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Fuzzy Logic Controller for Voltage and Frequency Stabilization in DC decoupled Micro grid system

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Abstract: ***An efficient Fuzzy Logic Controller (FLC) is proposed for maintaining constant voltage and frequency in a Decoupled DC micro grid system. The micro grid is modeled with solar, wind turbine, Fuel cell, battery and loads. Individual fuzzy MPPT (Maximum Power Point Tracking) controllers have proposed for solar, wind and fuel cell to extract maximum power from the sources and also to maintain constant voltage at DC bus. For the bidirectional power flow among the buses in the micro grid with power management strategy, an efficient Fuzzy logic controller is proposed for the bidirectional converter connected between DC and AC buses. The performance indices such as ITAE, ITSE, and settling time, rise time of DC link voltage has determined and it is being compared with the conventional Proportional Integral (PI) controller to endorse the performance of the proposed FLC. The results prove that the FLC has better performance in all aspects and it is more suitable for the power management in micro grid.***

Keywords: Micro grid, Fuzzy Logic Controller, Power management, Performance Indices, Utility Grid

I. INTRODUCTION

The choice of renewable energy sources in the low voltage level is increasing gradually in the current scenario. Non-conventional energy sources such as solar, wind are environmentally free, available in nature and easy to convert as electrical energy. And also, with these sources, one can generate and consume the power locally nearer to the load or at consumer end. The combination of such distributed generating sources, energy storage systems and the loads constitute the micro grid. It can be of AC micro grid, DC micro grid and Hybrid Micro grid (HMG). Due to the interfacing facility with the conventional utility grid, AC micro grids became popular in the last decade [1]. Since most of the renewable sources have DC interfacing, having DC sub grid becomes mandatory in the micro grid. DC sub grid has many advantages such as electric vehicle charging, storage facility, reduction in converter topologies etc.

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Since renewable sources have intermittent power supply with variable solar irradiation, wind velocity, the micro grids have to be operated with the utility grid. Hence, for the grid tied operating conditions, AC sub grids support the micro grid. Recently, HMGs are popular for the combined benefits of both AC and DC sub grids. The sources, loads and storage devices are segregated based on its supply and connected to its respective buses. Generally, wind turbines, diesel generators, hydro plants and ac loads such as fans, pumps are being connected to the AC sub grid along with utility grid. Photo voltaic, fuel cells, batteries and DC loads are connected with the DC sub grid. In HMGs, bidirectional converters play a significant role which connects both AC and DC sub grids [2]. These converters will act as rectifier when power is fed from AC to DC side; act as an inverter when power is fed from DC to AC sub gird. Control of micro grid plays a significant role in maintaining the constant voltage, frequency and having coordinated control among the sources. Control can be done in proper modeling of components, system modeling, developing power or Energy management strategies, developing algorithm or technique for coordinated control, enhancing the power quality, addressing protection and stability issues. Modeling aspects have been discussed in [3-5]; power management strategies have elaborated in [6-10]. Coordinated control is highlighted in [11-15]; stability analysis [16-18], power quality [19-20] and protection issues [21]. Among the various control techniques, power management is popular in various researches which refer to the active, reactive power control, storage control, AC/DC bus voltage control and the control of interlinking converter. Maintaining bus voltages and the frequency is treated as the primary objective in the micro grid when it is connected to the utility grid. The variation in the renewable source powers and the variation in loads will deviate the voltage. Hence, proper design of controller is needed in the system to detect the changes in the load and the sources and act accordingly. Controllers are needed in several applications of micro grid which provides flexible service to the loads under various operating conditions, effectively control the power flow between micro grid and utility gird, having self-sufficient operation in autonomous mode of operation. Variety of controllers has been proposed in the literature such as Centralized and Decentralized controllers by its control actions; Primary control, Secondary and tertiary Control based on control levels.

Centralized Controllers gathers information from the entire system using a dedicated central controller and determines the control actions via communication interfacing [22]. Decentralized Controllers receives the information only about the particular component to which it is locally attached.

Conventional PI controllers are very sensitive to the output variations and also the mathematical modeling of the control system with PI controllers is complex one. This drawback is eliminated with Fuzzy Logic concepts. Fuzzy logic is easy to understand flexible, model nonlinear functions for any input and output data, can be mixed with conventional techniques, and based on the natural language. The applications of Fuzzy concept in renewable source systems have been reviewed in [23]. The Fuzzy concept has mainly used for assessing the location of renewable plant, PV/wind installation, Maximum power point tracking (MPPT) for the solar/wind system and optimization concepts etc. A controller based on fuzzy Logic plays a significant part in the coordination of energy management in the Micro grid system. An Fuzzy Logic Controller (FLC) for a hybrid renewable energy systems consisting of solar, wind, battery and diesel system is proposed in [24]. The EMS (energy management system) using FLC for HMG have met the load demand and shows good performance under variable source conditions.

Fuzzy controlled power strategies for a grid connected micro grid has been proposed in [25] by considering solar and fuel as primary sources of power and battery for backup power. A similar kind of work has been done in an autonomous mode operated micro grid [26] in which a FLC was proposed to effectively control the micro grid voltage and frequency. A smart FLC (FLSC) has been developed in [27] to manage energy flow for a power system with solar, wind and storage. The excess energy has been used to produce hydrogen in an electrolysis system. The Fuzzy rules are framed to obtain the signals for various cases.

The fluctuation in the frequency and power in an isolated power systems has been analyzed with scaling factor FLC (SF-FLC) and compared with the combinations of PI, PD, PID with SF-FLC in [28].Using Harmony Search (HS) algorithm, the optimal tuning of parameters for reducing the frequency and power deviation has been proposed. A communication-free charging controller based on FLC for electric vehicles has been proposed in [29] which take into account the voltage profile and SoC (State of Charge) of a vehicle battery. Fuzzy along with PI algorithm has proposed in [30] micro grid coordinated control to optimize the closed loop control algorithm.

In this paper, micro grid is modeled with solar, wind, fuel cell, battery at DC bus and the utility grid, Loads at AC bus. The utility gird is coupled with the AC bus using a circuit breaker at point of common coupling (PCC). The sources have dedicated controller for its efficient operation. The variations in the sources are controlled by its individual controller for maintaining constant voltage at DC side. The bidirectional converter is connected between the DC and AC bus to allow the bidirectional power flow among the sources in both grid tied and autonomous mode of operation. The resistive loads are connected at AC side, which will be satisfied by the micro sources and battery during autonomous mode and by the conventional power grid during grid tied mode of operation. The variation in the loads affects the DC/AC bus voltage which subsequently affects the synchronization of the utility grid with micro grid. Hence an efficient controller based on fuzzy concept is proposed in this paper to control the bus voltages thereby maintaining the voltage and frequency. The novelty of this proposed work is the implementation of fuzzy logic controller for the individual controllers at the DC side and also for the bidirectional converter operation. The results prove that the FLC efficiently controls the voltage, have reduced ITAE, ITSE errors compared to conventional PI controller.

The paper is prepared as follows: Section 1 briefs about the significance of controller in micro grid with literature survey; Section 2 presents the modeling of components in micro grid with its controllers; Section 3 explains the FLC implementation in the micro grid; Section 4 elucidates the results and discussion; Section 5 concludes the paper.

II. MODELING OF MICRO GRID

The micro grid structure shown in figure 1 is having solar panels connected to DC bus via DC-DC boost converter with fuzzy MPPT controller, wind turbine with fuzzy based AC-DC & DC-DC converter, and fuel cell with fuzzy controlled DC-DC converter and Battery with bidirectional DC-DC converter.

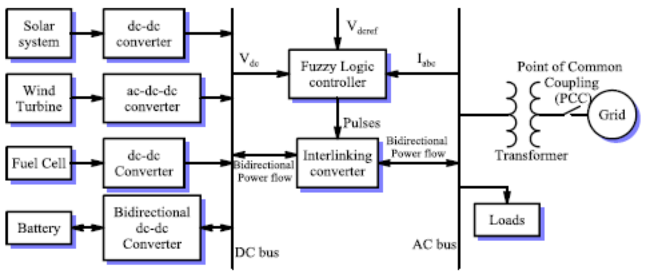

Fig.1.Structure of DC micro grid

A. Solar Cell

The equivalent circuit of solar cell used in this work comprises a diode, a constant current source, a series resistance and a parallel resistance as shown in figure 2.

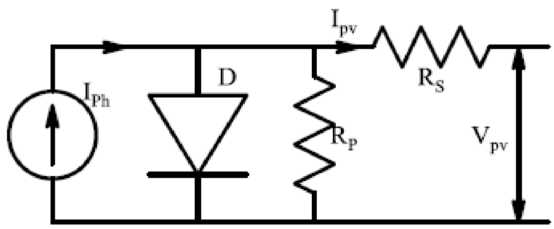

Fig.2. Equivalent Circuit of Solar Cell

$$I = N_p I_{ph} - N_p I_d \quad (1)$$

$$I_{ph} = \{I_{sc} + k_1(T_c - T_{ref})\}\frac{\lambda}{1000} \quad (2)$$

$$I_d = I_s\left[e^{\frac{qU}{N_s k T_c A}} - 1\right] \quad (3)$$

$$I_s = I_{rs}\left[T_c / T_{ref}\right]^3 e^{\left[\frac{qE_g[(\frac{1}{T_{ref}})-(\frac{1}{T_c})]}{kA}\right]} \quad (4)$$

where I_{pv} is the solar output current in A, Id is the diode current in A. I_{ph} and I_{sc} are the current due to light radiation, short circuit current in A.k1 is the cell short circuit current temperature coefficient in A/^{o}C, T_c, T_{ref} are the cell and reference temperature respectively in K. λ is the solar radiation in W/m$_2$, I_S is the module saturation current in A, q is the electron charge in C, V_{pv} voltage of PV cell in V, k is the Boltzmann constant in J/K, A is the p-n junctions ideality factor (assumed to be 1.5). I_{rs} is the module reverse saturation current in A, Eg is the semiconductor band gap energy (1.1eV), Ns, Np are the number of cells in series and parallel respectively.

The power from the solar panel is maximized by generating the suitable gate pulses with Fuzzy MPPT controller. Solar panel output voltage and current are considered as the inputs to the controllers as in figure 3.

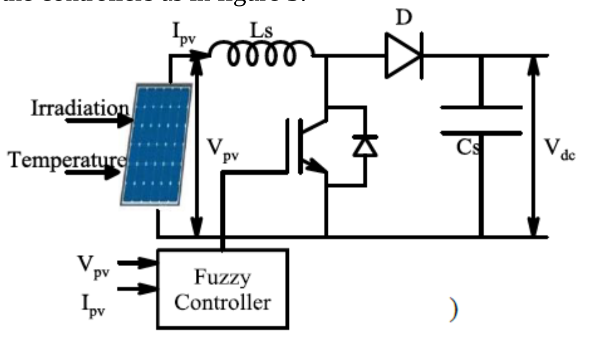

Fig.3. Fuzzy MPPT control for Solar Panel

B. Wind turbine

The wind turbine's output is variable and the maximum power that could be extracted by applying Betz limit is represented in equation (5).

$$C_p(\lambda) = \frac{2\,P_{wind}}{\lambda S V_{wind}^3} \quad (5)$$

The torque and power output can be calculated using the equations (6) and (7):

$$T_{mec} = \frac{1}{2}\frac{C_p(\lambda)\rho R S V_{wind}^2}{\lambda} \quad (6)$$

$$P_{wind} = \frac{1}{2} C_p(\lambda)\rho S V_{wind}^3 \quad (7)$$

where ρ is the density of air, R is the radius of the rotor in m, S is the area traversed by the rotor blades in m^2, V_{wind} is the speed of the wind in m/s, λ is the tip speed ratio. The wind turbine is coupled with Permanent Magnet Synchronous Generator (PMSG) to produce a three phase AC voltage. The PMSG is connected to a rectifier for converting into DC voltage and for boosting the voltage; DC-DC boost converter is used. Due to the high efficiency, high torque to inertia ratio, high power density and fast dynamic response of the PMSG, it has been employed in micro grid applications. Since constant magnet flux is provided by Permanent magnets, these types of machines have a slender constant power speed range (CPSR). One of the methods to increase the speed range is Flux or Field Weakening control method [31].

The rotor speed is given through the Flux Weakening block after which, it is passing to the FLC for generating the pulse for the DC-DC converter with Maximum Power Point Tracking (MPPT) operation. The control block diagram of wind turbine is shown in figure 4.

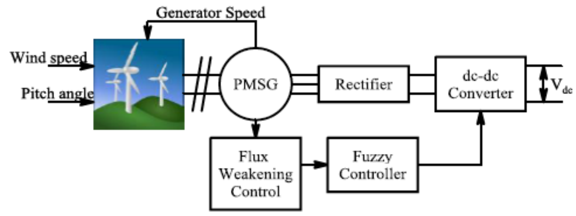

Fig.4. Fuzzy control for wind turbine

C. Fuel Cell

The fuel cell is defined as a static device that is used to transform chemical energy into electrical energy by chemical reactions. Since Fuel cells have high efficiency compared to conventional combustion engines, its application has been extended to the micro grid. Alkaline Fuel cells take oxygen and hydrogen to produce water and electricity by dissipating heat. The Alkaline Fuel Cell (AFC)'s (Bacon Fuel cell) chemical reactions at Anode and cathode electrodes are represented in equations (8) and (9) respectively [26]:

Reactions at Anode:

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^- \quad (8)$$

Reactions at Cathode:

$$\frac{1}{2}O_2 + 2H_2O + 2e^- \rightarrow 2OH^- \quad (9)$$

The main advantage of the AFC is low cost, high efficiency and accelerated oxidation of fuels. The operational temperature is 60-120^{o}C and efficiency is around 35-55%. The electrolyte used is Potassium Hydroxide (KOH). The AFC is the operating reserve to meet out the base load. The fuel cell is connected to DC bus via a DC-DC boost converter. The maximum output is obtained from the converter using Fuzzy controller as shown in Figure 5.

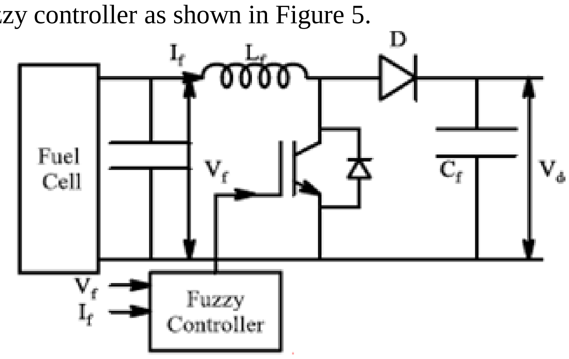

Fig.5. Fuzzy control circuit

D. Battery modeling

The battery has been modeled with three elements, viz., a controlled voltage source, the battery's internal resistance and the capacity factor of the battery which is shown in figure 6. The terminal voltage of the battery is defined in equation (10): [24].

$$U_{batt} = E_o - K\frac{\int I_b dt}{Q_o} - R_b . I_b \qquad (10)$$

where E_o is charged battery empty voltage in V, K is the battery constant , R_b is the battery internal resistance in Ω,I_b is the discharge current of the battery in A,Q_o is the capacity of the battery in Ah,$\frac{\int I_b dt}{Q_o}$ is the indication of the discharge status of the battery.

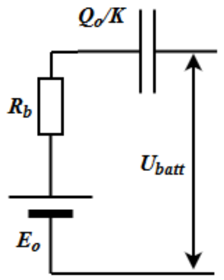

Fig.6. Equivalent Circuit of battery

III. FUZZY LOGIC CONTROLLER IMPLEMENTATION

In this paper, FLC is implemented for controlling the DC/AC bus voltages at the micro grid. The Fuzzy Inference system has three stages such as input stage also called as Fuzzification process, Inference stage or Processing stage and output stage also known as de-fuzzification stage. Since the objective is for maintaining the bus voltages constant, voltage error at DC bus is given to the FLC as shown in Figure 7.

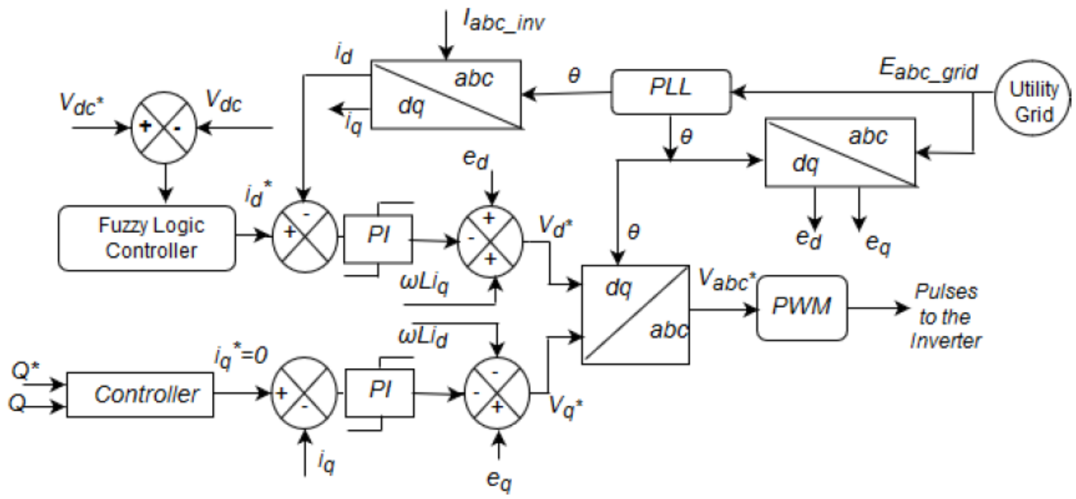

Fig.7. Controller Implementation using FLC

The control circuit has two control loops; outer voltage control and inner current control. The grid voltage that is measured is changed into synchronous d − q reference frame by the use of Park's transformation for determining the reference current of the inverter. The real and reactive power at AC bus is mentioned as follows:

$$P = \frac{3}{2}(V_d i_d + V_q i_q) \qquad (11)$$

$$Q = \frac{3}{2}(V_q i_d - V_d i_q) \qquad (12)$$

where P,Q –real and reactive power, V- grid voltage, i - inverter current. Earlier, by altering the direct in addition to quadrature current components the active as well as reactive power is controlled. If the reference frame is concerned with beside a grid voltage, V_q will be equivalent to zero. When battery SOC is between the SOC_{min} and SOC_{max}, the current reference for controlling real and reactive power in the d-axis and q-axis is given as,

$$i_d^* = \frac{2}{3V_d} P^* \qquad (13)$$

$$i_q^* = -\frac{2}{3V_d} Q^* \qquad (14)$$

where, P^*,Q^*- Reference real and reactive power (set to zero) respectively. When the inverter controls the DC bus voltage, i_q^* is fixed according to (14) and i_d^* is fixed according to the voltage controller in the DC bus. Furthermore, to improve the power factor of the grid injected current, the requisite reactive power of AC load linked to the AC bus will be compensated by the inverter.

A. *Outer voltage control*

In standalone or autonomous mode, the power from DGs' is fed to the DC bus. The bidirectional converter changes DC voltage into AC voltage which is maintained constant at AC bus.

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In order to maintain ac bus voltage at load side, the error between the actual dc link voltage and reference dc link voltage is given to the Fuzzy controller. Figure 8 shows the controller implementation for the d axis voltage control to generate d axis reference current.

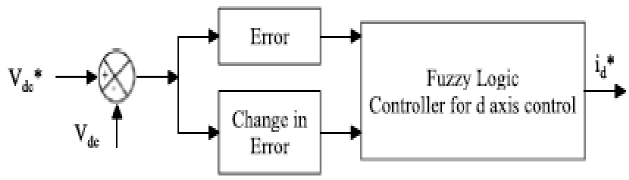
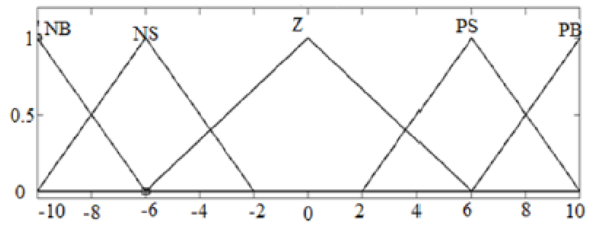
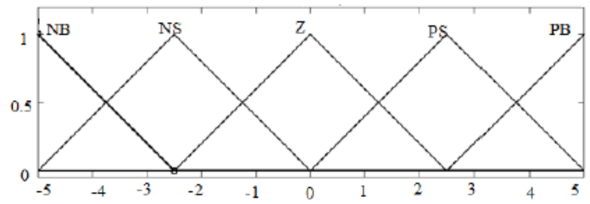


Fig.8. d axis voltage control

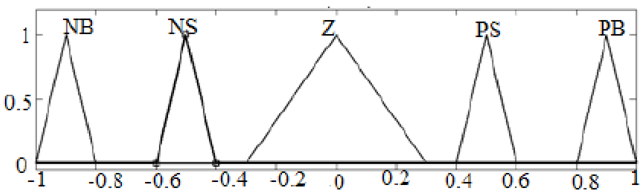
Figure 9 shows the membership functions of the inputs and the output. In figure 9, NB-Negative Big, NS-Negative Small, Z-Zero, PS-Positive Small and PB-Positive Big.



(a) Voltage Error



(b) Change in Voltage error



(c) Output (i_d^*)

Fig.9. Input and Output Membership Functions

The system equations in dq reference frame can be written as:

$$e_{dg} = R_g i_{dg} + L_g \frac{di_{dg}}{dt} - \omega_g L_g i_{qg} + \vartheta_{dg} \quad (15)$$

$$e_{qg} = R_g i_{qg} + L_g \frac{di_{qg}}{dt} + \omega_g L_g i_{dg} + \vartheta_{qg} \quad (16)$$

$$\frac{di_{dg}}{dt} = -\frac{R_g}{L_g} i_{dg} + \omega_g i_{qg} - \frac{\vartheta_{dg}}{L_g} + \frac{e_{dg}}{L_g} \quad (17)$$

$$\frac{di_{qg}}{dt} = -\frac{R_g}{L_g} i_{qg} - \omega_g i_{dg} - \frac{\vartheta_{qg}}{L_g} + \frac{e_{qg}}{L_g} \quad (18)$$

where $\theta = \omega_g t + \theta_0$; e_{dg}, e_{qg} - d-q axes grid side voltages; R_g, L_g- Resistance and Inductance of the coupling AC inductor, Ω,H; i_{dg}, i_{qg} - d-q axes actual grid side currents, A; ϑ_{dg}, ϑ_{qg}-d-q axes grid side converter voltages, V; ω_g -angular frequency of the gird, rad/sec; θ- Synchronous rotating angle, rad; θ_0 - Initial value, rad.

For the outer DC link voltage control loop, the d axis reference grid current can be framed as

$$i_{dg}^* = (v_{dc}^* - v_{dc})(FLC\ gain) \quad (19)$$

where v_{dc} is the actual dc link voltage, v_{dc}^* is the reference dc link voltage, $i_{dg}^*$is the d axis reference current. In this paper, Fuzzy has been implemented instead of PI controller at outer voltage control loop. Since the voltage control has been considered as the main objective, the reactive power control will be redundant in this case. Hence the q axis reference current has taken as zero.

$$i_{qg}^* = 0 \quad (20)$$

B. Inner Current Control

For the control of d-q axis grid currents in independent manner, the cross coupling effect due to the coupling inductor are decoupled and the control signals are written as:

$$u_{dg}^* = -v_{dg} + \omega_g L_g i_{qg} + e_{dg} \quad (21)$$

$$u_{qg}^* = -v_{qg} - \omega_g L_g i_{qg} + e_{qg} \quad (22)$$

From the inner current control loop, the control signals are

$$u_{dg}^* = k_p \left(\frac{1+pT_i}{pT_i}\right)\left(i_{dg}^* - i_{dg}\right) \quad (23)$$

$$u_{qg}^* = k_p \left(\frac{1+pT_i}{pT_i}\right)\left(i_{qg}^* - i_{qg}\right) \quad (24)$$

Hence the decoupled d-q axes reference voltages for the grid side converter can be written as:

$$v_{dg}^* = -u_{dg}^* + \omega_g L_g i_{qg} + e_{dg} \quad (25)$$

$$v_{qg}^* = -u_{qg}^* - \omega_g L_g i_{dg} + e_{qg} \quad (26)$$

Substituting the u_{dg}^* & u_{qg}^* values in the above equation, the state space model of d-q axis reference voltages are

$$\begin{bmatrix} v_{dg}^* \\ v_{qg}^* \end{bmatrix} = \begin{bmatrix} -k_p & -\omega_g L_g \\ -\omega_g L_g & -k_p \end{bmatrix}\begin{bmatrix} i_{dg} \\ i_{qg} \end{bmatrix} + \begin{bmatrix} k_p & 0 \\ 0 & k_p \end{bmatrix}\begin{bmatrix} i_{dg}^* \\ i_{qg}^* \end{bmatrix} + \begin{bmatrix} k_i & 0 \\ 0 & k_i \end{bmatrix}\begin{bmatrix} X_d \\ X_q \end{bmatrix} + \begin{bmatrix} e_{dg} \\ e_{qg} \end{bmatrix} \quad (27)$$

$$\text{where } \frac{dX_d}{dt} = i_d^* - i_d;\ \frac{dX_q}{dt} = i_q^* - i_q; \quad (28)$$

Using inverse park transformation, the abc reference voltages for the PWM modulator has been obtained and the pulses can be generated from the modulator to the inverter.

IV. RESULTS AND DISCUSSION

The specification of the micro grid is given in table 1.

Table 1. Micro grid system specifications

System Parameters	Values
DC bus voltage	220V
Frequency	50Hz

DC Link capacitor	5mF
Line impedance	R=0.8Ω ,L=0.1µH
Solar panel Rating	1.5kW , 90 cells per module, Np=66,Ns=2
Solar Boost converter	L=.08mH,C=2mF
Wind turbine Rating	5kW , PMSG ,base speed 5m/s
Wind turbine converter	L=1µH, C=2.5mF
Fuel cell Rating	16.8 kW With 48 V DC AFC
Fuel Cell Converter	L=2mH, C=8000µF
Battery Rating	1.5kW Lead Acid, 48V,50Ah rated capacity, 40 % initial SoC (State of Charge)
Battery converter	L=0.02mH,C=8µF
Filter	L=5mH,C=800µF
Step up Transformer	10KVA, 220/415V

The mode of operation along with the power generation from sources, load ratings are given in table 2.

Table 2. Modes of operation with the power ratings

Cases	Mode	Time in Sec	Source combination	Power from Sources in kW	Load power in kW
Autonomous	I	0.0-0.6	FC	15.45	15
	II	0.6-0.8	FC+S	16.2	16
	III	0.8-0.9	FC+S+W	17.7	16.2
	IV	0.9-1.0	FC+S+W +B	18.8	17.2
	V	1.0-1.2	FC+W	19.05	17.2
	IV	1.2-1.4	FC+W+B	20.15	19.7
Grid Connected	VII	1.4-2.0	Grid +B charging	-	22.5

The fuel cell is connected in all modes, since it is the basic source for meeting the load demand in the system. In grid connected mode, grid is connected to the system for meeting the load of 22.5kW. In this mode, although all sources are connected to the system, the generation is not sufficient to meet out the load, hence the grid is connected to charge the battery as well as meet out the load.

Figure 10.a shows the solar irradiation [32] and figure 10.b shows the wind velocity [33] over the period of simulation time in Chennai location. For the simulation period of 2s, the actual solar irradiation is scaled down and taken as input to the solar panel. The wind speed for a year is scaled down for a simulation period of 2s and taken for analysis as shown in figure 10.b. The simulation is performed in two steps. In step 1, DC link voltage is maintained constant for the variation in the input source with the help of fuzzy controller for the individual power sources. In step 2, the bus voltage is maintained at constant for the variable load with Fuzzy logic controller proposed for bidirectional converter connected between DC and AC bus

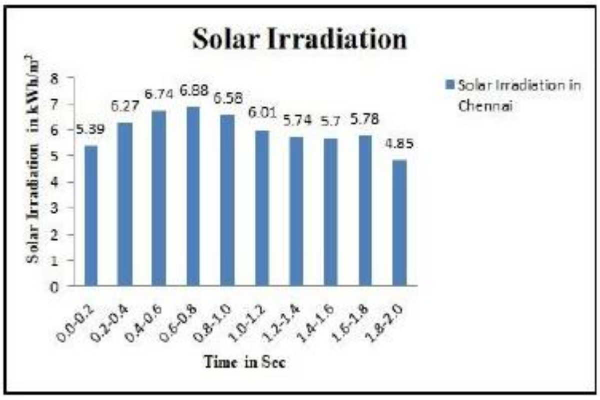


Fig.10.a) Solar irradiation

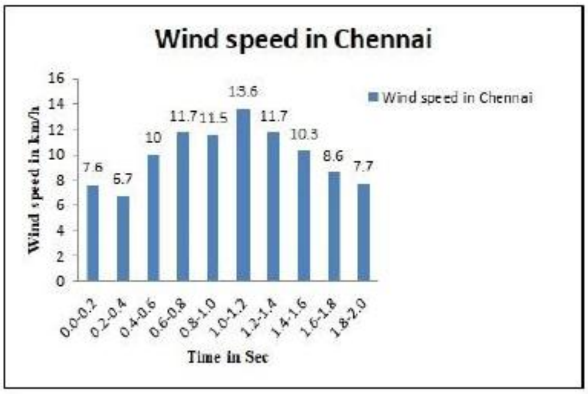


Fig.10.b) Wind speed

The DC link voltage of FLC is compared with Proportional Integral controller and shown in figure 11. It is clearly observed that the voltage is maintained within the limits. At grid connected period of 1.4s, there is a voltage change which is again within the limits. The variable load conditions are realized by connecting the loads at different period of time in the simulation with different ratings. The voltage and current of load3 is shown in figure 12. It is observed that the voltage is maintained at constant at the load level.

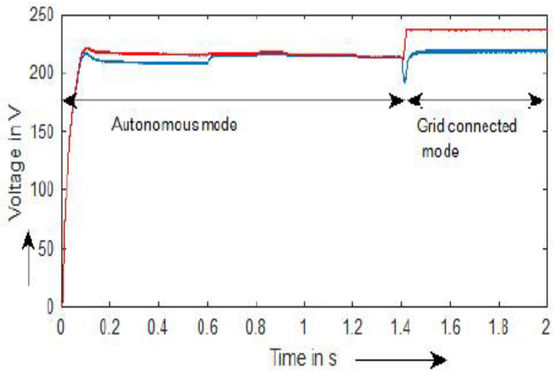


Figure 11. DC link voltage with FLC and PI

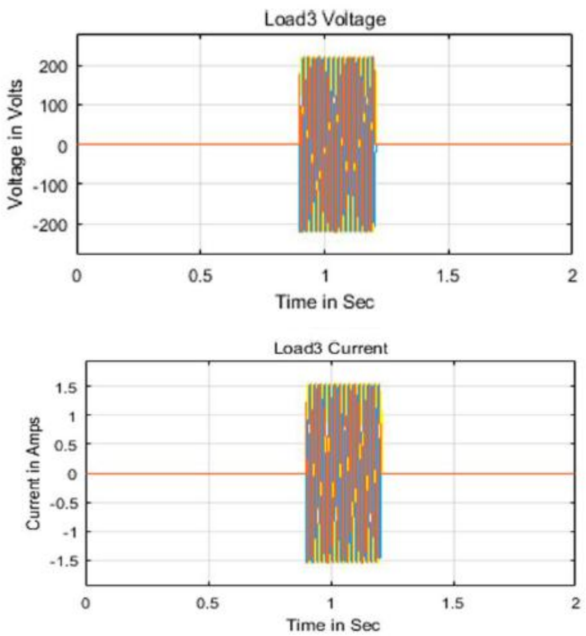


Fig.12. Load3 Voltage and current

During the simulation, the grid voltage is maintained at 1per unit and the current is zero at autonomous mode and during the grid connected mode, the power is drawn from the grid. The voltage and current at grid is shown in figure 13.

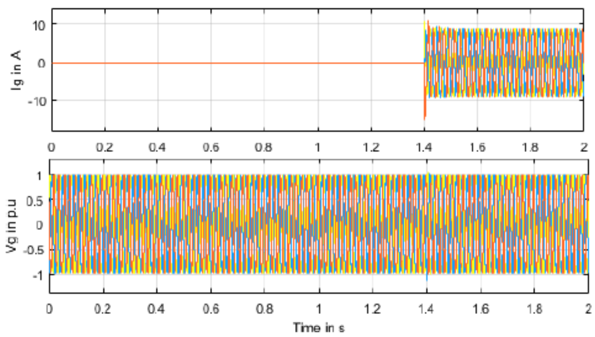


Fig.13. Grid voltage and current

The performance indices for of DC link voltage has been calculated and tabulated in table 3. For validating the performance of the fuzzy logic controller, the results have been compared with the conventional PI controller. From the table, it is evident that the proposed FLC for controlling DC/AC bus voltages at grid tied Micro grid is more suitable in all modes of operation. The results shown in Table 3 show that the settling time and rise times are lesser in FLC. The performances indices such as Integral of Time weighted Absolute Error and Integral of Time weighted Squared Error has been calculated for the test micro system using PI & FL controllers. It is observed that FLC has smaller values in both ITAE and ITSE than PI controller. Minimizing these errors is preferable one in designing of any controller.

Table 3.Comparison of Performance indices for DC link voltage

Description	PI Controller	Fuzzy Logic Controller
Settling time in sec	0.5688	0.4831
Rise time in sec	0.0468	0.0451
ITAE	1522	1083
ITSE	1896	970.8

V. CONCLUSION

An efficient Fuzzy Logic Controller is proposed in this paper for the decoupled DC micro grid to maintain the DC/AC bus voltage and frequency. The micro grid is modeled with solar, wind turbine, fuel cell, battery and loads. The simulation is done with grid connected and autonomous mode of operation. The power management among the sources, utility grid, battery and load is efficiently done by the proposed fuzzy logic controller. Different modes of operations are considered with variable load connections and separate fuzzy MPPT (Maximum Power Point Tracking) controllers are implemented for the solar, wind and fuzzy for extracting the maximum power from the sources and to maintain constant voltage at the DC bus. The results are compared with the conventional PI controllers to substantiate the performance of the proposed FLC and tabulated with performance indices. It is being observed that the proposed FLC is having better results than PI controller.

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