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Fuzzy logic control of fuel cell for stand-alone and grid connection

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Abstract

Fuel cells have become one of the major areas of research in the academia and the industry with the numerous advantages they provide over the batteries and especially over the other small-scale sources of electricity including the photovoltaic and solar cells. Fuel cells generate electricity from hydrogen by a chemical process and are environmentally safe and efficient. Fuel cells have numerous stand-alone and grid-connected applications. The aim of the paper is to achieve the control of the fuel cell for stand-alone and grid connection. This is achieved by designing a suitable power conditioning unit. The power conditioning unit is needed for processing of the raw power output of the fuel cell in order to make it usable. The power conditioning unit might have only dc/dc converter or the two stages of dc/dc converter and dc/ac inverter. For the stand-alone part, the concentration is on the controlled direct current (dc) power, thus, only a boost converter (dc/dc) stage is used. For the grid interface of the fuel cell, controlled alternating current (ac) power is needed at the interface point of the fuel cell and the utility grid; thus, both stages, boost converter as well as the inverter (dc/ac), are needed. A power conditioning unit is designed for the solid oxide fuel cell, which can be used for other fuel cells with converter and the inverter of different ratings, but the control strategy will remain the same. The fuzzy logic control strategy is used for designing the controllers for both the stages.

Keywords: Fuel cells; dc/dc converter; dc/ac inverter; Fuzzy logic; Grid

1. Introduction

Fuel cell (FC) technology is based on the concept of direct electrochemical energy conversion. The FCs are modular, efficient and have a lower environmental impact. Like batteries, FCs can be connected together in series to produce higher voltages. Clean, quiet, efficient, and compact, FCs generate electricity through chemistry instead of combustion [1]. The FCs have numerous stand-alone and grid-connected applications.

1.1. Fuel cells for stand-alone applications

A large number of FC systems for stationary power generation have been installed worldwide for use in hospitals, hotels, office buildings, schools, utility power plants and even airport terminals. FCs are also being tested for use at landfill and wastewater treatment plants. FCs are of critical importance to manned space missions. [1,2]. FCs are being used for portable electronics like laptop computers, cellular phones or even hearing aids. An FC produces electricity and significant amount of heat, so it is possible to heat water and help to generate heat without using any additional energy.

1.2. Fuel cells for grid-connected application (distributed generation)

Distributed generation (DG) can be defined as the implementation of various power-generating resources, near the site of need, either for reducing reliance on grid power or for feeding power directly into the grid or to support or boost performance of weak transmission and distribution systems. The current rapid progress in power deregulation and the environmental concerns have attracted attention towards FCs as distributed generators for power generation. Some FC technologies have potential to replace conventional combustion power plants. The FC technologies being developed for power plants will generate electricity directly from hydrogen in the FC, but will also use the heat and water produced in the cell to power steam turbines and generate more electricity [1,2].

Producing electrical power for working applications as mentioned above requires more than just the FC stack. An

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FC system includes fuel processing, thermal management, power conditioning, electric grid connection and energy storage modules. The major component of an FC system is the power conditioning equipment. This piece provides regulated direct current (dc) or alternating current (ac) power which most household appliances operate on. The purpose of conditioners is to adapt the electrical power from FC to suit the electrical needs of the application, whether it is a simple electrical motor or a complex utility power grid. Power conditioning includes controlling current flow, voltage, frequency and other characteristics of the electrical current/voltage to meet the needs of the application. The concentration of this paper is on the design and control of the power conditioning system.

2. Solid oxide fuel cell

Solid oxide fuel cells (SOFCs) are particularly attractive because they have the highest efficiency of any conventional FC design and the potential to use many fuels including gasoline and diesel without expensive external reformers that create more volatile chemicals [3]. SOFCs can operate at high temperatures, producing high-grade waste heat, or exhaust, which can be recovered and used for other applications, such as space heating and cooling, supplying homes with hot water, and even generating extra electricity by spinning a gas turbine linked to the unit. For the military, SOFCs offer the possibility of delivering quiet, clean, and uninterruptible energy to armed forces stationed in remote locations. SOFCs can also serve as auxiliary power units in motor vehicles, and leading automotive companies are already working with industrial partners to exploit their potential. The SOFCs are particularly attractive because they are the most efficient (in terms of fuel input to electricity output). The technology is most suited to applications in the DG (stationary power). The high operating temperature produces heat suited well to cogeneration applications. SOFCs do not contain noble metals and do not utilize liquid electrolytes, which can be problematic and expensive [1–3]. In an SOFC, there are no moving parts and the cells are therefore vibration free. Thus, the SOFCs are used as small-scale stand-alone power supplies and grid-connected power plants because of their high voltage output.

2.1. SOFC model

The dynamic model of the fuel cell is the electrochemical model with the component material balance equations. The model is also based upon the voltage activation, concentration and Ohmic losses (the Nernst voltage equation).

The SOFC stack model is based upon the following assumptions.

- Stack is fed with hydrogen and air (fuel processor dynamics not included).
- Uniform gas distribution among cells is assumed, since there is a small deviation of the gas distribution among the cells.
- Each cell has the same temperature and current density.

According to the mathematical model the stack voltage is given as:

$$V_{FC} = NV_o - RI \tag{1}$$

$$V^o = \left(E^o + \frac{RT^o}{2F} \ln \frac{x_{H_2} x^{1/2} O_2}{x_{H_2O}} \right) \tag{2}$$

where V^o is the open circuit reversible cell potential, E^o is the standard reversible cell potential, N is the number of cells, F is the Faraday's constant, I is the stack current, x_{H_2} is the hydrogen partial pressure.

This is the Nernst voltage equation for the SOFC mathematical model [3].

3. Power conditioning unit

The power conditioning system provides regulated dc or ac power appropriate for the application [4]. It is the major component of an FC system. The output of the FC is an unregulated dc voltage and it needs to be conditioned in order to be of practical use. The power conditioner section converts the raw power into useable power for different applications. The power conditioning unit also controls electricity's frequency and maintains harmonics to an acceptable level. The purpose of conditioners is to adapt the electrical current from FC to suit the electrical needs of the application. The general configuration of the system will be the FC followed by a boost converter followed by an inverter. In general, the load for the boost stage is a filter and the inverter system (for stand-alone purpose a purely resistive and a reactive load might be considered). The boost converter for the FC will be operated in the voltage control mode. The boost converter is ideally suited for interfacing the inverter system with the FC. Based on the load conditions, the boost stage can be commanded to draw a specific amount of current from the FC with a ripple well defined by the frequency, size of the inductor, and duty ratio. Similarly, the inverter is used for the interfacing of the FC system to the power grid to provide the grid with voltage/current with proper frequency phase and magnitude where the input for the inverter comes from the boost converter stage and the inverter (with the filter) becomes the load for the boost converter.

The power conditioner is also used for the grid connection of the FC. An electrical power-generating system that uses FC as the primary source of electricity generation and is intended to operate synchronously, and in parallel with the electric utility network is a grid-connected FC system [3–5]. Such systems may also include battery storage and other generating sources, and may operate on site loads independent of the utility network during outages. Grid-connected or utility-interactive FC systems are designed to operate

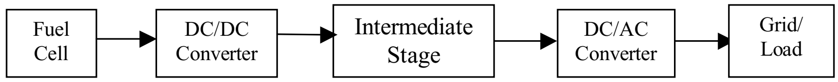

Fig. 1. Power conditioning system.

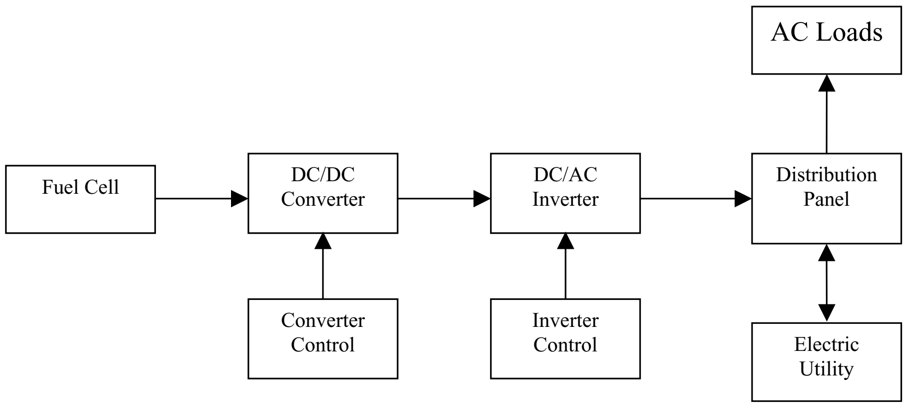

Fig. 2. Power conditioner and grid connection.

in parallel with and interconnected with the electric utility grid shown in Figs. 1 and 3. The primary component in grid-connected FC systems is inverter. The inverter converts dc power produced by the FC (after dc/dc converter stage) into ac power consistent with the voltage and power quality requirements of the utility grid.

3.1. *The stages in power conditioner*

The output voltage of FC at the series of the stacks is uncontrolled dc voltage, which fluctuates with load variations. It is to be converted to a controlled dc voltage. The controlled voltage thus obtained is fed to the dc/ac inverter after it is filtered. The power obtained from this inverter is added to the grid. The inverter acts as the grid interface. The system can be used as a stand alone after the dc/dc converter stage if dc power is needed or after the dc/ac stage if ac power is needed. This paper considers the stand-alone case and outputs controlled dc power. For the grid connection of FC, a sinusoidal current must flow from the FC inverter to the utility grid that matches with the grid frequency. Fig. 1 shows the power conditioning unit with the dc/dc converter and dc/ac inverter stages. There are other intermediate stages such as filters for suppressing harmonics and filtering out the undesired components of current and voltages obtained at the output of the dc/dc converter and the dc/ac inverter. A more elaborate power conditioning unit with the grid connection can be shown as in the Fig. 2.

3.1.1. *dc/dc converter*

The dc/dc converter is used for pre-processing of the dc voltage output of the FC. The raw voltage, which is unregulated and uncontrolled, is regulated to an average value with the help of dc/dc converter. The output of the FC needs to be controlled for the further stage of the dc/ac inverter stage.

3.1.2. *dc/ac inverter*

The dc/ac inverter accepts the regulated voltage from intermediate stage after the dc/dc converter. It converts the regulated dc voltage to an ac voltage. The magnitude and phase for voltage/current is then adjusted based upon the grid voltage/current with current or voltage control strategy. This ac output is fed to the load or grid.

3.2. *Power conditioner control*

The block diagram of the power conditioner with the control strategies incorporated is shown in Fig. 3. There are two separate control loops for the dc/dc converter control and the dc/ac inverter control.

3.2.1. *dc/dc converter control loop*

The unregulated output voltage of the FC is fed to the dc/dc boost converter. Being unregulated it has to be adjusted to a constant average value (regulated dc voltage) by adjusting the duty ratio to the required value. The voltage is boosted depending upon the duty ratio. The duty ratio of the boost converter is adjusted with the help of a fuzzy logic controller (FLC). The duty ratio is set at a particular

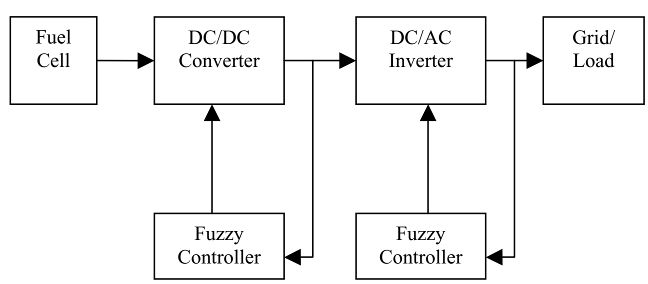

Fig. 3. Overall system block diagram.

value for the converter to provide desired average value of voltage at the output, and any fluctuation in the FC voltage due to change in fuel flow, in the load or in the characters of FC due to the chemistry involved takes the output voltage away from the desired average value of the voltage. The FLC changes the duty ratio appropriately to get the desired average value. The boost converter responds fast to the changes in the duty ratio. The duty ratio of the converter is changed by changing the pulses fed to the switch in the dc/dc converter circuit by the PWM generator. The fuel flow also needs to be adjusted, which takes effect gradually and controls the output voltage. Thus, both the strategies have to be combined for the efficient control of voltage of the FC. This paper concentrates only on the boost converter control strategy.

3.2.2. dc/ac inverter control loop

The output voltage of the dc/dc converter is filtered and fed to the inverter to produce an ac output voltage/current for grid connection (or a load). The inverter is a connecting link between the FC and the grid. The FLC uses predicted current control-based FLC strategy to control the inverter current for incorporating the FC into the utility grid at a desired frequency. The FLC does so by sourcing a sinusoidal current into the grid. The current is controlled by feeding controlled pulses to the switches of dc/ac inverter by PWM generator. Two of the switches are used to shape the wave-form of current to follow reference current and other two switches are used to correct polarity of the wave form. In this case, duty ratio of switches is controlled by adjusting the pulses (modulated by PWM generator) fed to four switches of the inverter. The FLC generates the error and adjusts duty ratio on a continuous basis to maintain sinusoidal inverter current at desired frequency to the utility grid.

4. dc/dc boost converter and control

dc/dc converters are used to convert the unregulated dc input voltage into a controlled dc output voltage at a desired average value. The FC converters will play an intricate role in FC technology. The power converter must have functions to protect the converter system from output fluctuations, reverse currents and sudden load variations and to assure their full lifetime.

4.1. The dc/dc boost converter

The output voltage is always greater than the input voltage. Battery-powered equipment uses dc/dc step-up converters to generate supply voltages for internal circuits that require voltages higher than the available battery voltage e.g. notebooks, mobile phones and camera flashes. It is also named the step-up converter [6].

4.2. Working of the boost converter

The circuit diagram of dc/dc boost converter is shown in Fig. 4. The on state occurs when switch is on and D off, the off state when switch is off and D on. The steady-state change in inductor current ΔI_L, during t_{on} is the same in magnitude but opposite in polarity to that which occurs during t_{off}. For the on state, equations relating voltage and current associated with the inductor are,

$$V_{dc} = L\frac{\Delta I_{on}}{t_{on}} \text{ or } t_{on} = L\frac{\Delta I_{on}}{V_{dc}} \tag{3}$$

where V_{dc} is the source voltage.

During t_{on}, output current is supplied completely by the capacitor charge. When the switch is open, the off-state equation is,

$$t_{off} = L\frac{\Delta I_{off}}{V_{dc} - V_o} \tag{4}$$

as $\Delta I_{off} = -\Delta I_{on}$ then,

$$t_{off}(V_o - V_{dc}) = t_{on}V_{dc}$$

Thus,

$$V_o = V_{dc}\frac{T_S}{(1 - D)T_S}$$

where T_S is the sampling time of the converter switch.

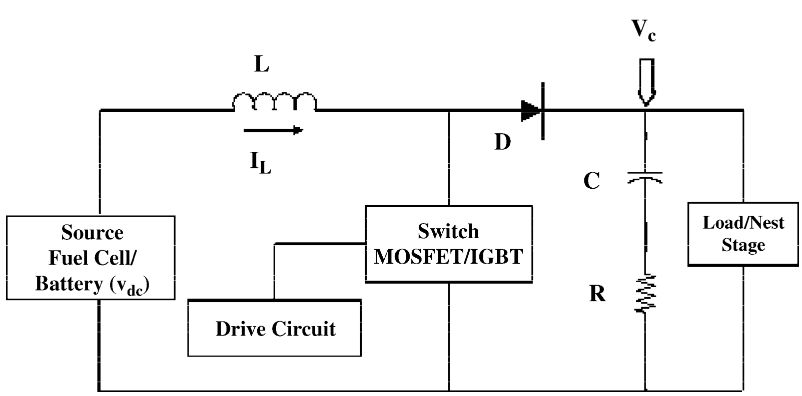

Fig. 4. Circuit diagram dc/dc boost converter.

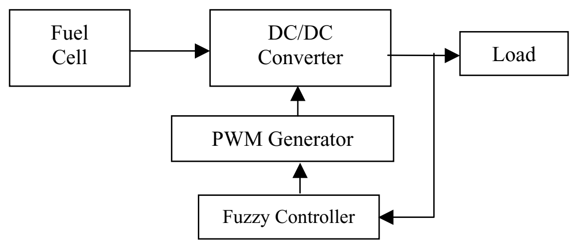

Fig. 5. Block diagram dc/dc converter control.

This produces the result that relates output voltage to input voltage [6].

$$V_o = \frac{V_{dc}}{1 - D} \tag{5}$$

4.3. Control strategy for the dc/dc boost converter

The dc/dc converter control block diagram is shown in Fig. 5. The response time of the dc/dc converter is very short compared to that of the reformer of the FC, which alters the fuel flow [7,8]. Thus, for the fast system response, initially the converter is controlled for load variations and the average voltage is adjusted in the transitional period by the boost converter. The output of the dc/dc converter is the boosted voltage that is fed to the load or to the next stage of filter to eventually pass on to the inverter stage. This boosted voltage is compared with a reference dc voltage to generate an error signal. The change in error is calculated. The error and the change in error are fed as inputs to the FLC. The FLC generates control signal based upon the inputs and rule base. The control signal is fed to the PWM generator. The PWM generator based upon the control signal adjusts the pulses of the switch of the boost converter. The boost converter generates output voltage based upon the duty ratio provided by the PWM generator [9,10]. The output voltage is controlled according to the Eq. (5). The voltage monitoring is done by the FLC continuously. Thus, the dc/dc power converter is switched on and off by a control signal (provided by FLC) to keep the average output voltage at the desired level.

5. dc/ac inverter and control

Inverters are devices that change the dc electricity produced by FC into ac electricity. Utility-interactive inverters are used in systems connected to a utility power line. The inverters produce ac electricity in synchronization with the power line, and of a quality acceptable to the utility company once the control strategy is implemented. The application of inverter is an improved approach for grid-connected FC systems without transformers or to avoid the use of bulky transformers. The single-phase full bridge is a reasonable solution for the FC systems, in order to interface it with the utility grid [11,12].

5.1. Working of the inverter

The single-phase full-bridge inverter consists of two identical legs as shown in Fig. 6 like the half-bridge single-phase converter. Specifically there are four switching elements (S_1, S_2, S_3, S_4) and four anti-parallel diodes (D_1, D_2, D_3, D_4) and a dc bus source voltage V_{dc} that can be single capacitor. The output voltage V_0 appears across the two points A and B. The control signals for switch pairs (S_1, S_2) and (S_3, S_4) must be complimentary to avoid any bridge destruction due to shoot through of infinite current. The control method for this topology treats the switches (S_1, S_4) and (S_2, S_3) as pair. This means that they are turned on and off at the same time and for same duration. The output current determines the conduction state of each switch.

As depicted in Fig. 6 when the two switches S_1 and S_4 are turned on, voltage at the output is equal to the dc bus voltage V_{dc}. Similarly, when switches S_2 and S_3 are turned on, the output voltage is equal to $-V_{dc}$. In the first case, when the direction of output current is positive, the current flows through switches S_1 and S_4 and the power is transferred from

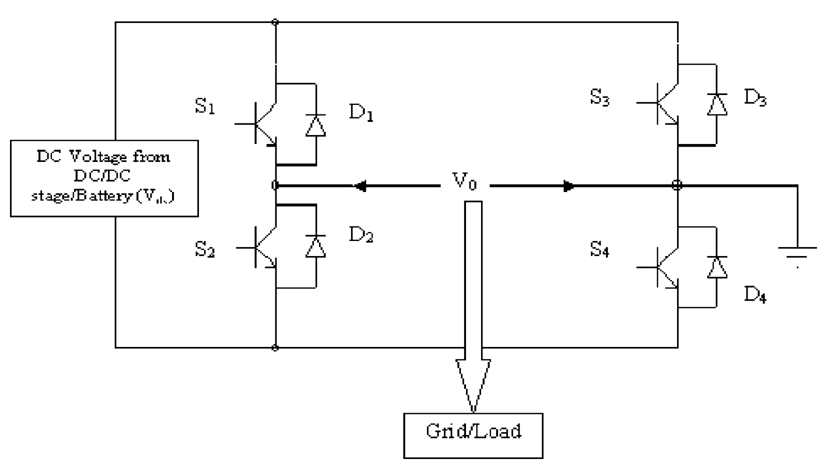

Fig. 6. Circuit diagram of dc/ac inverter.

the dc side to the ac. When the current becomes negative, although the switches S_1 and S_4 are turned on, diodes D_1 and D_4 conduct the current and return power back to the dc bus from ac side. For the other half of the period, when the switches S_2 and S_3 are turned on and the current is positive, the diodes D_2 and D_3 conduct. In this instance, power is also transferred back to the dc side from the ac side. Finally, when the current is negative, switches S_2 and S_3 carry the current and assist the converter to transfer power from the dc side to ac side. Thus, there are four distinct modes of operation for this converter when the control method mentioned above is employed. At all times two switches are turned on and the legs are controlled in a synchronized way [6].

5.2. Control strategy for the dc/ac inverter

As shown in the Fig. 7 the dc/dc converter sources power into the inverter (the FC and the converter control loop not shown). The LC filter stage comes after the inverter. The FC is connected to the grid using this structure [13,14]. As seen in Fig. 7, a current control strategy is used for the control of this inverter so that it injects proper current into the grid (a sinusoidal current at a proper phase). The control loop consists of an FLC which is based upon the predicted current control method. The inputs to the FLC are the change in the line current of the inverter and the reference grid source voltage signal. The FLC accepts these inputs and processes the control signals based upon the rule base. The control signal is fed to the switches of the bridge inverter in the form of controlled PWM pulses with a changing duty ratio based upon the change of the control signal.

The working of the predicted current control is explained here based on which the inputs are decided [14–16].The current of the single-phase bridge inverter is controlled by switches S_1–S_4(Fig. 6). The switch S_1 and S_2 are used to shape the wave form to follow the reference current and the switches S_3 and S_4 are used to correct the polarity of the current wave form.

In case of steady-state operation considering the voltage source converter power block diagram shown in Fig. 7, if T_S is assumed to be small in comparison with the period of the source voltage (V_s) then V_s can be assumed constant over the period T_S. Let t_n denote the time at the beginning of one period (neglecting the source resistance) and the change in the inverter current is:

$$\Delta I = I(t_n + T_S) - I(t_n) = \frac{V_s(t_n) - V_{inv}(t_n)}{L} T_S$$

where V_{inv} is the average value of ac-side inverter voltage over T_S.V_{inv} can then be found as,

$$V_{inv}(t_n) = V_s(t_n) - \frac{L}{T_S}[I(t_n + T_S) - I(t_n)] \quad (6)$$

V_{inv} can also be described as,

$$V_{inv} = d_k V_{dc} \quad (7)$$

where d_k is the duty ratio for switches S_1 and S_2 over one switching period.

The change in line current over one period can also be defined as:

$$\Delta I = I(t_n + T_S) - I(t_n) = I(t_n) - I(t_n - T_S)$$

From the above equations, we can define the duty ratio for the single-phase inverters as a function of source voltage (V_s) and the change in line current (ΔI) as,

$$d_k = f(V_s, \Delta I) = \frac{1}{V_{dc}}\left[V_s - \frac{L}{T_S}\Delta I\right] \quad (8)$$

The above equation gives the duty ratio to be implemented for the inverter switches by the predicted current control method [15,16]. The equation is used as a relation for FLC. The inputs of the FLC are based on this equation.

6. Fuzzy logic control

Fuzzy logic control is a problem-solving control system methodology. Fuzzy logic provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information. Thus, fuzzy control

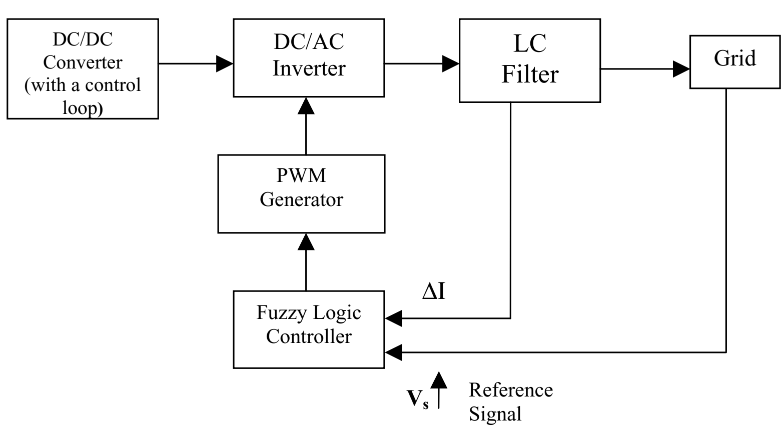

Fig. 7. Block diagram of dc/ac inverter control.

means a control law that is described by 'IF... THEN' rules with vague predicates and a fuzzy logic inference mechanism [17]. Some of the advantages of the FLC may be enumerated as follows [17,18]:

- FLC provide systematic efficient framework for incorporating linguistic fuzzy information form human experts.
- Easy to understand and simplifies design complexity; thus, simple, fast to implement and cost effective.
- Because of the rule-based operation, any reasonable number of inputs can be processed and numerous outputs generated.
- Fuzzy control is a model-free approach and provides non-linear controllers.

Fig. 8 shows the structure of the FLC.

The FLC is designed in the following sections for the dc/dc converter and the dc/ac inverter. The functions, inputs and the rule base of these two controllers are entirely different. With the two FLC strategies the FC may be used for the stand alone working or for the grid connection of the FC to source power into the grid.

6.1. FLC for the dc/dc converter (FLC-1)

In this section, the FLC for the dc/dc converter is designed. The inputs to the FLC are decided and the output obtained is the change in the control signal. The control signal is conditioned by a PWM generator which generates the pulses and these are fed to the dc/dc converter which generates the desired average voltage for the inverter stage.

The rule base of the FLC for the dc/dc converter is based upon the Mac-Vicar Whelan rule base [8,17]. The actual voltage at the dc/dc converter and the reference voltage are compared and the error generated is one of the inputs for the FLC; the change in the error (the derivative or the change with respect to time) derived from the error is the other input. The FLC based upon these inputs and the fuzzy rules generate the desired control signal for the system and control the unregulated voltage coming from the FC to a regulated dc voltage with a fixed average value. Thus, inputs to the FLC are the error, $e(k)$, and change in error $de(k)$. The controller output which is change in the control signal is the change in the duty ratio. The duty ratio change is fed to the PWM generator, which adjusts the duty ratio of the

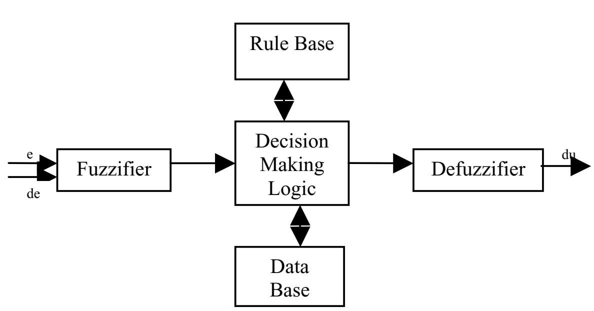

Fig. 8. Fuzzy logic controller.

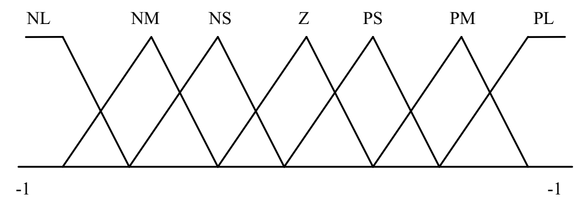

Fig. 9. Membership functions for 'error', 'change in error' and 'change in duty ratio'.

boost converter by feeding the pulses to the switches of the boost converter and accordingly adjusts the output dc voltage of the converter [8]. The error and the change in error are:

$$e(k) = V_{\text{ref}} - V_{\text{out}} \tag{9a}$$

$$de(k) = \frac{(e(k) - e(k-1))}{T} \tag{9b}$$

where T is the sampling time, $e(k)$ is the error, $de(k)$ is the change in error, V_{ref} is the reference dc voltage, V_{out} is voltage at the terminals of the converter

The three variables of FLC, error, change in error and change in the control signal, have seven membership functions each. The fuzzy partition of membership functions for error, change of error and change of control action are as shown in Fig. 9. The fuzzy variables are expressed by linguistic variables 'positive large (PL)', 'positive medium (PM)', 'positive small (PS)', 'zero (Z)', 'negative small (NS)', 'negative medium (NM)', 'negative large (NL)'. The linguistic denominations for membership functions are same for all the three variables. Table 1 shows the rule base for the FLC. A rule in the rule base can be expressed in the form: If (*e* is NL) and (*de* is NL), then (change in duty ratio is NL).

The rule base used is the Mac-Vicar Whelan rule base as shown in the Table 1 as a starting point with some modifications. This is the general rule base used when the characteristics of the system are not known. The number of rules can be set as desired. The numbers of rules set for the dc/dc converter control are 49 as there are seven linguistic variables each for the membership functions of error and change in error (inputs of the FLC).

The inference method used is basic and simple, and is developed from minimum operation function rule as a fuzzy

Table 1

Error	Rate of change of error						
	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NM	NS	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PS	PM	PL
PM	NS	Z	PS	PM	PM	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

implementing function. The commonly used MIN–MAX method is implemented. The output membership function of each rule is given by minimum (MIN) operator, whereas combined fuzzy output is given by maximum (MAX) operator. Defuzzification is done using the centroid or center of area (COA) method to generate the crisp control signal to change the duty ratio of the dc/dc converter [17].

6.2. FLC for the dc/ac inverter (FLC-2)

In this section, the FLC for dc/ac inverter is designed. The inputs to the FLC are decided and the output obtained is change in the control signal. The control signal is conditioned and given to dc/ac inverter, which generates the desired current wave form for interfacing the FC with the utility grid.

The source voltage or the utility voltage (the grid voltage) is used as one of the inputs for the FLC; the other input is current change over the period smaller than T_S (the sampling time) obtained from the current generated at the terminals of the dc/ac inverter. These inputs based upon the fuzzy rules generate the desired control signal to control the current output of the dc/ac inverter to a sinusoidal current of desired frequency for interface of the FC with the grid. Thus, inputs to the FLC are the source voltage V_s and the inverter output current change ΔI. The FLC output or control signal is the change in the duty ratio fed to the PWM generator to generate pulses for the switches of the bridge inverter. The duty ratio change is then fed to the inverter, which accordingly adjusts the output current [14,15]. The source voltage and change in current for the inverter are:

$$V_s - \text{source voltage} \quad (10a)$$

$$\Delta I = I(t_n + T_S) - I(t_n) = \frac{V_s(t_n) - V_{inv}(t_n)}{L} T_S \quad (10b)$$

where T_S is the sampling time, L is the inductor of the LC filter, t_n is the time at the beginning of $T_{S,}$ and V_{inv} is voltage at the terminals of the inverter

The three variables of the FLC, the source voltage, the change in inverter output current and the control signal, have seven membership functions each. The basic fuzzy partitions of membership functions for the variables are as shown in the Figs. 10 and 11. The fuzzy variables are expressed by linguistic variables ‘positive large (PL)’, ‘positive medium (PM)’, ‘positive small (PS)’, ‘zero (Z)’, ‘negative small (NS)’, ‘negative medium (NM)’, ‘negative large (NL)’, for the source voltage and the current change. The duty ratio is expressed by the fuzzy variables ‘D0’ to ‘D6’. Table 2 shows the rule base for the FLC. A rule in the rule base can be expressed in the form: If (V_s is NL) and (ΔI is NL), then (change in duty ratio is NL). The rules are set based upon the knowledge of the system and the working of the system. The rule base adjusts the duty ratio for the PWM of the inverter based upon the changes in the input to the FLC. The number of rules can be set as desired. The numbers of rules are 49 based upon the seven membership functions for the source voltage and the change in inverter current (inputs of the FLC).

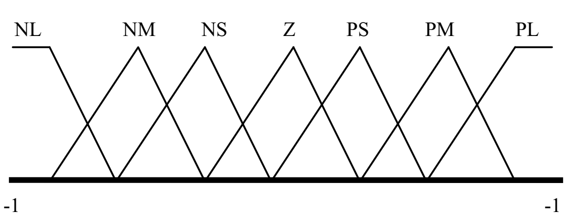

Fig. 10. Membership function for ‘source voltage’ and ‘current change’.

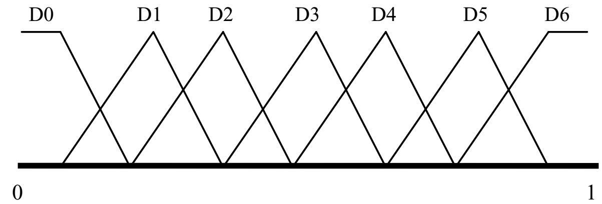

Fig. 11. Membership function for ‘duty ratio’.

The inference method used is developed from minimum operation function rule as a fuzzy implementing function. The commonly used MIN–MAX method is implemented. Defuzzification is done using centroid or center of area (COA) method to generate crisp control signal for change in duty ratio of the PWM switching of dc/ac inverter [17].

7. Simulation results

7.1. dc/dc converter control

Output voltage at the terminals of the dc/dc boost converter is controlled to be constant average value by using an FLC. The output voltage of the FC is an unregulated voltage of 60 V dc. This unregulated voltage is controlled and boosted to an average value of 120 V with the help of a dc/dc boost converter and an FLC. Two cases are considered for the change in the load at the terminals of the dc/dc converter, which will lead to the change in voltage. The change in the output voltage may occur in the input fuel flow of the FC or due to inherent characteristics of the FC.

Table 2

Current change	Source voltage						
	NL	NM	NS	Z	PS	PM	PL
NL	D0	D0	D0	D0	D1	D2	D3
NM	D0	D0	D0	D1	D2	D3	D4
NS	D0	D1	D2	D2	D3	D4	D5
Z	D0	D1	D2	D3	D4	D5	D6
PS	D1	D2	D3	D4	D4	D5	D6
PM	D2	D3	D4	D5	D5	D6	D6
PL	D3	D4	D5	D6	D6	D6	D6

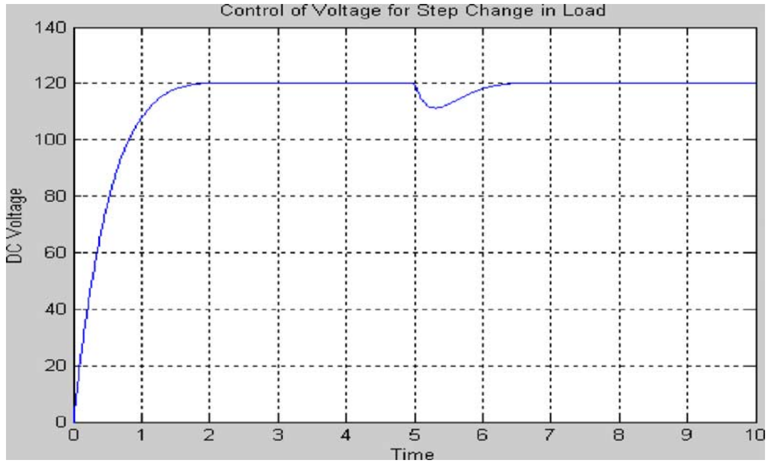

Fig. 12. Average output voltage of dc/dc converter for step change in load.

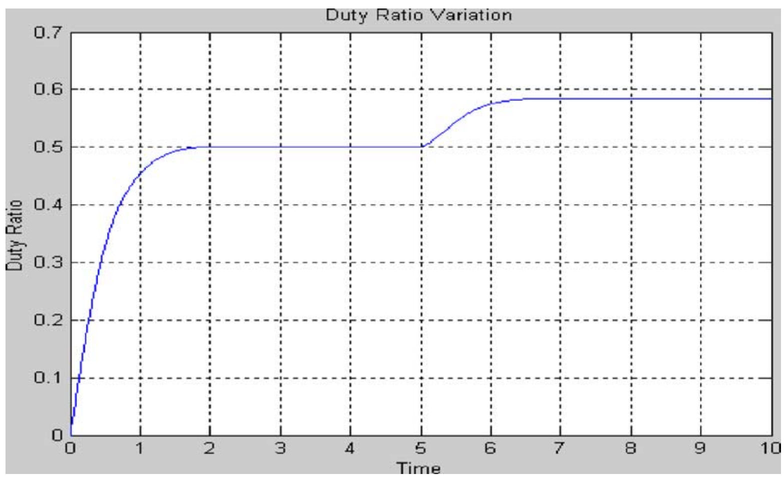

Fig. 13. Duty ratio of dc/dc converter for step change in load.

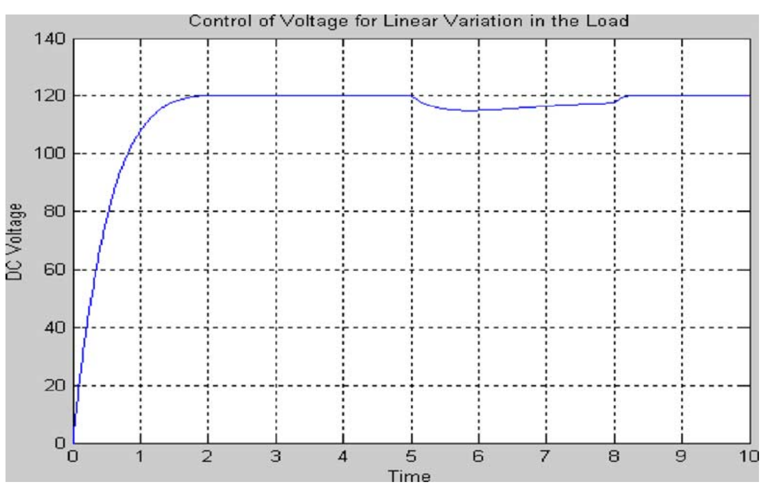

Fig. 14. Average output voltage of dc/dc converter for linear variation in load.

7.1.1. Step change in the load

As shown in Fig. 12 when the load experiences a step increase the output voltage is maintained to its average value. This is achieved by controlling the duty ratio of the boost converter. Since the response time of the boost converter is very fast, the output voltage recovers steady state quickly and the voltage that experienced a step change is brought back to 120 V. Fig. 13 shows the change in the duty ratio generated by the PWM from 0.5 to 0.58. It is clearly seen that the duty ratio of the boost converter is increased in order

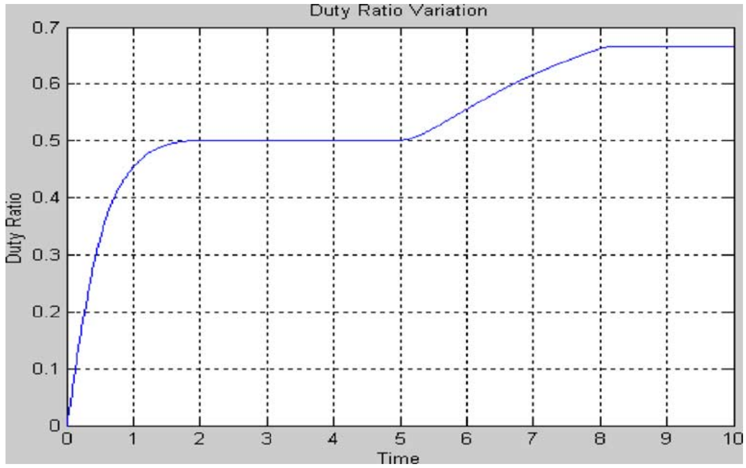

Fig. 15. Duty ratio of dc/dc converter for linear variation in load.

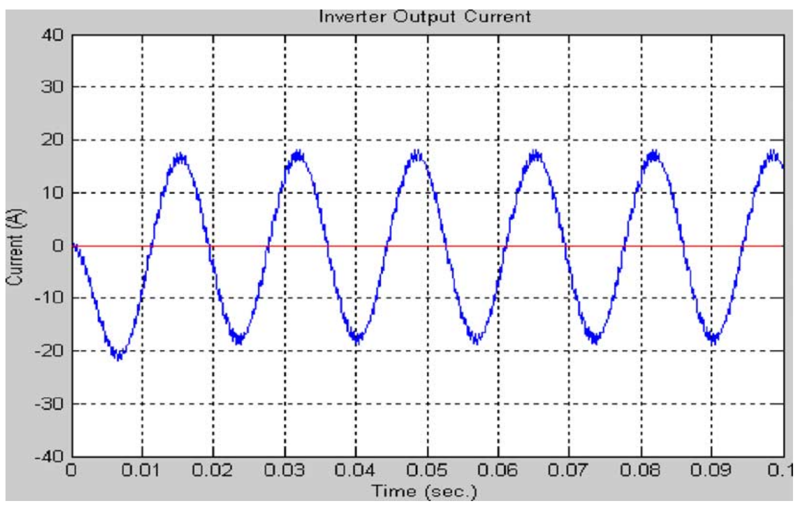

Fig. 16. Output current of dc/ac inverter.

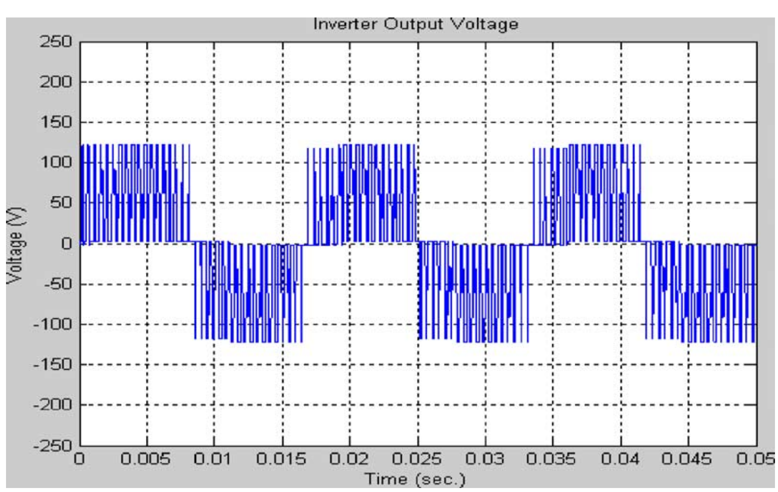

Fig. 17. Output voltage of dc/ac inverter.

to compensate for the loss of voltage due to change in the load.

7.1.2. Linear variation in the load

As shown in Fig. 14, even when the load experiences a linear change, output voltage is maintained to its average value of 120 V. The FLC is efficient in controlling the output voltage of the boost converter and brings it back quickly to its desired value. The change in the duty ratio from the original value of 0.5–0.66 is shown in Fig. 15. The FLC responds to the change in the voltage due to the load change and changes the duty ratio of the switch of the dc/dc converter to a value so that the converter provides the desired voltage.

7.2. dc/ac inverter control

Fig. 16 shows the peak value of output current of inverter after the inverter is controlled with the FLC. The output inverter current is a sinusoidal with very less distortion and the frequency of 60 Hz as desired to interface the fuel cell to the utility grid. The voltage wave form of the inverter is shown in Fig. 17. The harmonics in the voltage need to be filtered in order to obtain a purely sinusoidal voltage at the terminals of the inverter of the FC system.

The results are obtained by performing the simulations in the MATLAB/SIMULINK environment. The block diagrams in Sections 5 and 6 (Figs. 5 and 7) were simulated using the simulink toolbox, fuzzy logic toolbox and power system blockset to obtain the results presented in this section.

8. Conclusions and discussion

8.1. Fuzzy logic for dc/dc converter

The output of the FC generation system has a high voltage fluctuation rate in response to the load variations. The output voltage of the FC changes with the change in load or change in the fuel input of FC. The FC produces an unregulated voltage due to its internal dynamics (inherent properties) as well. An FLC is used to control the average output voltage of the converter by controlling the duty ratio to keep the voltage at a desired value.

The FLC acts to any changes (fluctuations) in the desired average value of boost converter. The voltage responses indicate the efficiency of FLC. The FLC is quick to act and accurately brings back voltage to the desired average value with zero steady-state error and small response time. The FLC is used to overcome inherent disadvantages such as uncontrollable large overshoot. The FLC offers high system stability and performance.

8.2. Fuzzy logic for dc/ac inverter

The FC is connected to the grid through dc/ac inverter. In order to incorporate the FC into the grid, output current of the dc/ac inverter is a sinusoidal current with frequency of the utility grid. The sinusoidal current is achieved with the FLC. FLC for the inverter uses the predicted current control strategy to control the output current of the inverter. The output of the inverter depends upon the pulses fed to the switches of the inverter. In order to generate a desired current wave form from the inverter, PWM generator is controlled. The PWM generator feeds the switches with pulses, which generate a proper duty ratio. Analysis of the predicted current control method using fuzzy logic control is provided. Thus, for grid-connected FC systems the control of a single-phase full-bridge inverter without transformer has been presented.

The implementation of FLC is easier and cost effective, since the FLC requires less complex mathematical operations than classical controllers; its implementation does not require a computationally sophisticated microcontroller.

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