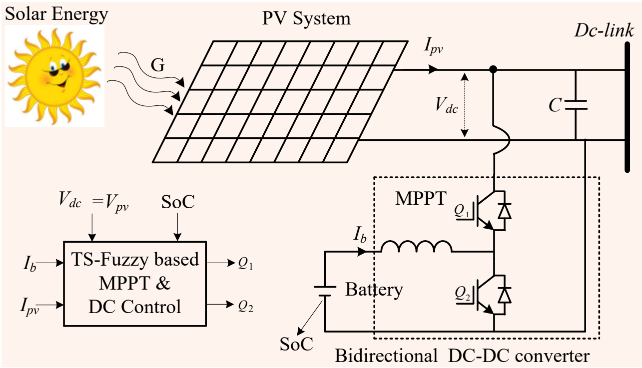

Fig. 1: PV-Battery based DC power supply model with MPPT.

3. MODELING OF PV AND MPPT METHOD

PV cells are used to produce electricity directly from solar energy (i.e., irradiance). A mathematical representation of a conventional PV cell is denoted by below fundamental nonlinear equation.

$$I_{pv} = I_{ph} - \frac{(V_{pv} + I_{pv}R_s)}{R_{sh}} - I_{rs}\left[\exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{AKT}\right) - 1\right] \quad (1)$$

here, $I_{ph} = [k(T - T_r) + I_{sc}]\frac{G}{1000}$; $I_{rs} = I_{rr}\exp\left(\frac{qV_D}{AK}\left[\frac{1}{T_r} - \frac{1}{T}\right]\right)\left[\frac{T}{T_r}\right]^3$.

By using above equations, a PC cell can be represented as shown in Fig. 2(a). In general a group of PV cells must be arranged in the combination of parallel and series to produce required power at rated voltage which is shown in Fig. 2(b) called s PV array. Where, V_{PV} & I_{PV} are voltage at PV terminals and current generated by PV array. A detailed modeling of PV array by using above fundamental equations is depicted in Fig. 3. The list of parameters including for model a PV array is given in Table-1.

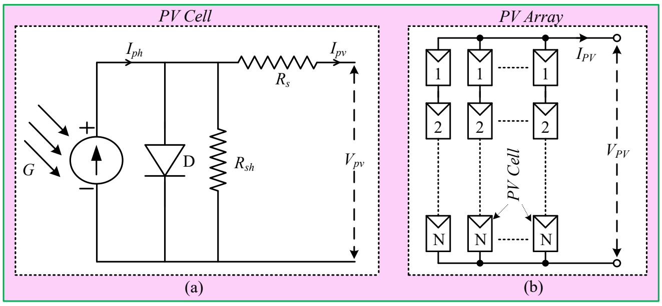

Fig. 2: Model representation of a PV (a) Cell; (b) Array.

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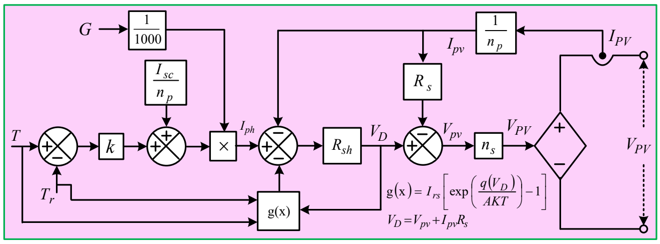

Fig. 3: Schematic representation of a PV array.

Table-1: Values of PV.

Module voltage when Opens circuit $V_{oc.}$	36.9V
Current when Short circuited $I_{sc..}$	8.01A
$V_{mpp.}$	30.31V
$I_{mpp.}$	7.11A
Series resistance $R_{s.}$	0.0044
Shunt resistance $R_{sh.}$	0.9821
V_D at MPP..	0.5366
Parallel cells/module.	Vary.
Series cells/module $N_{s.}$	Vary.
Temperature value $T_{r.}$	25^0C
Thermal voltage $V_{t.}$	26mV
Diode current at MPP.	0.3635.
Reverse saturation current I_{rr} at T=$T_{r.}$	3.93x10-$^{-10}$
Voltage of diode at MPPT $V_{dm.}$	0.5366
Modules in series $n_{s.}$	22.0
G*.	1000W/m^2
Rated power.	4.72kW

Ns=Round (V_{oc}/0.611)

$$I_{dm} = -I_{mpp} - \frac{V_{dm}}{R_p} + I_{sc}\,.$$

$$I_{rr} = \frac{\left(I_{sc} - \dfrac{V_{oc}}{N_s R_{sh}}\right) \Big/ \left(\exp\left(\dfrac{V_{oc}}{N_s V_t}\right) - 1\right)}{\left[\dfrac{T}{T_r}\right]^3 \exp\left(\dfrac{qV_D}{AK}\left[\dfrac{1}{T_r} - \dfrac{1}{T}\right]\right)}\,.$$

$$V_{dm} = V_t \times \log\left(I_{dm} / I_{rr} + 1\right).$$

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$$R_s = \frac{\left(V_{dm} - \frac{V_{mpp}}{N_s}\right)}{I_{mpp}},\ R_{sh} = \frac{\left(\frac{V_{mpp}}{N_s I_{mpp}} - R_s\right) \times R_p}{\left(R_p - \frac{V_{mpp}}{N_s I_{mpp}} + R_s\right)}.$$

$$I_{pt} = \frac{V_t}{R_{sh}},\ R_p = \frac{V_{dm}}{\left(I_{sc} - I_{mpp} - I_{pt}\right)}.$$

$$R_p = 100 \times \frac{V_{oc}}{N_s I_{sc}} \text{ and } V_{dm} = \frac{V_{oc}}{N_s}.$$

In order to obtain maximum possible energy from PV modules, they must be operated at particular voltage denoted by voltage at maximum power point (V_{mpp}). The set of P-V curves of PV system is depicted in Fig. 4. The famous and simplest algorithm to identify V_{mpp} is P&O algorithm. The V_{mpp} can be obtained by using equation (2).

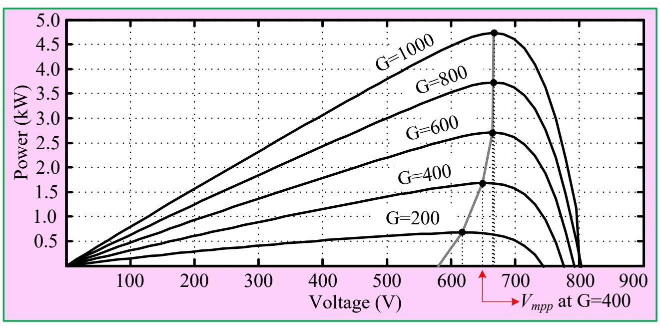

Fig. 4: Power vs Voltage curves at various irradiances.

$$V_{mpp}(k+1) = \Delta V \times \text{sign}\left(\frac{dP_{PV}}{dV_{PV}}\right) + V_{mpp}(k) \qquad (2)$$

Where, k is the iteration and ΔV is steep in voltage.

As already stated, a dc to dc bidirectional circuit is placed to control the voltage at dc-link. A TS-Fuzzy controller based novel control method is developed in this paper by considering V_{mpp} as an input signal. The proposed control scheme to regulate the dc-link voltage at V_{mpp} is shown in Fig. 5. The parameter SoC also incorporated into the proposed control method to manage the overcharging and discharging of the battery. By comparing dc-link voltage (V_{dc}) with its reference value (V_{mpp}), the error signal is obtain. Further the error signal is giving as an input to the TS-Fuzzy controller for producing reference battery current (I_b^*). Further, this I_b^* will be comparing with actual battery current for generating required pulses through a hysteresis controller. Therefore, the voltage at dc-link will be regulate at V_{mpp} which can helps to operate PV system at MPPT level without using any extra dc converter for MPPT. The complete hybrid control of dc to dc bidirectional circuit is shown in Fig. 5.

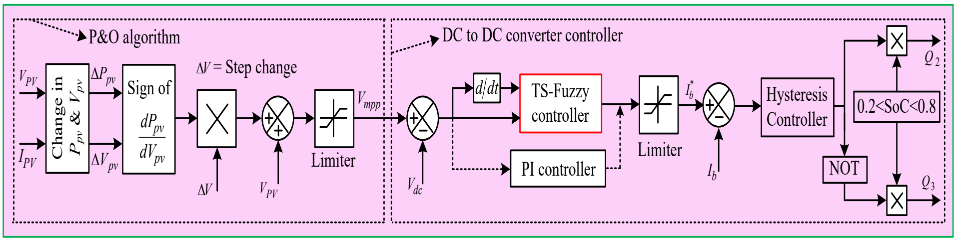

Fig. 5: Hybrid control of a dc to dc circuit to work as MPPT.

4. MODELING OF BATTERY BANK

Basic mathematical equations of a battery including temperature parameter are obtained from [3-7, 15-17] in this work. The SoC is also considered while doing modeling of the battery bank. The basic model of the battery is shown in Fig. 6.

$$E_m = E_{m0} - K_E(273+\theta)(1-SOC) \tag{3}$$

$$I_p = V_{PN} G_{P0} \exp\left(\frac{V_{PN}}{V_{P0}(\tau_p s+1)} + A_P\left(1-\frac{\theta}{\theta_f}\right)\right) \tag{4}$$

$$Q_e(t) = Q_{e\_init} + \int_0^t -I_m(\tau)d\tau \tag{5}$$

$$C(I,\theta) = \frac{K_c C_{0*} K_t}{1+(K_c-1)(I/I^*)^{\delta}},\ K_t = LUT(\theta) \tag{6}$$

Where, $SOC = 1 - \frac{Q_e}{C(0,\theta)}$; $\theta(t) = \theta_{init} + \int_0^t \frac{\left(Ps - \frac{(\theta-\theta_a)}{R_\theta}\right)}{C_\theta} d\tau$

where, voltage at open circuit and voltage at full charging are denoted by E_m and E_{mo} . I_m is current of the main branch. Electrolyte temperature (^{0}C) is represented by θ . Q_e is the extracted charge (A S). K_E , G_{P0} and δ are constants and C is the battery capacity (A-H).

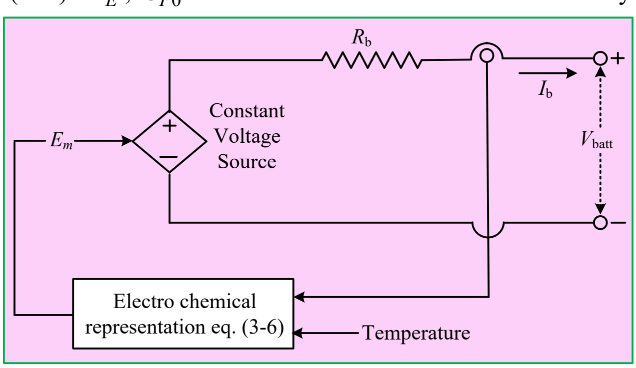

Fig. 6: Block diagram of battery bank.

Various parameters of the battery are listed in Table-2. The rating of the battery bank is calculated by using below equation.

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Battery capacity($I_{b\text{-}Ah}$) = $\dfrac{Time \times Power}{V_{bat} \times SoC_{avg}}$.

10kW of load is assumed to run for 24hrs on battery only at 300V of 60% SoC.

$$I_{b\text{-}Ah} = \frac{24 \times 10000 \times 100}{300 \times 60} \approx 1335\ Ah.$$

Table-2: Values of battery bank.

S.No	Parameters	Values
1	Voltage rating of battery bank	300V.
2	Rated capacity	1333Ah.
3	Initial SoC	60%.
4	Battery type	Lead-acid.
5	Fully charged voltage	327.
6	Resistance	0.0024.
7	Battery response time	31sec.

DESIGNING OF TS-FUZZY CONTROLLERS

Two inputs namely error (x_i) & its derivative ($\dot{x}_i$) are taken to model of a TS-Fuzzy controller which is shown in Fig. 7. Following fundamental equations representing the membership functions and defuzzyfication will be considered to generate required output. A set of rules is listed in Table-3.

$$\mu_P(x_i) = \begin{cases} 0, & x_i < L_1 \\ \dfrac{L_1 + x_i}{2L_1}, & -L_1 \le x_i \le L_1 \\ 1, & x_i > L_1 \end{cases} \qquad \mu_P(\dot{x}_i) = \begin{cases} 0, & \dot{x}_i < L_2 \\ \dfrac{L_2 + \dot{x}_i}{2L_2}, & -L_2 \le \dot{x}_i \le L_2 \\ 1, & \dot{x}_i > L_2 \end{cases}$$

$$\mu_N(x_i) = \begin{cases} 1, & x_i < L_1 \\ \dfrac{L_1 - x_i}{2L_1}, & -L_1 \le x_i \le L_1 \\ 0, & x_i > L_1 \end{cases} \qquad \mu_N(\dot{x}_i) = \begin{cases} 1, & \dot{x}_i < L_2 \\ \dfrac{L_2 - \dot{x}_i}{2L_2}, & -L_2 \le \dot{x}_i \le L_2 \\ 0, & \dot{x}_i > L_2 \end{cases}$$

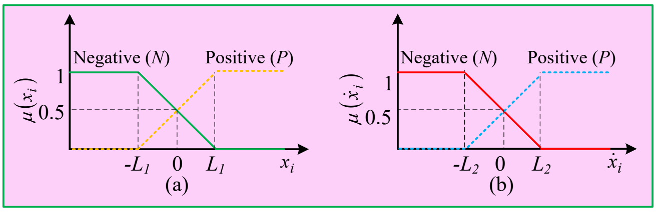

Fig. 7: Membership functions of a TS-Fuzzy controller.

Table-3: The TS-fuzzy controller rules

Rules (R)	$\dot{x}_i$(k)	x_i(k)	Values
R-A	N	N	$Z_1 = a_1 x_i(k) + a_2 \dot{x}_i(k)$
R-B	P	N	$a_3 Z_1 = Z_2$
R-C	N	P	$a_4 Z_1 = Z_3$
R-D	P	P	$a_5 Z_1 = Z_4$

The output (Y) of TS-Fuzzy controllers can be represented by below equation.

$$Y = \frac{\sum_{i=1}^{4} Z_i F_i}{\sum_{i=1}^{4} Z_i} \tag{7}$$

where, F_i= min.{ $\mu_p(x_i)$, $\mu_p(\dot{x}_i)$ }.

5. Results and Discussions

Real Time Systems (RTSs) are designed to perform tasks like real time experience with real time management [1, 4]. Broad outcomes are removing through one more PC for inspect results. Fig. 8 shows the integration of two OPAL-RT modules to establishment of HIL block. The proposed model displayed in Fig. 1 is partitioned in to plant and controller. Other parameters of the system are adopted from [21-23].

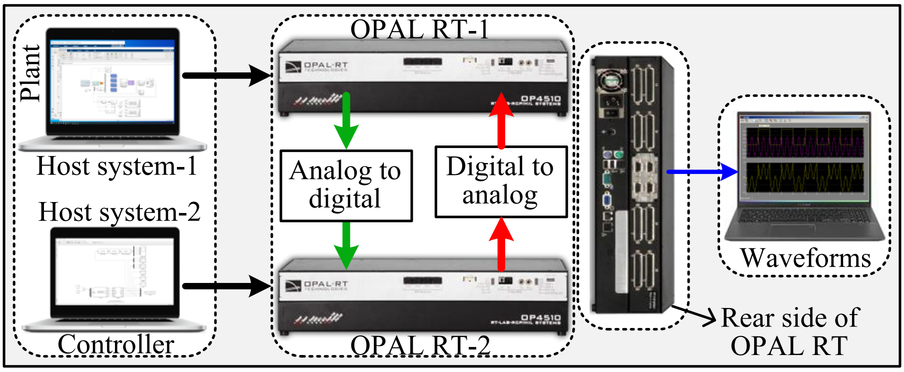

Fig. 8: Configuration of an OPAL-RT setup.

Case-1: MPPT response of PV system with PI and TS-Fuzzy controller:

A step change of 1000w/m2 to 750w/m^2 in solar irradiance is considered to analyze the response of MPPT under PI and TS-Fuzzy controller in this case study. The obtained power waveform is depicted with using TS-Fuzzy and PI controllers in Fig. 9. The dc to dc bidirectional circuit is acting as MPPT circuit which performance depending on controllers used such are TS-Fuzzy and PI. The tuned gains of PI controller may not be perfect at irradiance 700w/m^2. Therefore PI performance is slightly bad as compared with TS-Fuzzy since the fuzzy block can able to adjust their gains according to changes in the system.

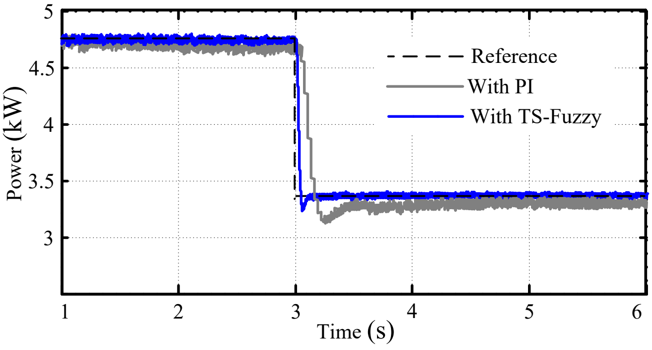

Fig. 9: PV MPPT performance under PI & TS-Fuzzy.

Case-2: System under variation in load:

A step change of load is applied at t=2.0 sec. According to the change in load, the battery controller is responding by charging and discharging instantly to meet the load demand accurately as shown in Fig. 10(a). Corresponding SoC of the battery and voltage at dc-link are presented in Fig. 10(b) and (c) respectively.

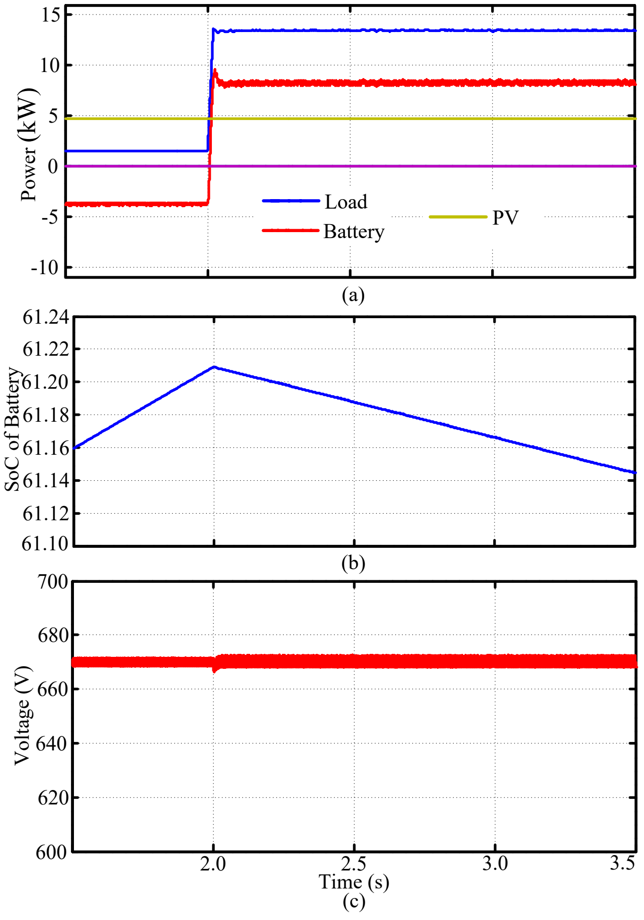

Fig. 10: (a) Powers in the system, (b) SoC, and (c) voltage at dc-link.

6. CONCLUSION

The performance of MPPT of the PV system under uniform irradiance by integrating TS-Fuzzy controller is presented in this paper. Compared to PI, TS-Fuzzy controller is performing well for harvesting more energy due to its ability of adjusting their gains. Detailed modeling analysis of TS-Fuzzy controller, novel control of dc to dc bidirectional circuit, battery bank are presented in this paper. Extensive performances are presented with the help of HIL which is designed by using two OPAL-RT modules.

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