4th International Conference on
Energy, Environment and Sustainable Development 2016 (EESD 2016)

290. An Intelligent MPPT Design of DC-DC Converter for PV in a PV/SC Hybrid Power System

Tariq Kamal[a,*], Mithulananthan Nadarajah[a], Syed Zulqadar Hassan[b], Umair Younas[c], Hina Gohar[d], Alfredo Vaccaro[e]

[a]Power and Energy System Group, School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, QLD 4072, Australia
[b]State Key Laboratory of Power Transmission Equipment and System Security and New Technology, School of Electrical Engineering, Chongqing University, Chongqing, 400044, China
[c]Department of Electrical Engineering, COMSATS Institute of Information Technology, 22060, Abbottabad
[d]Balochistan University of Information Technology & Management Sciences BUITMS, Quetta, 87300, Pakistan
[e]Department of Engineering, University of Sannio, Benevent, 82100, Italy
E-mail address: tariq.kamal.pk@ieee.org

Abstract

The current literature is greatly populated with various conventional control schemes for Photovoltaic (PV) system to acquire maximum power from it. This piece of work presents an intelligent fuzzy logic Maximum Power Point Tracking (MPPT) controller for a boost converter to control PV under variable real weather conditions in a PV/Super-capacitor (SC) hybrid power system. The proposed intelligent fuzzy logic controller makes the control of nonlinear characteristic of PV array more feasible. Additionally, a SC module is used to regulate the DC bus voltage and store energy during surplus power and/or backup device during load demand. The proposed hybrid power system operates under classical-based supervisory switching algorithm. The performance of proposed controller is compared with/without Proportional Integral Derivative (PID) perturb and observe MPPT controllers for the real weather patterns and load conditions at Sibi, Pakistan. MATLAB results indicate the effectiveness of proposed controller in terms of feasibility and dynamic response.

Keywords: *Fuzzy logic MPPT controller; PV system; Super-capacitor; Hybrid power system; Load tracking*

1. Introduction

The researchers are keen to develop technologies which are inexpensive, efficient, and environmentally friendly. The demand for the renewable energy is increasing due to the increasing demand of electrical energy. In Pakistan, the total energy supply is above 24,000 MW in the year 2014-2015 as reported in [1]. The report also concludes that only 106 MW (0.43% of total generation) is generated from Renewable Energy Sources (RES) while the remaining power is produced from fossil fuels. In recent years the Pakistan government initiated various RES mini projects to reduces the use of fossil fuels and protect the environment from excessive pollutions [2], [3], [4]. Therefore, PV industry annual growth rate is significantly raised to 40% in the recent years [5]. PV based power generation is becoming progressively important as RES since they present many advantages such as pollution free, emitting no noise, non-depleted, incurring no fuel costs, and requiring less maintenance among others. However, PV needs a favorable condition as the power and cost of electricity are greatly dependent on the local climatological variables. The output power of PV systems is heavily dependent on the weather patterns and thus the instantaneous power available from PV often does not meet the instantaneous load demand. Energy storage systems support transient stability during the rapid solar radiation change and load variations while electronic interface is used to extract maximum power from PV and also convert into AC appropriate voltage level [6]. Maximum Power Point (MPP) of PV has a non-linear relationship with cell temperature and solar irradiance. Hence, in order to operates PV at MPP, the system must have MPP tracker [7]. Several intelligent and conventional control schemes are established by different experts and researchers to capture maximum power and achieve optimum efficiency [8]. Conventional schemes contain perturbation and observation (P&O), voltage-feedback methods, Hill Climbing (HC) and Incremental Conductance (IC) etc., while intelligent method includes Fuzzy Logic Control (FLC), Genetic Algorithm (GA), Ant Colony Optimization (ACO) and Neural Network (NN),etc. [9]–[12].

Several studies have been performed on conventional and intelligent control MPPT based schemes. In [13]–[16], the authors track the MPP with P&O, IC and HC schemes due to its simple operation. Nevertheless, the authors are unable to eliminate the power oscillation created on MPP and divergence caused due to weather changes. For example, the P&O algorithm, which moves the operating point near to the MPP through increasing or decreasing the array voltage periodically, is often applied in many PV power applications. This method is beneficial in a situation where the irradiation does not fluctuate quickly with time; however, the P&O method is slow and get confused due to quick variations of atmospheric conditions. The IC algorithm is also often used in the PV based power systems. This method tracks the MPP by matching the incremental and instantaneous conductance of the PV array. The IC method provides good performance during rapidly changing weather conditions. Nevertheless, the IC technique has two parts, and the structure is analogous to the P&O method due to the condition $dP/dV = 0$ that rarely occurs. Moreover, in the IC technique, four sensors are essential to accomplish the measurements for computations and decision making. Therefore, it is required to have an appropriate MPPT which can reduce oscillation and coverage quickly. Hence, intelligent control methods are used to overcome the drawbacks of conventional control techniques [17].

In literature different researcher established intelligent control based MPPT schemes in different studies [18], [19]. GA is used to increase the accuracy of an ANN-based MPPT algorithm and reported in [20]. Population size, mutation rate and number of generations are the common expected problems with GA. In [21], the authors used PSO with the capability of direct duty cycle to track MPP of a PV system but PSO still has the dependency problem on initial values of the particles. In [22], a novel ACO is implemented to get the PI-MPPT controller gains. ACO is used to enhance both the design efficiency of PI control systems and its performance to get optimal PI parameters. In ACO, the optimal selection of number of ants, solution archive and locality of search space etc., are some thoughtful issues.

In this manuscript, an Artificial Intelligent (AI) based MPPT PID controller is designed. The proposed controller extracts maximum power from PV system and operates on two primary inputs i.e., PV voltage and power and generates an appropriate duty cycle. This study mainly targets on investigating MPPT performance, which was created by studying P-I graph of PV array and determining rule base of fuzzy logic controller with different weather conditions. Diffident linguistic variables are used to develop fuzzy model.

This work is distributed in six different sections. Introduction is covered in Section 1. Section 2 defines the proposed test-bed. PV array modelling is covered in Section 3. Section 4 describes the proposed methodology for designing intelligent fuzzy logic MPPT controller. Section 5 explains the detailed simulation results followed by conclusion in Section 6.

2. Proposed Test-bed

The test-bed comprises a PV system along with storage device (i.e., SC) which is connected to Utility Grid (UG) via three phase inverter. The PV is connected to inverter via DC-DC boost converter, which is controlled by an intelligent fuzzy logic MPPT controller. SC is added to regulate the DC bus voltage and also provide backup to the grid during demand. UG receives power from PV and SC during peak hours while delivering power to SC for charging during off peak hours. Power sharing between different sources is performed by Power Management System (PMS). The complete architecture of test-bed is shown in figure 1.

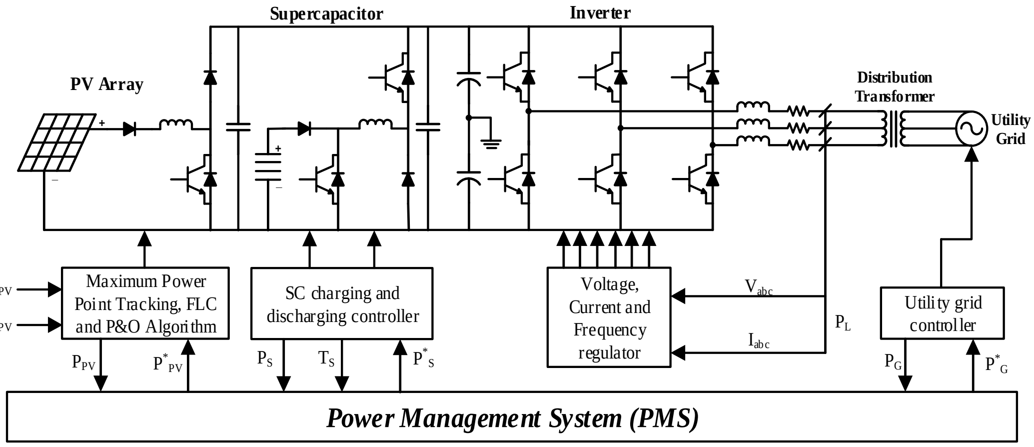


Fig. 1. Architecture of proposed system

3. PV Modeling

The structural unit of PV array is the solar cell (SC), which is fundamentally a p–n semiconductor junction. The current–voltage (I-V) characteristic of a solar PV is a non-linear nature and is given by [23], [24].

$$V_{PV} = N_s \left(\frac{AkT}{Q} \right) \ln \left\{ \frac{(N_p I_{SC} - I_{PV} + N_p I')}{N_p I'} \right\} - \frac{N_s}{N_p} I_{PV} R_S \tag{1}$$

where, I_{sc} is the short circuit current, N_s is number of cells in series of a PV module, N_p is number of cells in parallel of a PV module, I_o is diode saturation current, T is PV cell temperature, A is temperature coefficient for short-circuit current, q is charge of an electron and k is Boltzman's constant. The output power delivered by the PV system into the DC bus could be written as

$$P_{PV} = V_{PV} I_{PV} \tag{2}$$

Eqs. (1) and (2) are implemented during the simulations to get the output characteristics of PV system at weather patterns. The output power of PV system varies according to atmospheric condition or load current as shown in figure. 2.

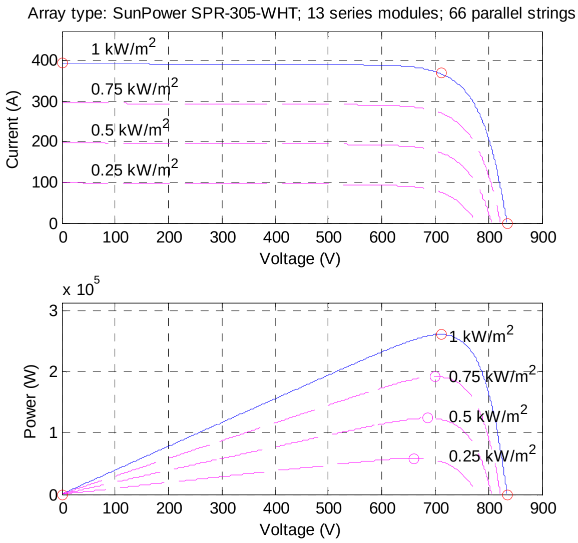


Fig. 2. P-V and I-V characteristic curves of PV

The parameters used in the modelling of PV are given in table 1. At 1000 W/m^2, the maximum output power is 260 kW.

Table 1. PV Parameters

Parameter	Value
Model	SunPower SPR-305-WHT
No of cells used/module	96
No of series string used	13
No of parallel strings used	66
Voltage at MPP per module	54.7 V
Current at MPP per module	5.58 A
Short Circuit Voltage	5.98 V
Open Circuit Current	64.2 A

4. Proposed Methodology

Modelling a non-linear system with a conventional controller in terms of regulation, damping, etc is difficult. The intelligent fuzzy logic MPPT controller is based on the set of fuzzy rules developed using expert knowledge. An intelligent fuzzy logic MPPT controller contains a fuzzifier, fuzzy inference engine, fuzzy rule base and defuzzifier as shown in figure 3. In this research, Mamdani fuzzy model is used

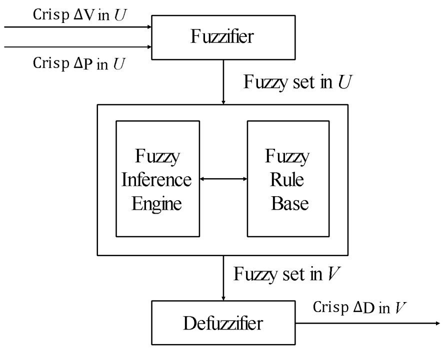


Fig. 3. Intelligent fuzzy logic MPPT controller

For designing fuzzy-PID hybrid controller, initially it is recommended to find out the variables for the proposed system. In this paper, two input parameters i.e., Change in array power (ΔP) and array voltage (ΔV), and one output (Change in duty cycle (Δk)) are used to develop intelligent fuzzy logic MPPT controller. Input and output variables of intelligent fuzzy logic MPPT controller are defined as;

$$\Delta V = [V(n) - V(n-1)] \times Z_1 \tag{3}$$

$$\Delta P = [P(n) - P(n-1)] \times Z_2 \tag{4}$$

$$k(n+1) = [k \pm \Delta k] \times Z_3 \tag{5}$$

where n represents the time index, Z_1, Z_2 and Z_3 are input and output scaling gains, $V(n)$ and $P(n)$ represents the instantaneous voltage and power of PV array.

Five fuzzy sets are established using seven linguistic variables. These linguistic variables are associated on two input variables. The linguistic terms used in establishing a fuzzy model are Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS) and Positive Big (PB). The Membership Functions (MFs) are defined in interval of [-1,-1] with Z_1 and Z_2 as input scalar and Z_3 as output. Initially, different types of MFs are selected i.e., Trapezium, Cauchy, Gaussian, Triangle, etc. Using expert knowledge [25], trial and error method, Triangle and Trapezium methods are used together. MFs for ΔV, ΔP and ΔD are shown in figures 4, 5 and 6, respectively.

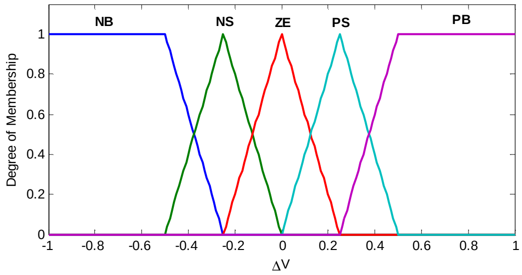


Fig. 4. MF for input variable ΔV

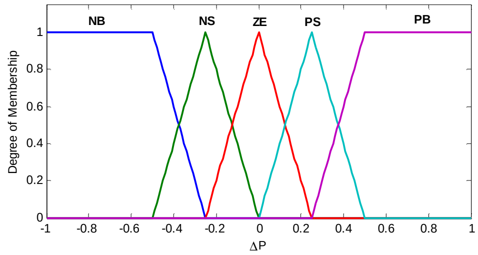


Fig. 5. MF for input variable ΔP

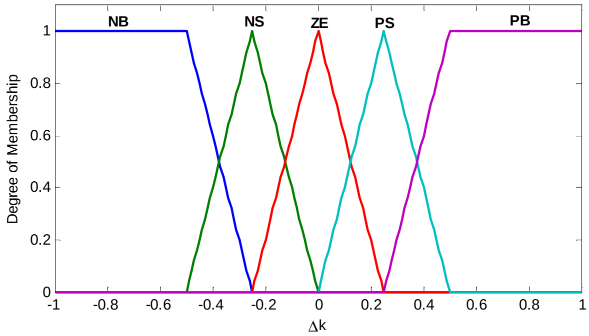


Fig. 6. MF for input variable Δk

The input-output control surface for fuzzy controller is shown in figure 7. After understanding system parameters and error manipulations, the rules are developed for intelligent fuzzy logic MPPT controller. The rule based developed for system is shown in table 2. The fuzzy inferences system is designed using Mamdani model.

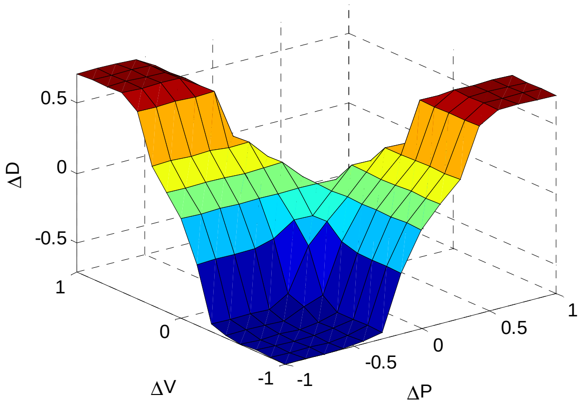


Fig. 7. I/O surface waveform of intelligent fuzzy logic MPPT controller

Table 2. Rule base of intelligent fuzzy logic MPPT controller

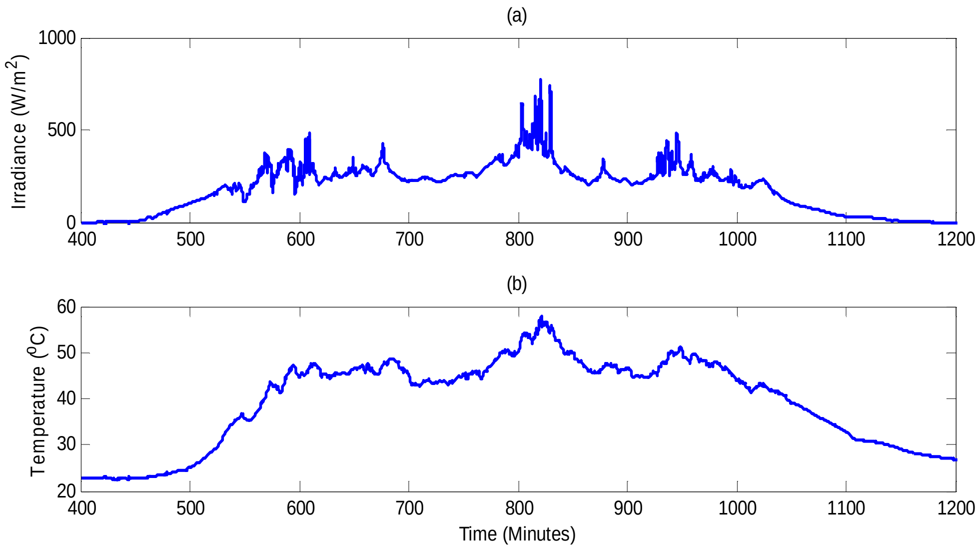
ΔP \ ΔV	NB	NS	ZE	PS	PB
NB	NB	NB	ZE	PS	PB
NS	NB	NS	ZE	PS	PS
ZE	ZE	ZE	ZE	ZE	ZE
PS	PS	PS	ZE	NS	NB
PB	PB	PS	ZE	NB	NB

During designing of intelligent fuzzy logic MPPT controller, a base of 9 rules was used due to its low computational cost, but it does perform so well. Therefore, in this research a base of 25 rules is used for better performance. To find an optimal MPP, P-V characteristics of PV panel are taken. Based on input parameters (ΔP and ΔV), appropriate output signal (Δk) is generated. The output is a Pulse Width Modulator (PWM) signal. The PWM signal (known as k) is fed to DC/DC boost converter to operate inverter. The crisp output is obtained by center of gravity defuzzification process [26].

$$k = \frac{\sum_{j=1}^{n} k_j \mu_A(k_i)}{\sum_{j=1}^{n} \mu_A(k_i)} \quad (6)$$

5. Simulation Results and Discussion

In this research, the real time weather data (solar irradiance and temperature) of Sibi, Pakistan is used. The weather statistics is recovered by Pakistan Metrological Department (PMD) for 1st July, 2016 [27], [28]. The weather data for Sibi, Pakistan is shown in figure 8. However, for simplicity, only minutes



when sun rises and sets are shown in figure which are nearly 6 AM and 8PM.

Fig. 8. Weather data of Sibi, Pakistan (1st July 2016)

Initially, to test the proposed system, all the energy sources are modeled ideally in MATLAB/Simulink via simpower system toolbox. The PV boost converter is simulated without any control applied to the boost converter attached to it. Hereafter, the conventional PID based MPPT controller is installed. The PID is tuned with automatic build-in tuner in Simulink. The PID based system is simulated and the results are stored. Finally, based on corresponding inputs (ΔP and ΔV), rules based fuzzy control is developed through Fuzzy toolbox.

The simulation results of PV MPPT controller in terms of PV output power are shown in figure 9. The black dotted line, blue solid line, brown dashed line and pink dot-dashed line represents the PV power reference (P^*_{PV}) (theoretically calculated with formula), actual power using FLC (P_{FLC}), PV actual power via PID technique (P_{PID}) and without any controller (P_{WC}), respectively. From figure 9, due to continuous change in irradiance level, the output powers using FLC and PID controllers are likely to be nearly same. However, in zoom figure, the power difference is clearly visible at 676.5 minute.

The performance of any controller is evaluated by plotting absolute difference of reference and actual powers obtained from each controller. Using the same idea, absolute error is calculated at each sample and plotted with respect to time is shown in figure 10. From figure 10, without any controller, the average absolute error is 12 kW with a peak error of 20 kW. Similarly, the average absolute error using PID controller is 1 kW while with fuzzy controller it’s 0.5 kW.

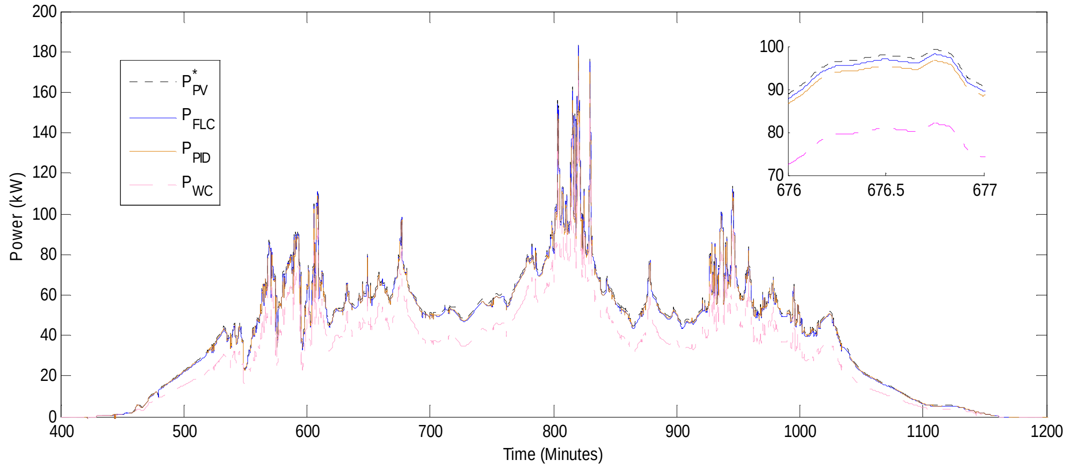


Fig. 9. PV array output power with different controllers

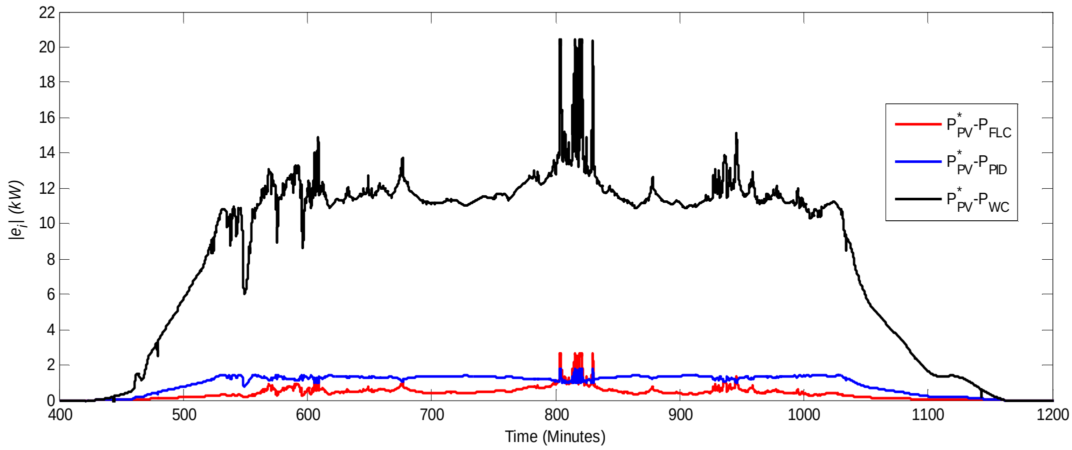


Fig. 10. Error in PV power with respect to reference power

The average absolute error for each controller is calculated as;

$$\bar{e}_i = \frac{1}{T}\int_0^T \left(P_{PV}^*(t) - P_i(t)\right) dt \quad i = FLC, PID, WC \tag{7}$$

Using above equation, the efficiency of proposed FLC is calculated as;

$$\eta_i = \frac{\bar{P}_{PV}^* - \bar{e}_i}{\bar{P}_{PV}^*} \% \tag{8}$$

where $\bar{P}_{PV}^*$ is the average reference power and calculated as;

$$\bar{P}_{PV}^* = \frac{1}{T}\int_0^T P_{PV}^*(t) dt \tag{9}$$

After evaluating the above equations, the $\bar{P}_{PV}^*$ is calculated as 23.4 kW for complete day. Similarly, using equation (7), the average error for proposed FLC, PLD and without controller are obtained as 0.208 kW, 0.519 kW and 4.582 kW, respectively. Putting the values of average errors of each controller into equation (8), the efficiency for proposed FLC, PID and without controller are calculated as 99.11%, 97.7% and 80.41 %, respectively. So, it is concluded that, after applying proposed FLC based MPPT algorithm to boost converter, its efficiency is significantly improved.

Before finally concluding the performance of proposed FLC, let go through the impact of proposed FLC on power system voltage, frequency and Total Harmonic Distortion (THD). In light of IEEE 1547 Standards [29], the maximum alteration in system voltage RMS, frequency and THD level are 0.8%, 6% and 5%, respectively. The test-bed simulated in this research have a fundamental system frequency of 50 Hz with line-line RMS voltage of 440V. Keeping these facts, the allowable alteration in system frequency/voltage RMS are ±0.2Hz/±26V. Now, the figure 11 represents that, the alteration in system parameters are in allowable range.

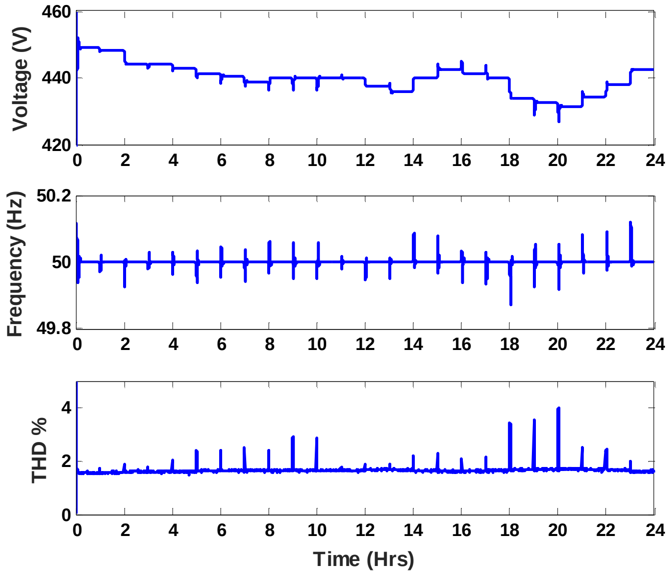


Fig. 11. System RMS voltage, frequency and THD level.

6. Conclusion

The intelligent fuzzy logic MPPT control of boost converter for PV is established to provide power to the grid in PV/SC hybrid power system. Evidently, the proposed controller outperformed in transitional states than with and without P&O PID based MPPT schemes. The feasibility of the proposed controller is supported by the simulations done in MATLAB under real-world record of weather patterns. The proposed method concludes that that MPP of any PV systems find with intelligent controller in shorter time runs compared to classical control methods.

Acknowledgements

The authors wish to thank Australian Government and the University of Queensland for financial support during the completion of this research work and also Pakistan Meteorological Department for providing weather statistical data for Sibi, Pakistan.

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