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A Hybrid AC/DC Microgrid with Multi-Bus DC Sub-Grid Optimal Operation

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Abstract: In this research work economic operation of power system and its incremental cost management has been maintained through identical distributed generation. At first, configuration of Hybrid (Alternating current/direct current) AC/DC Micro grid (MG)DC sub-grid (SG) is designed and then a droop control method based on incremental cost is implemented for synchronization of sub-grid's DC bus voltage & AC bus frequency to equalize incremental cost. However, droop method causes deviations in dc bus voltages and AC bus fervency. Secondly, distributed fuzzy logic control architecture with incremental cost-based droops is proposed and implemented which allows uncertainly distributed generations communicate with their neighbor ones thus reducing communication weights and enhances the uncertain system performance. Due to existence of fuzzy logic controller in proposed architecture the transient behavior of the system voltage and frequency is reduced and reaches to steady state in minimal time. Moreover, the incremental cost of all distributed generations is equalized. To show the efficiency of planned control strategy using a platform called MATLAB/Simulink to verify results.

Keywords: *Economic operation, DG (Distributed Generation), Incremental Cost (IC)based droop, Multi-Bus System (MBS).*

1. Introduction:

The latest report of Indian government on climate change has painted a dire picture of earth and mankind's future global warming. It will be impossible to keep it minimal unless greenhouse gas emissions are quickly and drastically reduced. The solution to the problem is large scale usage of renewables for electricity generation to meet the world's largest energy crisis. To integrate huge renewables into system, the only way is distribution generation (DG). The affective way to take advantage of a greater number of DGs is microgrids [1]. Configurations such as DC micro grids and AC networks have been created in the last several years. Hybrid AC/DC MGs are developed to combine the advantages of both (Alternate current & distribute current) AC& DC MG's and also to avoid the multiple conversions [2]. Power converters play a major role and forms as a bridging unit in distribution generation for power exchange [3]. Hybrid ac/dc MGs functioned as in grid linked mode and also in autonomous or islanded mode [4]. Much research has done in the area of operating challenges i.e power management strategies among power converters and DGs [5]. At present, more attention on economic operation of microgrid is also required.

Generally, for working of Hybrid AC/DC MG's autonomously, the general two control methods considered are master/slave method [6] and peer to peer control method [7]. In case of master/slave method, a reference DG acts as master and coordinates all the remaining DGs for balanced power flow. Whereas peer to peer control method also adopts same strategy for power balance but uses droop method for frequency and voltage restoration i.e control of real and reactive power. In past, many researchers worked on economic operation strategies and proposed different iterative methods such as a Linear programming based method [8] to linearized the non-linear cost equation which is computationally expensive as well as unreliable, a Lagrangian Relaxation method [9] by decomposing large problem to few sub problems for easy solving and to obtain optimal solution, (Fast Newton Raphson Method)FNRM [10] using a Quadratic Programming approach to incorporate flow constraints and emissions costs by changing the Jacobian matrix at each step [11] formulated Objective operation based on unit expenditure curve for optimal solution, a genetic algorithm equipped with multiplier updating [12] for efficient searching and explored the solutions actively, and new self-organizing particle swarm optimization method [13] to handle premature convergence problems assuming no convexity for optimal solution. All these optimization methods are accurate and controllable but suffer from single point failure issues with high communication and computational burdens.

To compensate difficulties faced using centralized economic dispatch schemes, decentralized methods without communication network are rigorously studied to obtain the solution of economic dispatch problems. In [14] a cost prioritized droop scheme is implemented, where the DGs with high operating cost are turned off during light load conditions. Self-optimizing control technique for balanced load sharing based on the notion of equal incremental cost is presented in [15], however it does not implement the plug-and-play properties. Droop techniques based on incremental cost are

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used in [16]-[18] in a completely decentralized manner to avoid the aforementioned problem. But the common drawback faced using decentralized methods is voltage and frequency cannot be restored properly after sudden load change occurred in the system.

Overcoming the shortcomings experienced by centralized and decentralized methods, the research moved towards the distributed methods and is much preferred for better scalability with less communication burden. Generally, most of the distributed methods are presented in [19]-[21] and are customized to individual either AC microgrid or DC microgrid. Implementing the concept of distributed control to Hybrid AC/DC MG's, a generalized DG control using conventional PI controller based on incremental cost (IC) droop is reported in [22] [23] for Voltage of DC (Direct current) bus &frequency of AC(Alternating current) bus restoration. Considering same concept and to fill the research gaps, a distributed control using Fuzzy Logic Controller is proposed and implemented to a Hybrid AC/DC MG's configured with multi-DC bus for global economic operation [24][25]. The following is a breakdown of the structure of the document. As an introduction, Section I summarises the researchers' prior work, including any unanswered questions. A short description of a hybrid AC/DC MG's setup with several DC sub grids is provided in Section II. Section III presents the suggested disseminated control architecture using fuzzy logic controller and, Section IV presents the results followed by conclusions in Section V.

2. Configuration of Hybrid AC/DC MG's with Multi-DC Bus Sub Grid (SG):

An AC/DC hybrid motor generator with numerous DC motors is seen in Figure 1.One Alternating Current(AC) subgrid and one Direct Current(DC) subgrid with three DC buses make up this system. The bus voltages for three DC buses are 700V, 380V and 1000V respectively. To interlink all the subgrids Bidirectional Inter-Allied Converter (BIAC) plays a major role for power interaction and acts as bridging unit. Three BIACS are required for the proposed configuration and are named as BIAC1, BIAC2 and BIAC3 respectively which were operated in power control mode. BIAC1 acts as a bridging unit for DC subgrid 1 AC subgrid, BIAC2 and BIAC3 connect DC subgrids 2 and 3 to DC subgrid 1, respectively, so that they may communicate with one another. The local loads of individual subgrids are represented as P_{LDC1}, P_{LDC2}, P_{LDC3}, and P_{LAC}.

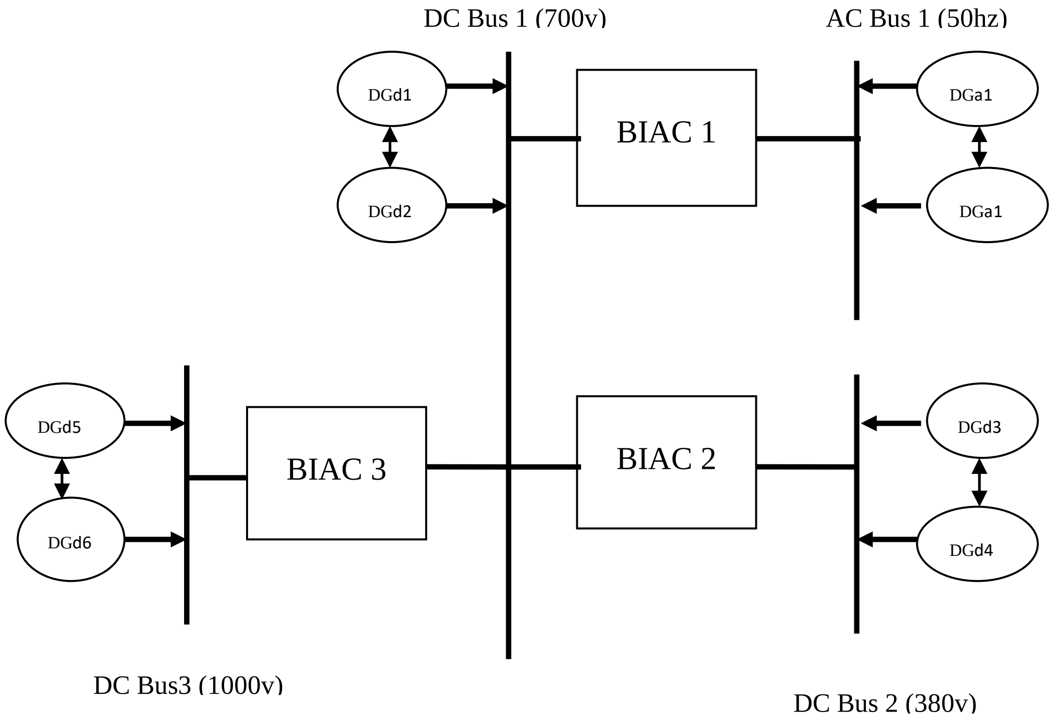

Figure.1 Proposed system (Hybrid AC/DC MG's with multi-Dc buses)

In traditional power systems, operation cost of different DGs such as diesel generators, micro turbines and batteries etc, depends on fuel cost which relates to output power and many factors. Hence, the operational cost of i^{th} DG can be represented in the form of quadratic equation i.e

$$C_{DGi} = \frac{1}{2} a_i P_{DGi}^2 + b_i P_{DGi} + C_i \quad (\$/hr) \qquad (1)$$

ai, bi, and ci are the cost coefficients.

For economic operation of system, consider the total load is supplied by two DG's with unequal IC costs. Then the DG with high IC cost transfers the load continuously to the DG with low IC cost until the DGs with equal IC cost. The same principle is extended to 'N' number of DG's, where the cost of operation of hybrid AC/DCMG multiple with DC bus is

$$C_T = C_{DG1} + C_{DG2} + \dots\dots\dots\dots + C_{DGN} = \sum_{i=1}^{N} C_{DGi} \qquad (2)$$

The 'N' number of DG's present in the Hybrid AC/DC MG's system supplies load; hence the total power is given by

$$P_{Load} = P_{DG1} + P_{DG2} + \dots\dots\dots\dots + P_{DGN} = \sum_{i=1}^{N} P_{DGi} \qquad (3)$$

Hybrid AC/DC MGs with multi-bus DC may be derived from the goal function, "Economic Performance."

Min $C_T = \sum_{i=1}^{N} C_{DGi}$;

Subjected to; $P_{Load} = \sum_{i=1}^{N} P_{DGi}$;

$$P_{DGi,\min} \leq P_{DGi} \leq P_{DGi,\max} \qquad (4)$$

The necessary and sufficient condition for minimal operation of the system with certain limitations of P_{DGi} is determination of incremental operation cost. Thus, the IC of any DG can be attained by differentiating equation (1) and equate to some indefinite value i.e Lagrangian Multiplier λ, then

$$IC_{DGi} = \lambda = \frac{dC_{DGi}}{dP_{DGi}} = a_i P_{DGi} + b_i \qquad (5)$$

In long-established droop method, voltage of DC bus and frequency of AC bus can be synchronized by fine-tuning the output active power. But the output power is always related to operating cost i.e IC for economic operation. Hence, the expressions for f_{ac} and V_{dc} based on IC values are represented in equation (6) & (7).

$$f_{ac} = f_{ac\max} - d_{ac} IC_{DGk} \text{ ; k}\epsilon\text{ [1, m]} \qquad (6)$$

$$V_{dc} = V_{dc\max} - d_{dc} IC_{DGl} \text{ ; l}\epsilon\text{ [1, n]} \qquad (7)$$

Where
$f_{ac\max}$ = Maximum frequency of AC bus.
$V_{dc\max}$ = Maximum voltage of DC bus.
d_{ac}, d_{dc} are AC subgrid droop co-effients& DC subgrid, and whose expressions were represented as

$$d_{ac} = \frac{f_{ac\max} - f_{ac\min}}{P_{ac\max}} \qquad (8)$$

$$d_{dc} = \frac{V_{dc\max} - V_{dc\min}}{P_{dc\max}} \qquad (9)$$

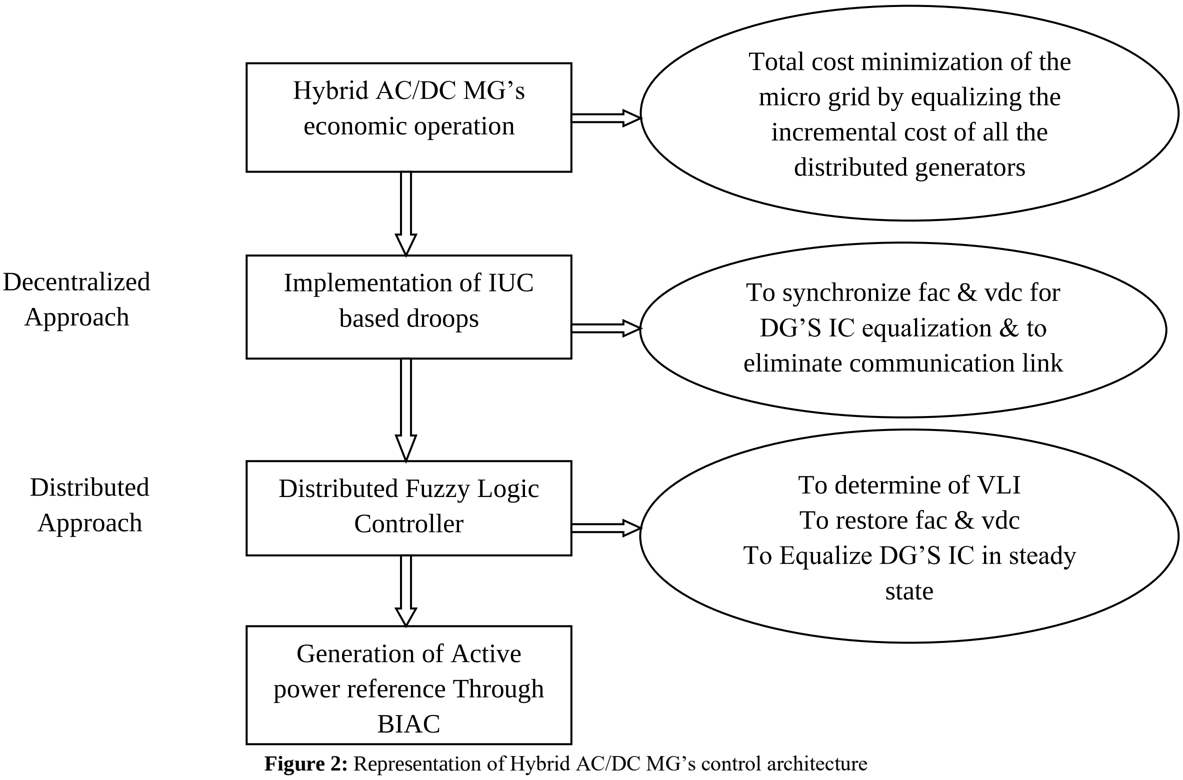

Figure 2: Representation of Hybrid AC/DC MG's control architecture

In steady state IC's of all DG's in individual subgrid are same i.e
In case of AC subgrid,

$$IC_1 = \ldots\ldots\ldots\ldots = IC_K = \ldots\ldots\ldots\ldots = IC_m \qquad (10)$$

Similarly, in case of DC subgrid

$$IC_1 = \ldots\ldots\ldots\ldots = IC_l = \ldots\ldots\ldots\ldots = IC_n \qquad (11)$$

Equation (6) to (11), represents decentralized approach i.e independent of communication link. But due to transient behavior of f_{ac} and V_{dc} caused by droops distributed approach is much preferred. For restoration of f_{ac} and V_{dc}, a distributed fuzzy logic controller (DFLC) is proposed.

The representation of proposed distributed approach for economic performance of Hybrid ac/dc MG's multiple with DC bus is shown in figure 2.ThisHybrid ac/dc MG's device architecture consists of both Decentralized Approach & Distributed Approach to to eliminate incremental costs of the proposed system.

3. Proposed Uncertain Distributed Fuzzy Logic Control Architecture

At first a decentralized approach without communication link for synchronization of f_{ac} and V_{dc} usingIC based droops is implemented. But it is renowned that, droops causeinstability in f_{ac} and V_{dc}. To determine the hidden loading condition for f_{ac} and V_{dc} restoration, aconstraint called virtual loading index (VLI) is established in the proposed work. For easy analysis, f_{ac} and V_{dc} are represented as a single variable 'y'. To normalize 'y' to nominal value yn, the compensating value Δy is generated. Now, fluctuation in y represents the loading condition of the microgrid. Therefore the original value of VLI is given by

$$VLI(y)=\frac{y-y_n'}{\delta y};\quad y_n'=y_n+\Delta y \tag{12}$$

Where $y_n=(y_{\max}+y_{\min})/2$ and $\delta_y=(y_{\max}-y_{\min})/2$, which is a constant and it denotes the deviation from y to yn.

To determine the compensating value Δy, VLI is calculated and which helps to schedule the power in BIACs until the value of VLI of both the subgrids AC and DC becomes equal.

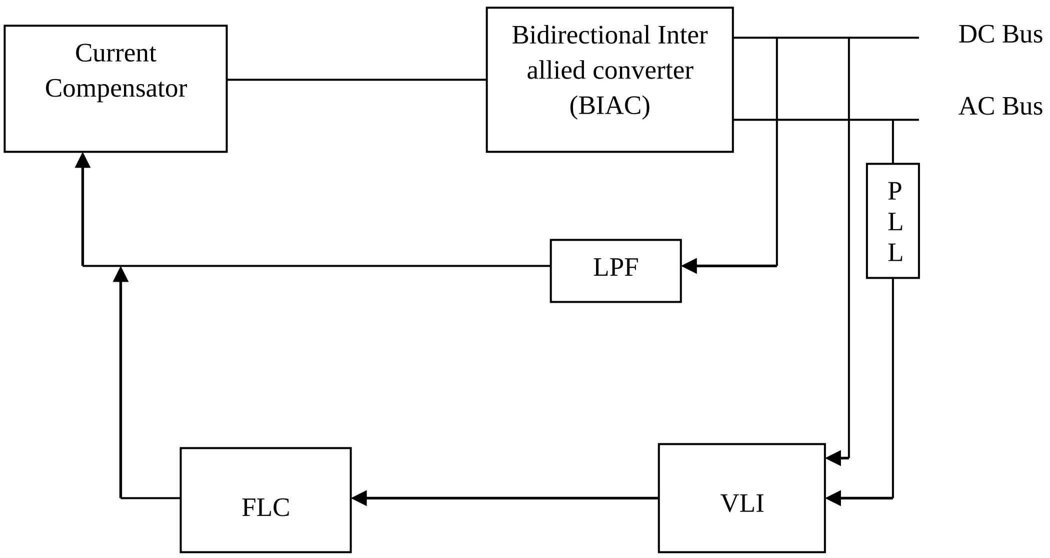

Figure. 3 Proposed distributed architecture for BIAC using fuzzy logic controller

The variation of VLI (f_{ac}) and VLI (V_{dc}) is processed by DFLC which generates reference value of active power for Bidirectional Inter allied converter (BIAC) with Fuzzy Logic Controller (FLC) shown in figure.3.

The mechanism objectives of proposed distributed architecture using FLC are

1) To regulate the DG output power in such a manner that the IC's of all the DG's must be equal and
2) To ensure the plug-and-play property for normal operation of the system.

Responding to the above two control objectives a distributed fuzzy logic controller with sugeno fuzzy inference system is proposed& represented below. Regulation of DG's power output depends on the loading conditions of both the subgrids. Hence, the difference in loading conditions of the subgrids is error in loading condition (eLC). Therefore, eLC and rate of change of eLC (ΔeLC) are 2 inputs to the FLC &power as outcome.

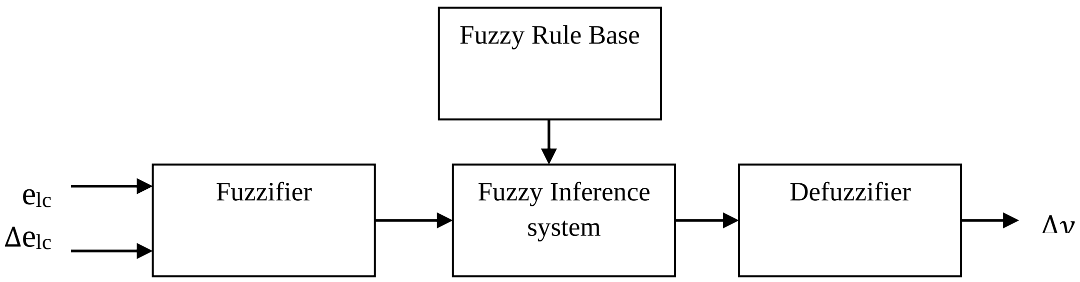

Figure. 4 FLC Block diagram

After proper identification of fuzzy variables confined with economical operation problem of hybrid ac/dc MG, the fuzzy sets were selected and are normalized between certain limits to define these variables. With reference to the selected fuzzy sets, triangular membership functions for two input variables and its surface view are presented in Figure 5 and 6.

Figure 4 shows a distributed fuzzy logic controller with a sugeno fuzzy inference system that is designed to meet the aforementioned two control goals.

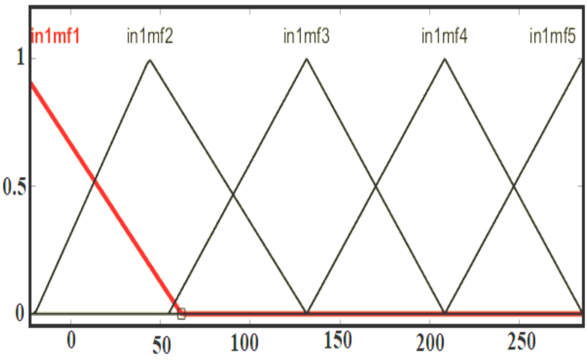

Figure 5. Triangular membership function of input variable to FLC

With consideration given to the chosen fuzzy sets, the triangle membership functions for two input variables as well as the surface view of the function are shown in figures 5 & 6 respectively.

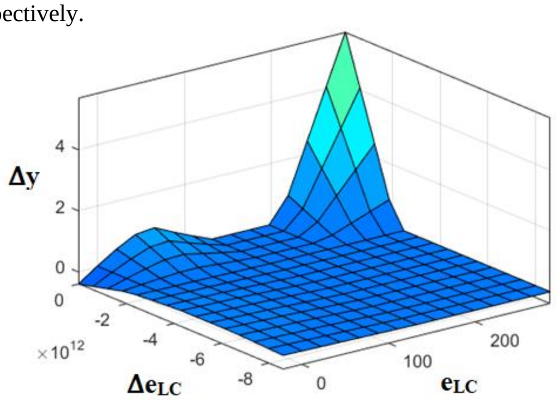

Figure 6 surface view fuzzy logic controllers with input and output

In the proposed work 25 if-then fuzzy rules are formed by relating input variables to output variable presented in Table 1 and There are four types of parameters: Negative Large (NL), Negative Small (NS), a value of Zero (ZR), & a value of positive small (PS) (PL). These are arranged based on their triangular membership functions using AND operator. Hence the fuzzy outputs of the inference system are de-fuzzified by using the most commonly used Centroid method.

Table 1 Fuzzy logic with input & output parameters

e_L / Δe_L	@NL	@NS	@ZR	@PS	@PL
@NL	@PS	@PS	@ZR	@ZR	@ZR
@NS	@PS	@PS	@ZR	@ZR	@ZR
@ZR	@PS	@PS	@ZR	@ZR	@ZR
@PS	@PS	@PS	@ZR	@ZR	@PL
@PL	@NL	@PS	@ZR	@ZR	@PL

The output of fuzzy logic controller generates power reference which helps to drive the converter circuit for proper power interchange through BIAC. The process continues until the existence of difference in VLI values of both the subgrids for IC value equalization.

4. Results

Matlab/Simulation is used to test the commercial functioning of a hybrid ac/dc microgrid with multi-bus DC subgrid, and the findings of recommended control architecture are validated. The system requirements for the proposed task are shown in Table 2.

Table 2 System specifications

Parameter	Description	Value
# V_{dc1}	DC Bus 1 Voltage	700V
# V_{dc2}	DC Bus 2 Voltage	380V
# V_{dc3}	DC Bus 3 Voltage	1000V
# f_{ac}	Frequency of AC bus	50Hz

For normal operation of the microgrid system the AC bus frequency should be maintained as 50Hz is plotted in Figure 7. Figure 8 depicts the voltage level on DC bus 1 being maintained at 700V despite rapid load fluctuations at various instants of time. Figure 9 and Figure 10 illustrate the voltage level on DC bus 2 and DC & 3 respectively, with 380V and 1000V, respectively.

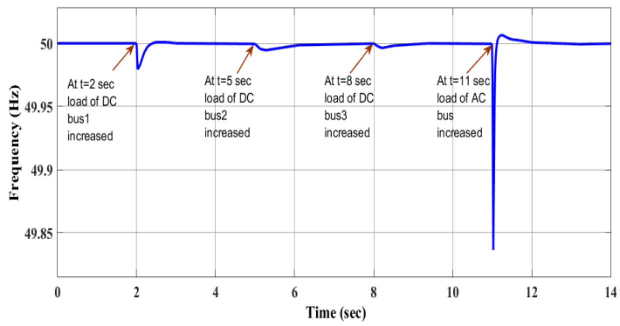

Figure.7 AC bus frequency of microgrid system

Figure 7 shows that the AC bus frequency has to be kept at 50 hertz in order to ensure that the microgrid system operates properly.

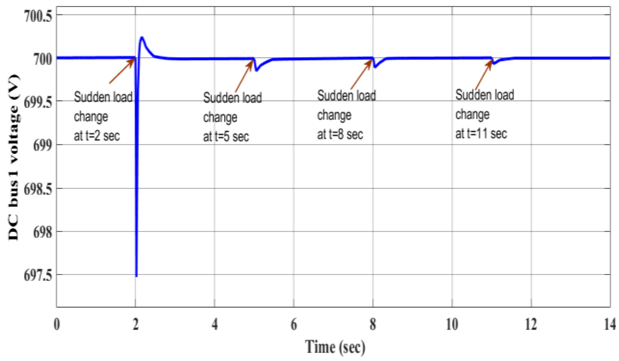

Figure. 8 Voltage level of DC bus 1

Figure 8 shows that the voltage level on DC bus 1 is maintained at 700V despite rapid fluctuations in the load at various points in time.

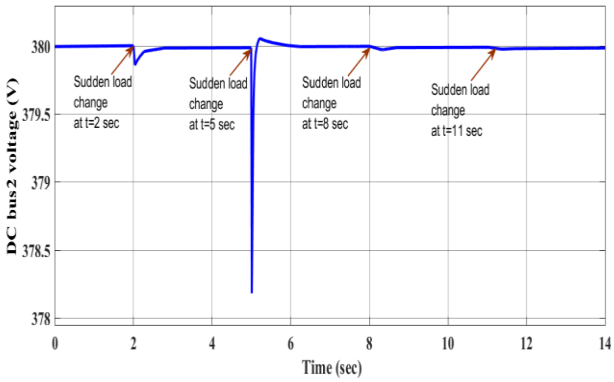

Figure. 9 DC bus 2 Voltage level

Figure 9 shows that the voltage level on DC bus 2 is maintained at 380V despite rapid fluctuations in the load at various points in time.

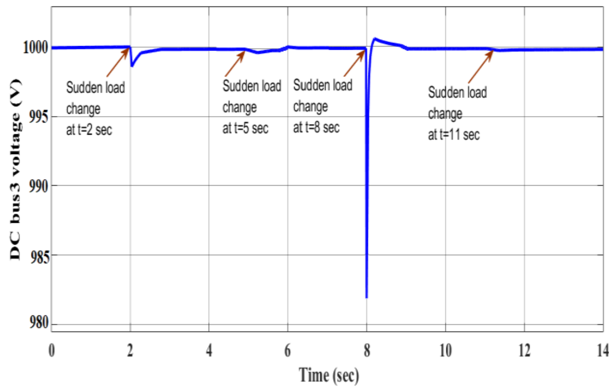

Figure.10 DC Bus 3 Voltage level

Figure.10 shows the voltage level on DC bus 3 is maintained at 1000V despite rapid fluctuations in the load at various points in time.

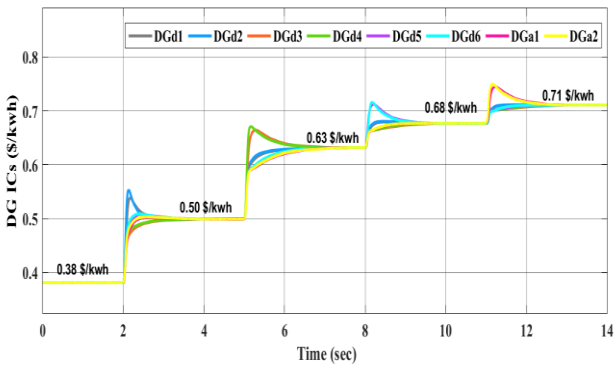

Figure.11 IC values of all DG's in Hybrid ac/dc microgrid configured with uncertainmultiple DC bus

Figure.11 shows the IC values of all DG's. From t=0 to 2sec IC values of all DG's present in the hybrid microgrid read as0.38 $/kwh. As the load increases gradually at different instants of time i.e at t=5sec, 8sec, and 11sec the DG's IC values read as 00.50 $/kwh, 00.64$/kwh, 00.68$/kwh and 00.71$/kwh by maintaining IC value equalization.

5. Conclusions

This paper presents theuncertainIC droop based distributed control structure using fuzzy logic controller for the working principle of Hybrid AC/DC MG's with multi DC bus system economically. The distributed control structure implements IC droops to maintain steady state voltage of all DC buses and AC bus systems. It is well known that droop schemes results frequency and voltage variations for sudden changes in load. Hence, a distributed control structure with fuzzy logic controller including the value of VLI is proposed and implemented to determine the unseen loading condition as well as to equalize the IC values of all the DGs even present in hybrid c/dc MG. Comparing the values of VLI of both the subgrids, power reference can be generated using fuzzy logic controller to drive BIAC. Proper scheduling of BIAC results identical IC values of all the DG's, which indicates the economical working principle of Hybrid AC/DC MG's. To improve overall stability of the system, impact of communication time delay is also considered in control structure of the MG's. Finally, MATLAB/Simulation results show viability and efficiency of proposed uncertain system work.

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