A Hybrid Firefly-Asymmetrical Fuzzy Logic Controller based MPPT for PV-Wind-Fuel Grid Integration

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Received: 02.03.2017 Accepted:01.05.2017

Abstract-In this research paper, a firefly asymmetrical fuzzy logic controller (FAFLC) based unified maximum power point tracking (MPPT) hybrid controller is proposed for grid connected power system. It is a combination of solar, wind and fuel based energy power system. The FAFLC based heuristics optimized MPPT algorithm depends on intensity of light followed by inverse square law which improves the dynamic uncertainty under complex and transient weather conditions. Also duty ratio of the cuk converter has been decided according to the position of firefly. The proposed MPPT controller works efficiently in dynamic conditions like variable solar irradiance, hydrogen consumption and wind speed which tracks high power and able to find global maximum power point (MPP). The experimental validation has been done through dSPACE DS 1104 real time control board.

Keywords: AFLC, dSPACE, MPP, MPPT, PV, PWM

1. Introduction

During the last few decades, the fossil fuels and nuclear fission are decaying exponentially and there is a necessary requirement of green renewable energy sources. The renewable energy sources are important ingredient to produce alternative electrical power [1-5]. The hybrid energy sources are the promising technology to provide efficient and considerable electrical power to the utility grid. Hybrid energy system is the combination of two or more energy sources. Due to intermittent wind speed and sun irradiance level, the hybrid system play vital role to produce electrical power demand. It integrates wind, solar and battery storage that provides reliable power to utility grid [6-10]. The solar irradiance and ambient temperatures are the varying parameters on which the power extraction from PV panels depends. The productions of power from the wind turbine are greatly dependent on wind speed whereas level of hydrogen consumption affects the power produced from fuel cell. The performance of battery is improved when nature of wind and solar irradiance are complementary to each other. The experimental implementation of control system is very difficult during combination of more than two energy systems. The practical design of hybrid control system is still a challenge to the researchers. The battery deliver realistic performance during strong irradiance and high wind speed operating conditions. During adverse weather conditions, the high capacity battery storage system is required to provide reliable operation.Numerous MPPT algorithms were already discussed to obtain the peak power. The conventional MPPT algorithms like perturb and observe (P&O), Hill climbing (HC) method, incremental conductance (INC) etc have failed to work during non-linear atmospheric variations [11-12]. The neural network (NN) and fuzzy logic control (FLC) based MPPT algorithms are the best solution which provides better tracking efficiency under these conditions. However, the main disadvantages of NN based MPPT has less precision, requirement of large training data as well as slow convergence speed under variable ambient conditions. There are mainly two types of fuzzy membership functions namely symmetrical and asymmetrical. Compared to symmetrical fuzzy logic controller, an asymmetrical fuzzy logic controller (AFLC) based MPPT controller generates appropriate PWM control pulses under adverse transient conditions [13].Alternatively, the evolutionary algorithms are best solution for non-linear variations in operating conditions. However, the Genetic algorithm (GA) based stochastic MPPT algorithm have disadvantages such as no guarantee to find global maxima, slow convergence speed and complexity to find fitness function under variable weather conditions [14]. Compared to GA based MPPT, the stochastic evolution based particle swarm optimization (PSO) has very less parameters for adjustment. Nevertheless, PSO MPPT algorithm has exploration loss abilities as well as it requires more computational convergence time to obtain MPP [15]. Artificial bee colony (ABC) being a bio –inspired algorithm has limited control parameters as well as it falls on local maxima and has high cost with complex design implementation [16]. The firefly algorithm (FA) is an optimization algorithm based on movement of lighting fireflies. The main advantage of firefly based MPPT algorithm has fast convergence speed, less computational time, low cost and simple design. Laabidi et al [5] has implemented PSIM simulation based PV-WIND system for grid integration. The classical P and O and voltage oriented control methods have been used as a MPPT and inverter control, respectively. However, the experimental validation and PV-wind-fuel integration to the utility grid has not been discussed in this research work. Rosli et al [9] has focused the multi input converter for PV-Wind-fuel connected to utility grid. In this study the conventional P and O based MPPT has been accomplished. MATLAB/Simulink environment has been used to validate the design control circuitry. Nevertheless, the practical verification of the hybrid system has not been discussed. The hardware implementation of multi-input converter based this hybrid system is expensive due to demand of high capacity battery storage in this work**.** Keyrouz et al., [17] has discussed a simulation based novel unified MPPT for hybrid system. Nevertheless, the practical performance investigation of the hybrid system has not been presented in this study. In this paper firefly asymmetrical fuzzy logic controller (FAFLC) based hybrid MPPT algorithm is proposed to obtain optimal duty ratio by automatic adjustment of input and output membership functions under transient operating conditions. The proposed MPPT provides optimal duty ratio with high tracking efficiency and negligible oscillations around MPP compared to conventional P and O MPPT algorithm. It provides fast convergence speed, less controlling parameters, easy implementation and high power tracking ability with respect to other conventional MPPT algorithms used in literature. During variable weather conditions, the integration of PV, wind and fuel cell based hybrid system provide guarantee for stable and realistic operation.

Several inverter control methods have been used in literature [18-21], the space vector pulse width modulation (SVPWM) is most preferred control due to its fixed switching pattern, precise dynamic response and less total harmonic distortion (THD). For generation of gating pulses for power switches, here two levels SVPWM based inverter control has been employed which synchronizes the utility grid. In this paper, an asymmetrical MPPT based control system is designed to provide smart functioning power generation. It provides low cost, optimum power and better response time under variable irradiance, wind speed and hydrogen consumption. The experimental responses have been validated through dSPACE 1104 controller interface.The novelty of this research paper is experimental verification of hybrid FAFLC based MPPT controller using dSPACE platform for PV-Wind-Fuel integrated to grid has neither been discussed nor implemented before by author’s best accomplishment.

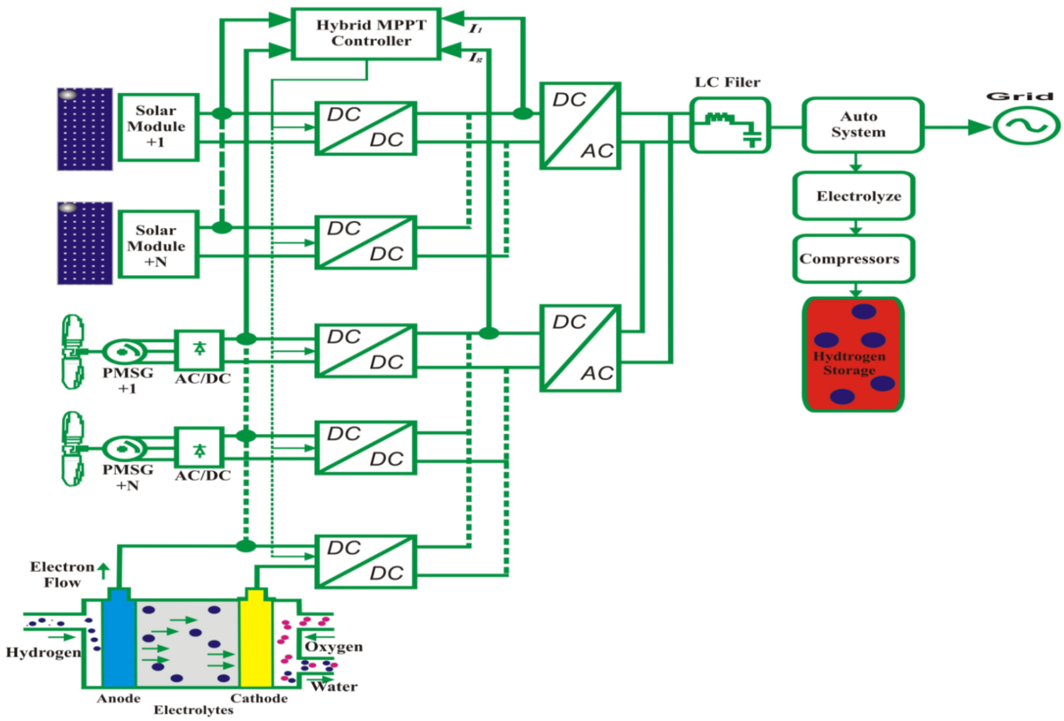


Fig. 1 Proposed PV-wind-fuel cell based hybrid system structure

2. Structure and Mathematical Modelling of PV-Wind-Fuel cell based Hybrid System

Fig. 1 shows the proposed PV-wind-fuel cell based hybrid system structure. The cuk dc-dc converter acts as an interface between PV module and the inverter [22].

The FAFLC based MPPT controller is used to generate the switching pulses to power MOSFET of cuk converter. The output power from wind turbine and fuel cell is fed to the inverter through cuk converter. The switching signal to the 2-level inverter is generated using SVPWM through dSPACE DS1104 control board. The generated power from PV module and wind turbine are delivered to load as per requirement or supplied to the H_2 production block which comprises electrolyser and storage tank. As the generated power from PV and wind is greater than the load demand, H_2 is produced by electrolyser and stored in a compressed tank. Moreover, when load requirement is more compared to generated power from PV and wind, H_2 is supplied to fuel cell for production of extra power. Compared to conventional battery storage conversion system, the storage of H_2 is efficient which provides better reliable solution. This is because hydrogen has high energy mass density as inherent property which provides long term storing capacity.The intermittent power from solar and wind energy sources have been sensed before dc link and then the cuk dc-dc converter is controlled by employing single MPPT. Outputs from PV and Wind energy sources are maintained at common dc link voltage level by application of dc bus bar and then VSI converts dc voltage to ac voltage which is finally injected to the utility grid. The fuel cell based ultra-capacitor compensates the variation of power from solar and wind. The voltage source inverter regulates the dc link voltage and resultant active power during transient conditions, which can be fed to utility grid to maintain steady state. Therefore, the power injected to the utility grid maintains constant even though the sun irradiance and wind speed varies.

2.1 Mathematical Model of Wind Turbine

The mechanical power obtained mathematically from wind turbine is expressed as [5]:

$$P_{mechanical} = \frac{1}{2}\pi\rho_{a.d}C_{t.p}(\lambda,\beta)R^2{}_{turbine}v^3{}_{wind} \quad (1)$$

Where

$\rho_{a.d}$ =density of air

$C_{t.p}(\lambda,\beta)$ =Coefficient Of turbine power

$R_{turbine}$ =Turbine blade radius

v_{wind} = wind velocity

β = Pitch angle of blade

The mechanical power generated from wind turbine is directly proportional to the coefficient of turbine power for a specific wind turbine system.

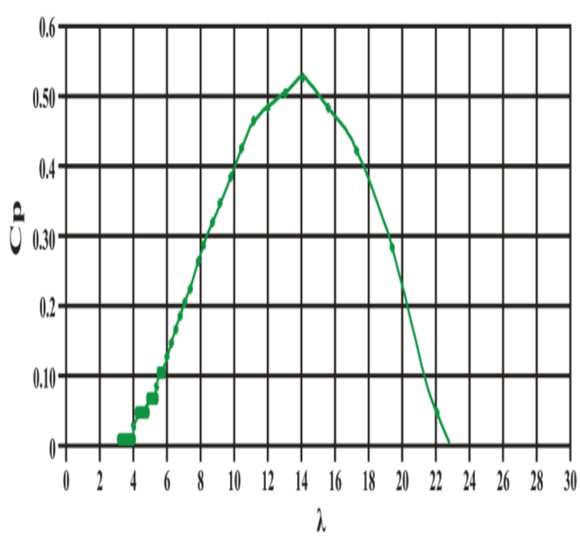


Fig. 2 Coefficient of turbine power Vs tip speed ratio curve

The coefficient of turbine power versus tip speed ratio curve is presented by Fig.2. The tip speed ratio is calculated as:

$$\lambda_{tip} = \frac{\omega_r * R_{turbine}}{v_{wind}} \quad (2)$$

Where

ω_r = Shaft rotating speed

The mathematical relation between turbine performance coefficient and tip speed ratio is expressed as:

$$C_{t.p}(\lambda,\beta) = C_1 * \left[\frac{C_2}{\lambda_i} - C_3 * \beta - C_4 \right] * e^{-\frac{C_5}{\lambda_i}} + C_6 * \lambda \quad (3)$$

Where

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \quad (4)$$

And C_1, C2, C3, C4, C_5 and C_6 are 0.73, 151, 0.58, 0.002, 13.2 and 18.4 respectively.

Also, the aerodynamic torque is found mathematically as:

$$T^{max} = \frac{1}{2}\pi\rho_{a.d}C_{t.p}(\lambda,\beta)R^2{}_{turbine}\frac{v^3{}_{wind}}{\omega_r} \quad (5)$$

Where, T^{max} = Aerodynamic torque

The turbine speed-power characteristics is shown by Fig.3 which reveals that at any wind speed , there is a specific speed of turbine by which maximum power is tracked from wind.

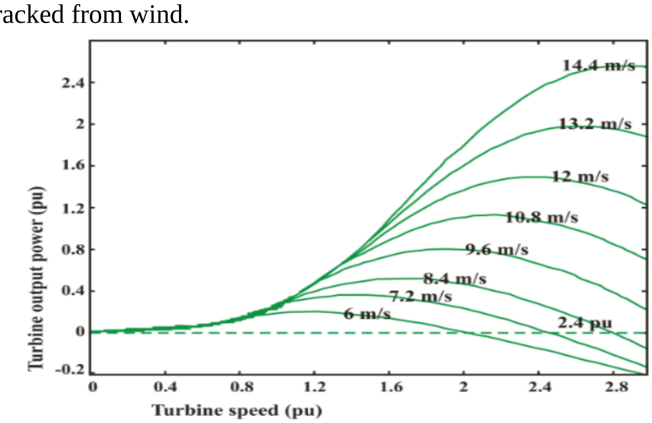


Fig. 3 Turbine speed-power characteristics

2.2 PV Generator Mathematical Modelling

To facilitate the computational analysis, here a single diode model (Fig. 4) is adopted for designing PV module which is simpler and effective compared to other PV module. Mathematically it can be modelled as[9]:

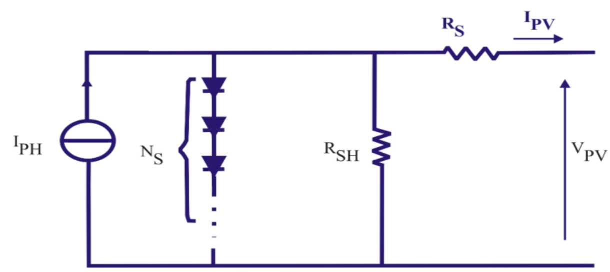


Fig. 4 Single diode model of PV module

$$I_0 = I_{PH} - I_d\left[e^{\frac{V_{PV}+R_S*I_0}{N_S V_t}} - 1\right] - \frac{V_{PV} + R_S * I_0}{R_{SH}} \qquad (6)$$

Where,

I_0 = PV cell output current

I_{PH} = Short circuit photon current

I_d = Reverse diode saturation current

V_{pv} = PV cell output voltage

R_S = Resistance in series

R_{SH} = Shunt resistance

V_t = Terminal voltage

N_S = PV cells in series

2.3 Fuel cell mathematical modelling

An electrochemical device that produces electrical power by processing H_2 and O_2 is called fuel cell. In this context, a proton exchange membrane fuel cell (PEMFC) has been adopted. It comprises cathode, anode and electrolyte membrane as major components. The H_2 gas at anode terminal gets ionized and O_2 is present at cathode terminal. The electrochemical reaction is processed on the presence of platinum catalyst as:

$$\frac{1}{2}H_2 \Leftrightarrow H^+ + e^- \qquad (7)$$

Also, the single cell output is derived mathematically as [9]:

$$V_0 = E_{Ner} - V_{activation} - V_{ohm} - V_{concen} \qquad (8)$$

Where,

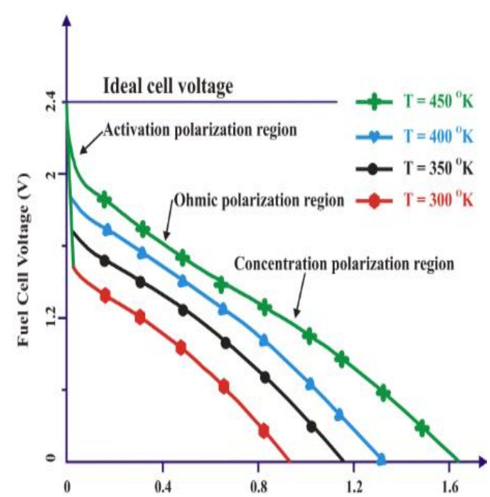
V_0 = Single cell output voltage

E_{Ner} = Electrode Potential

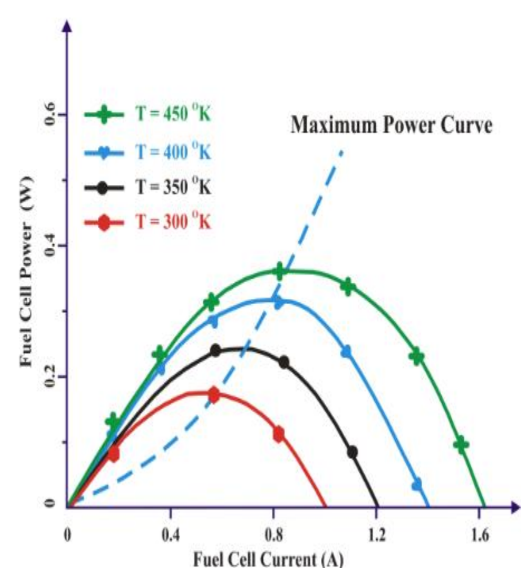
V_{ohm} = Ohmic voltage drop

V_{concen} = Voltage drop due to concentration

The V-I and P-I characteristics of fuel cell are presented by Fig. 5 (a) & (b) respectively at different temperatures.



(a)



(b)

Fig. 5 Characteristics of fuel cell at different temperature (a) V-I (b) P-I

3. Control Scheme

3.1 Firefly Asymmetrical Fuzzy Logic Controller (FAFLC) based MPPT

The classical MPPT algorithms are not suitable for non-linear variations of environmental conditions because of variations in settling time and peak overshoot. Fuzzy logic controller based MPPT is more appropriate and gives accurate response during these conditions. In this research work, a firefly asymmetrical FLC based MPPT has been proposed to improve the dynamic uncertainty under complex and transient operating conditions. The FA MPPT heuristic algorithm was introduced by Yang in 2009. Intensity of light and brightness is determined by inverse square law and fitness function respectively. This MPPT algorithm is more powerful method because of its ability to obtain MPP with high convergence speed. It is based on flashing of firefly which depends on relative brightness of two fireflies. The firefly with less brightness will follow the brighter one. Moreover, firefly with equal brightness will move randomly which is evaluated by the objective function. The population size, FA constants and termination inertia have been fixed during implementation of this algorithm. Moreover, the position and brightness of the firefly has been treated as duty ratio of cuk converter and power generated from PV respectively. The position of the fireflies lies in the range d^{min} and d^{max} of the duty cycle of cuk converter. Also brighter firefly remains in the position while other firefly updates their positions. In first step of FA based MPPT algorithm the control parameters as reference voltage (V_{ref}), size of population etc. are set. Also, the initial populations of fireflies are generated in second step. The fitness function is determined to evaluate the brightness of the firefly. Moreover, the Euclidean distance equation is used to find the update position of firefly. Best global position is obtained once the termination criterion has been achieved else go to step 3 and determine fitness function. FA algorithm again restarts as sensor detects the change in irradiance level.

The proposed firefly algorithm tunes the membership function of fuzzy logic controller which tracks optimal power from PV-Wind-Fuel based hybrid system. The tracking efficiency and tracking convergence speed can be improved by proper adjustment of FA parameters. By reducing the randomization parameters (β) in each iteration of 0.0001, the high tracking efficiency with zero oscillation around MPP is obtained. Also, degree of attractiveness (α) provides tuned and fast convergence speed by addition of 0.1 in each iteration. The firefly position and brightness represent the duty cycle and net output power respectively.

Ajiatmo et al [23] has discussed the FLC-FA based MPPT for solar car application using PSIM simulation environment. The FLC-FA based MPPT provides better tracking efficiency compared to P&O and FLC algorithm based MPPT. However, the validation of the FLC-FA based MPPT controller has not been discussed experimentally In this research work FA based AFLC algorithm has been proposed for PV-Wind-Fuel cell based hybrid system. The novelty of this research work is the firefly algorithm with asymmetrical FLC has not been discussed by any researchers for PV-Wind-Fuel based MPPT controller. Also, experimental verification of hybrid FAFLC based MPPT using dSPACE real time control board for hybrid energy sources validates the novelty of the proposed controller design by author's best knowledge.

In this research paper the hybrid FAFLC algorithm of MPPT has been proposed to achieve global power point under adverse weather conditions. Fig 6 describes the flow chart of firefly algorithm in which step by step process of this method has been explained.

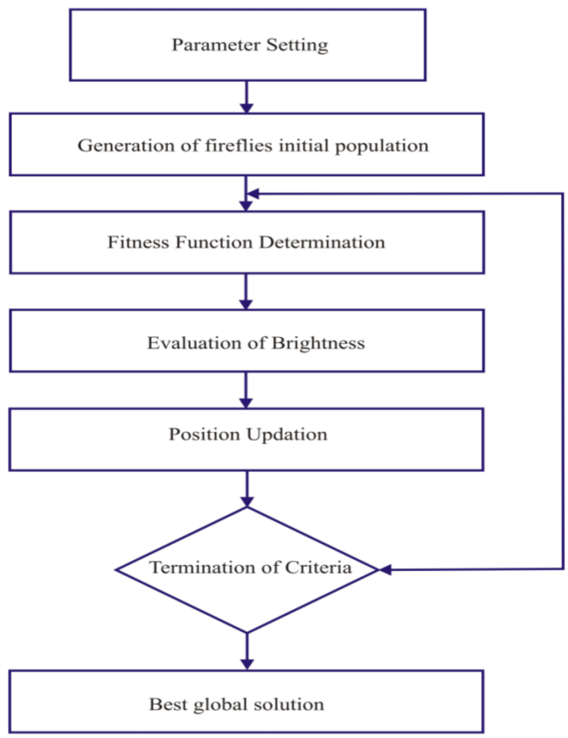


Fig. 6 Flow chart Firefly algorithm

Consider D_i and D_j are the positions of two fireflies, respectively. The distance (d_{ij}) between two fireflies can be calculated mathematically as

$$d_{ij} = \|D_i - D_j\| = \sqrt{\sum_{K=1}^{r} (D_{iK} - D_{jK})^2} \tag{9}$$

Also, the degree of attractiveness α can be expressed as a function of distance with initial attractiveness (α_0) and absorption coefficient (β) as:

$$\alpha(d) = \alpha_0 * e^{-\beta^2}, 0 < \beta < 10 \tag{10}$$

Let the ith firefly has less brightness compared to jth firefly. The ith firefly's new position can calculated mathematically as:

$$D_i^{T+1} = D_i^T + \alpha_0 * e^{-\beta d_{ij}^2} (D_j^T - D_i^T) + \beta_1 (Rand - 0.5) \tag{11}$$

Where β_i =Random movement factor = constant

$$0 \le \beta_i \le 1, \; 0 < Rand < 1$$

The FLC controller comprises fuzzification, rule base and defuzzification as major blocks which are presented by Fig 7.

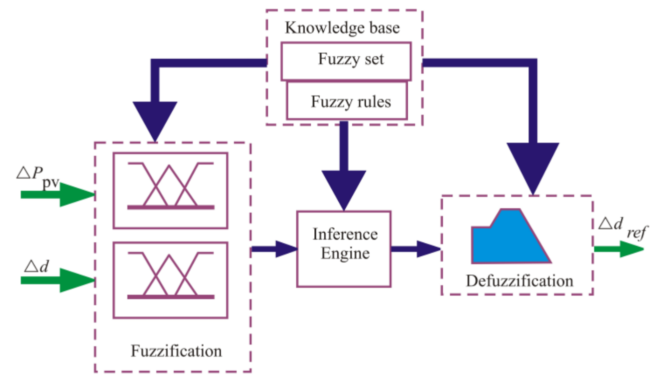
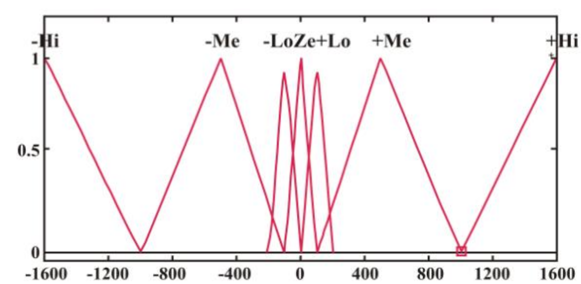


Fig. 7 FLC Controller

In fuzzification, asymmetrical membership functions have been employed as negative high, negative medium, negative low, zero, positive low, positive medium and positive high depicted in Fig 8.



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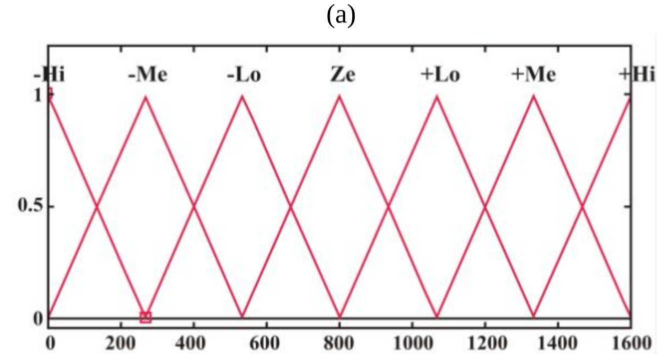

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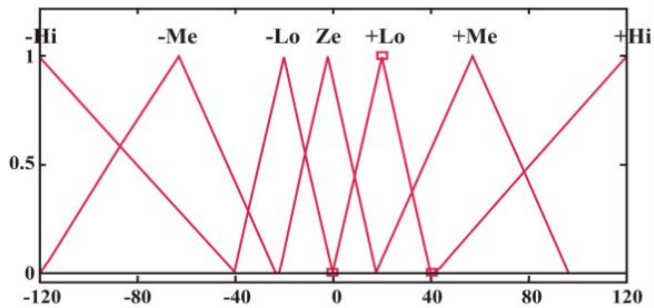


(c)

Fig. 8 Membership function (a) dP_{PV} (b) d (c) d_{re}

There are 49 fuzzy rules which have been assigned based on max-min composition. Table 1 shows the assigned fuzzy inference rule base. The gating pulse for power switch of cuk dc-dc converter has been generated by the method of defuzzification.

Table 1. Inference Rule base for Fuzzy Controller

Δd / ΔP$_{pv}$	-Hi	-Me	-Lo	Ze	+Lo	+Me	+Hi
-Hi	-Hi	+Lo	-Lo	-Lo	Ze	+Hi	+Me
-Me	-Lo	Ze	-Hi	Ze	+Lo	-Lo	+Lo
-Lo	-Hi	Ze	+Lo	+Lo	+Lo	-Me	+Lo
Ze	Ze	-Lo	+Lo	+Lo	+Hi	-Hi	Ze
+Lo	-Hi	+Lo	-Lo	+Hi	+Hi	+Lo	-Lo
+Me	-Me	+Me	+Hi	Ze	-Lo	Ze	-Me
+Hi	-Lo	-Me	-Hi	-Lo	Ze	+Me	-Hi

3.2 SVPWM based inverter control

Compared to other inverter control techniques, the SVPWM method is most acceptable for generation of sinusoidal signal to the power switches of inverter. In this technique, the d-q rotating synchronized frame based current control has been realized. Fig. 9 shows the complete closed loop control block diagram of voltage source inverter.

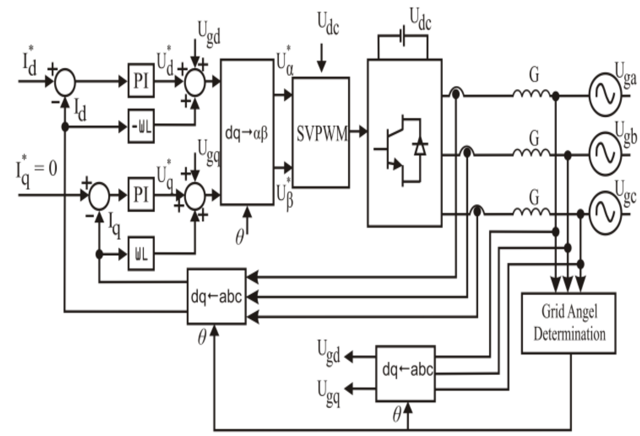


Fig. 9 Closed loop control of VSI

The PI controllers are used for minimization of error produced in d-q axis. The following mathematical expressions of output d-q axis reference voltage have been used for realization of current control scheme.

$$U_d - L_G \frac{dI_d}{dt} - U_{gd} + \omega L_G I_q = 0 \qquad (12)$$

$$U_q - L_G \frac{dI_q}{dt} - U_{gq} + \omega L_G I_d = 0 \qquad (13)$$

The d-q components of inverter voltage have been transformed to α-β frame and fed to SVPWM control block. The 6 active and 2 zero vectors have been generated is depicted by Fig. 10 as an output of SVPWM sectors. The Grid angle is determined and it is synchronized by the method of zero-crossing.

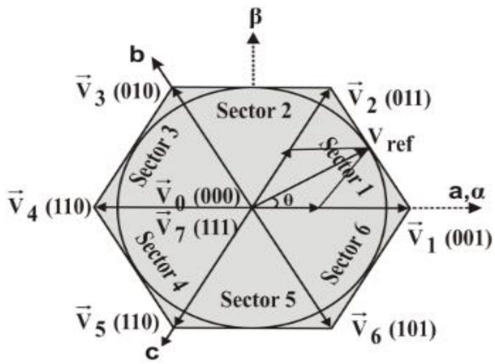


Fig. 10 SVPWM active and zero vectors

4. Results and Discussion

To validate the proposed hybrid MPPT control, the simulink model run through dSPACE DS1104 real time interface. The switching signal to the switch is generated using data acquisition dSPACE 1104 control board.

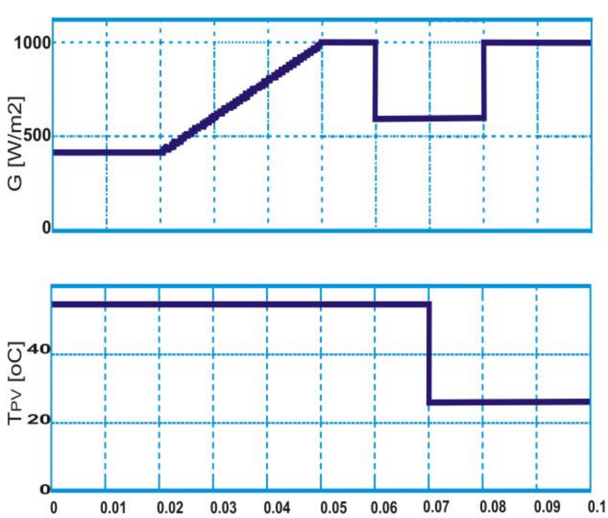


Fig. 11 Variable ambient condition

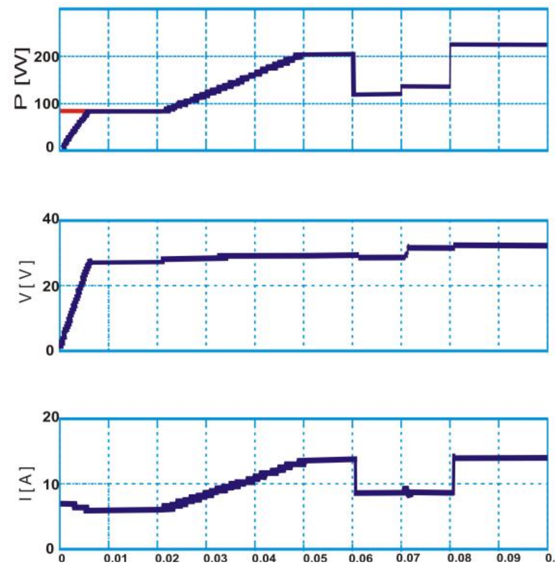


Fig. 12 Experimental responses of PV power, voltage and current using proposed MPPT control

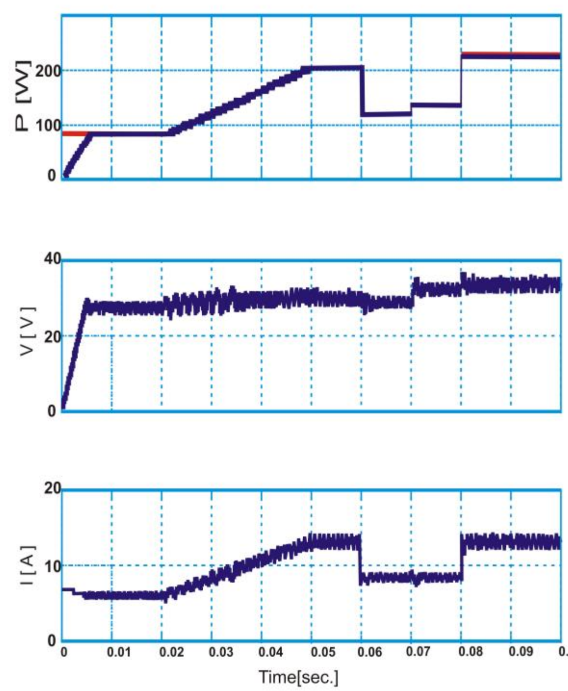
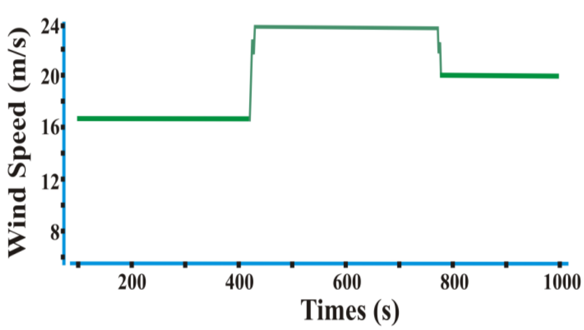


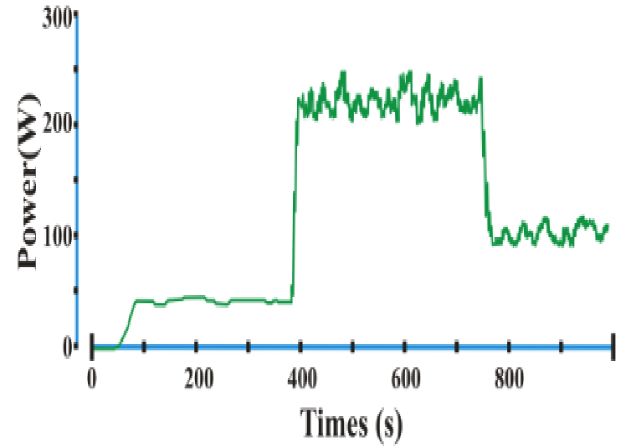
Fig. 13 Experimental responses of PV power, voltage and current using conventional hill climbing MPPT control

The level of irradiance, wind speed and hydrogen consumption level have been applied as input variables to the proposed MPPT controller for generation of required gating signal. The produced signal has been passed through DS 1104 SL_DSP_PWM control block to get the PWM pulses for power switch of dc-dc converter.

The personal computer is employed to observe the fuel cell voltage and current through control desk and data is logged to heliocentric through data acquisition. IRFZ24N MOSFET is used as a power switch of dc-dc converter and ACS712ELCTR-30A-T as a current sensor. Fig. 11 shows the variable environmental condition applied to test the proposed and conventional MPPT based control strategies. The comparison waveforms of PV current, voltage and power at variable irradiance and temperature level using proposed Fuzzy logic and conventional hill climbing based MPPT methods are shown in Fig. 12 & 13 respectively. From hardware results, it is clear that the proposed FLC based MPPT has effective and accurate power tracking performance under similar ambient conditions compared to conventional hill climbing method. In case of conventional MPPT algorithm, PV current, voltage and power waveforms have oscillation compared to the proposed Fuzzy logic based MPPT algorithm which is depicted in Fig. 13.



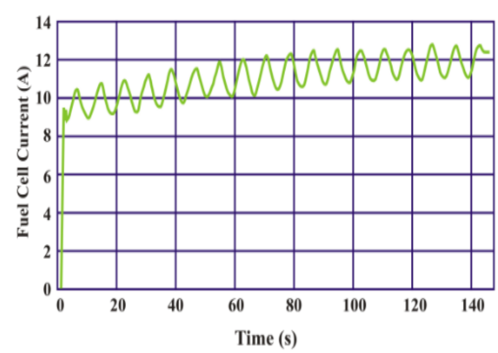
(a)



(b)

Fig. 14 Experimental (a) wind speed profile (b) Wind power

Fig. 14 (a) shows the experimental wind speed applied to the proposed MPPT controller so that it follows the maximum power point region effectively which is presented in Fig 14 (b). The proposed controller is able to track accurate and precise maximum power from wind turbine under variable wind speed.



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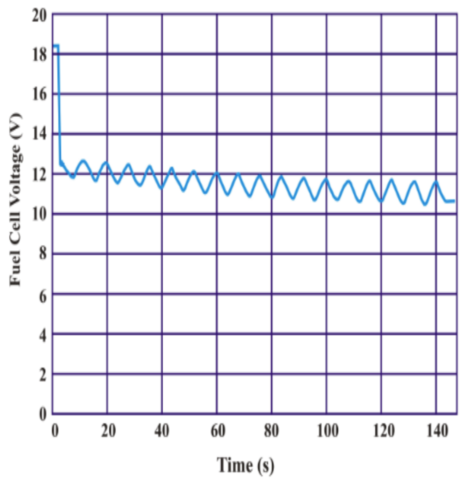

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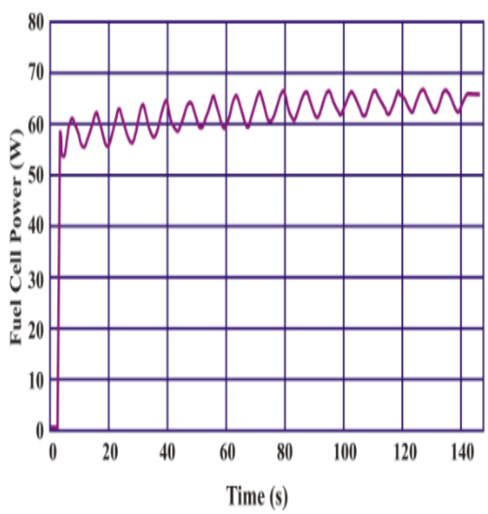


(c)

Fig. 15 Experimental obtained fuel cell (a) current (b) voltage (c) power

The practical results are shown in Fig. 15 reveals that the maximum power is obtained from fuel cell with very less ripple content. It validates the promising relevance of the proposed controller as it has high convergence speed with optimal power point tracking capability.The hardware responses of PV power, voltage, current and gate drive signal are presented in Fig. 16 under steady state conditions. From the tracking performance test responses, it is clear that the MPP is achieved and tracking power error is minimized.

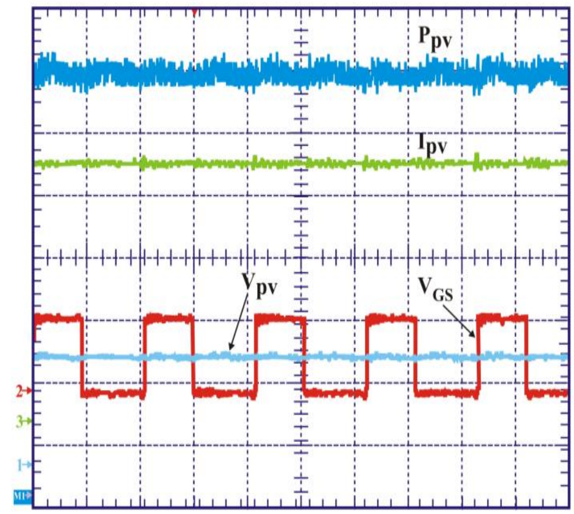


Fig. 16 Experimental PV power, voltage, current and gate drive at steady state

The proposed controller is tested experimentally under transient weather conditions. The PV power, voltage, current and gate signal are presented experimentally in Fig. 17. From practical results, it is clear that the proposed controller works accurately and successfully under cloudy weather conditions and able to find MPP with high tracking efficiency.

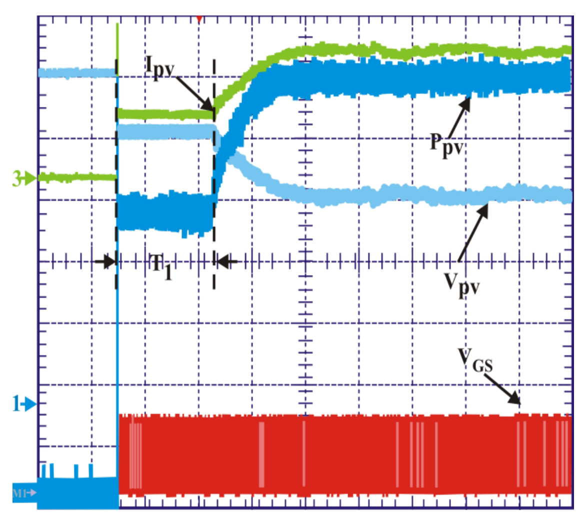


Fig. 17 Experimental PV power, voltage, current and gate drive at dynamic state

The practically obtained inverter voltage and current is depicted by Fig 18 under steady state condition. The digital oscilloscope (DPO 3014) is used to measure the frequency of inverter current. From experimental results, it is clear that the proposed controller is able to provide unity power factor with grid synchronization.

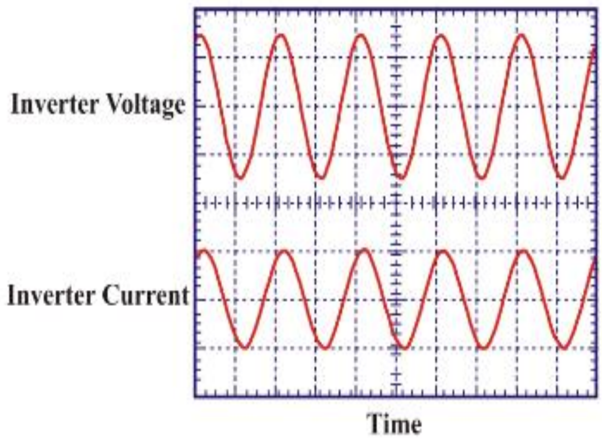


Fig. 18 Experimental obtained inverter voltage and current at steady state

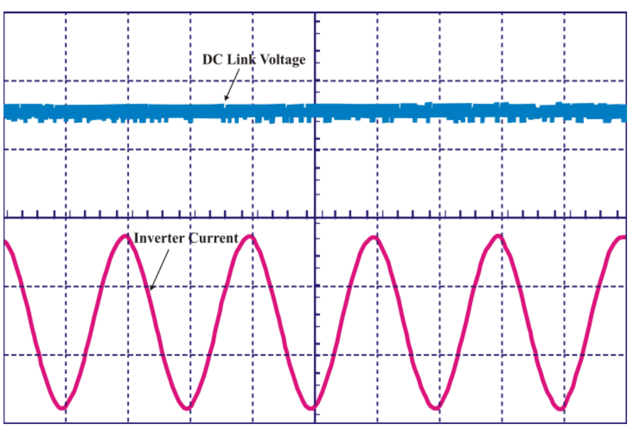


Fig. 19 Experimental dc-link voltage and inverter output at steady state

The dc-link voltage and inverter output is obtained experimentally and presented by Fig. 19. The inverter voltage is pure sinusoidal in nature and has smooth output voltage from dc-dc converter with less fluctuations which validates the excellent performance of the proposed controller.

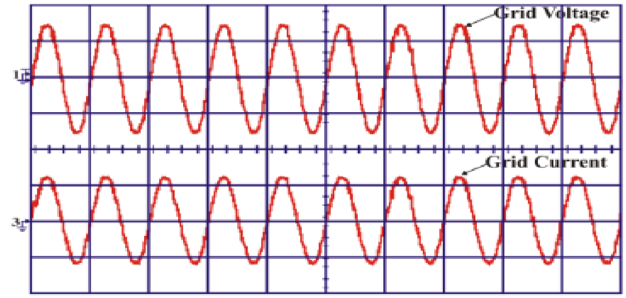


Fig. 20 Experimental obtained grid voltage and current at steady state

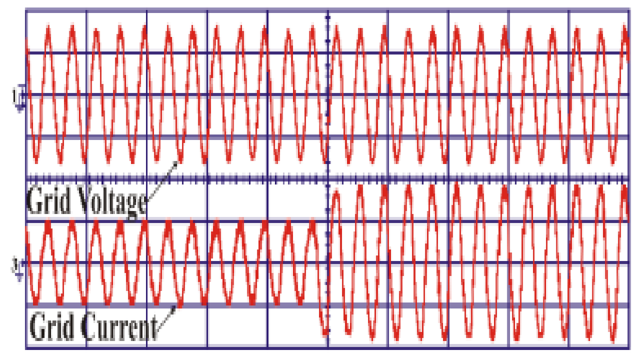
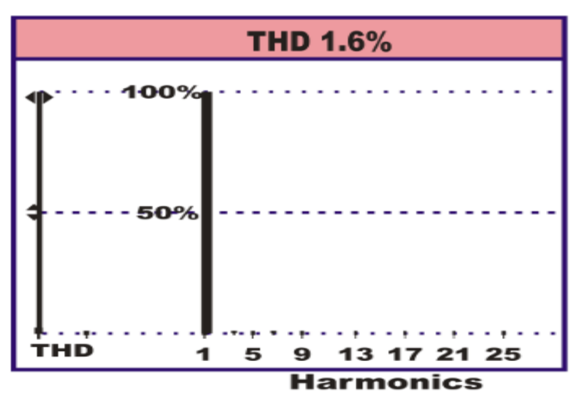
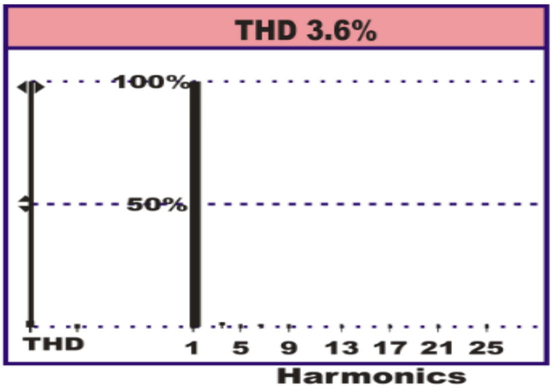


Fig. 21 Experimental obtained grid voltage and current at dynamic state

The hardware grid voltage and current results obtained experimentally are presented by Fig. 20 & 21 under steady and dynamic operating conditions respectively.



(a)



(b)

Fig. 22 Experimental obtained THD of grid (a) voltage (b) current

From practical results, it is evident that the inverter injects sinusoidal current to the utility grid to make power factor unity under steady as well as dynamic weather conditions. The power quality analyzer has been employed to measure the THD of grid voltage and current. Experimentally it is found that grid voltage and current has 1.6 and 3.6 percentage THD value presented by Fig 22 (a) & (b) respectively which strictly follows the IEEE 519 grid recommendation.

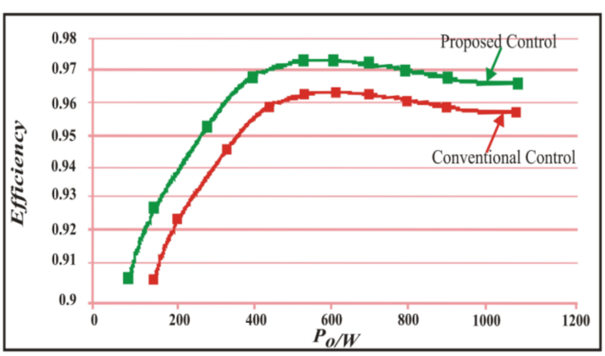


Fig. 23 Practically obtained proposed Vs conventional MPPT performance

Moreover, the practically obtained tracking efficiency of the proposed versus conventional MPPT controller is explained by Fig 23. Experimental measured tracking efficiency curve reveals that the proposed MPPT controller provides high tracking efficiency, good dynamic response and negligible steady state error under abnormal weather conditions. The practical responses validate the effective design of the proposed hybrid MPPT controller for grid integration.

Fig. 24 Experimental hybrid controller using dSPACE platform

Fig. 24 depicts the developed experimental set up of hybrid controller integrated with grid in the research laboratory. In this work PV simulator, personal computer, cuk converter with 10 kHz switching frequency, grid emulator and oscilloscope used as a major components. The proposed MPPT and inverter control has been implemented in dSPACE real time board which is fully programmed using Simulink and interfaced with external hardware. The wind turbine is connected with cuk dc-dc converter. Heliocentris constructor fuel cell system is employed which works on H_2 and air with no humidification. The practically implemented hybrid controller works efficiently with high performance under dynamic conditions such as variable solar irradiance, hydrogen consumption and changing wind speed. The outcome of the results reveals that when solar and wind energies are complementary to each other naturally, the hybrid system will minimize the total system cost as well as reduces battery storage capacity considerably. This research paper presents the FAFLC based MPPT controller for PV-Wind-Fuel integration to the utility grid under varying solar irradiance, wind speed and hydrogen consumption. Compared to other MPPT algorithm discussed in literature, the FAFLC based MPPT provides high tracked power in small convergence period under varying environmental conditions. Moreover, the tracking power from hybrid system has been maximized with minimum fuel consumption.

5. Conclusion

In this research work, the performance of PV, wind and fuel cell based hybrid system integrated to utility grid has been investigated practically using dSPACE DS 1104 controller interface. The hybrid MPPT is obtained through

FAFLC control. The SVPWM based current controller is employed for grid side inverter to minimize THD and improve inverter current at point of common coupling. The experimental results have been validated using dSPACE DS 1104 hardware platform under variable irradiance level, wind speed and hydrogen consumption with improved performance, high tracking efficiency and low hydrogen consumption.

Appendix

Grid voltage: 230 V

Grid Frequency: 50Hz

Controller Used: dSPACE real time board

Type of MOSFET: IRFZ24N

Used Diode: BYW98-20

Current sensor : ACS712ELCTR-30A-T

Wind turbine Specification

Rated power: 200 W

Type of Generator: PMSG

Rated Speed: 1800 rpm

Number of poles: 4

Solar Panel Specification

Peak Power**:** 200 W

Peak Voltage: 26.6 V

Peak current; 7.52 A

Open Circuit Voltage: 33.2 V

Short Circuit Current: 8.36 A

Fuel Cell Specification

Ideal thermodynamic predicted voltage (E_{Thermo}) = 1.3 V

Total cell internal resistance (R_{Ohmic}) = 0.375 cm^2

Peak temperature of stack= 70^0C

Hydrogen Pressure= 0.55-0.65 bar

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