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A NOVEL METHOD OF CONTROLLER AREA NETWORK ASSISTED GRID SYNCHRONIZATION SCHEME FOR INTEGRATION OF RES AND ENERGY STORAGE USING FUZZY CONTROLLER

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ABSTRACT-
Micro-grid is a promising area that might provide a solid solution for more and more stress on the utility supply and transmission line. Generally micro-grid comprise of renewable energy sources such as photovoltaic (PV), wind, fuel cell (FC) stack etc., as micro-grid involves renewable energy sources which have a significantly different dynamic behavior, dissimilar generating capacities and disruptive effects such as voltage dips and fluctuations, frequency variation, and harmonic distortion are handled through centralized monitoring in conjunction with hierarchical control. This paper proposes a GS technique based on controller area network (CAN) communication. CAN is a robust fault tolerant multi host serial communication network capable of providing 1 Mb/s data rate. The proposed scheme is based on CAN communication between the microgrid master controller (MMC), local controllers (LC), load controller and grid synchronization system. The reliability and sustainability of the resulting complex micro-grid synchronization is ensured through the proposed reconfigurable control and power network of the micro-grid, supported by a comprising fuzzy controller area network.

Key Words: *Black-start, controller area network (CAN), grid synchronization (GS), island mode, microgrid, smart grid, fuzzy logic controller.*

I. INTRODUCTION

With the wider integration of Renewable Energy Sources (RES) to the power networks, especially in distribution levels, operational reliability and resilience of microgrids have attracted increasing interest for enhanced integration in future smart grid architectures of power systems [1]. The microgrids in distribution networks can be operated autonomously for a grid-connected or islanded mode to improve reliability and quality of power delivery [2]. In these microgrids, the RESs are either small-scale synchronous generators or converter-interfaced sources (e.g. PV, energy storage, wind, etc.) resulting in a small inertia of the network [3]. In addition, whereas the renewable energy resources are mostly intermittent in nature, it is assumable that the microgrid will require importing power from the main grid when the renewable resource and/or the synchronous generation are not sufficient for supplying and sustaining local loads. Under such circumstances, if an unintentional islanding event occurs, the local network will be at risk of experiencing significant frequency degradation in a short period of time with the added complexity of small inertia of the power system [4-6].

Converter interfaced DG units must be synchronized with the utility system. Grid synchronization is a challenging task especially when the utility signal is polluted with disturbances and harmonics or is of a distorted frequency [7]. A phase detecting technique provides a reference phase signal synchronized with the grid voltage that is required to control and meet the power quality standards [8]. This is critical in converter interfaced DG units where the synchronization scheme should provide a high degree of insensitivity to power system disturbances, unbalances, harmonics, voltage sags, and other types of pollutions that exist in the grid signal [9], [12]. In general, a good synchronization scheme must i) proficiently detect the phase angle of the utility signal, ii) Track the phase and frequency variations smoothly, and iii) forcefully reject disturbances and harmonics. These factors, together with the implementation simplicity and the cost are all important when examining the credibility of a synchronization scheme [13].

This paper a fuzzy logic controller based synchronization method is proposed for achieving the grid synchronization with controller area network (CAN) in terms of frequency, phase angle, amplitude of output voltages, active power and reactive power in between converter output and Distributed Energy Resource Converters (DERCs). The fuzzy logic controller is replaced by proportional integral (PI) controller for obtaining fast dynamic response, low steady error and for stable operation of the grid as explained in [14]-[15].

II. REVIEW OF GRID SYNCHRONIZATION TECHNIQUES

Fig.1 shows a typical power electronic interface between the microgrid and the main grid. In order to operate the microgrid in grid connected mode, it is required to close the static switch (STS). Prior to closing STS, the microgrid as a whole should operate in voltage mode control, controlling both amplitude and frequency of the voltage at the point of common coupling (PCC). In a typical microgrids scenario, multi loop control comprising a fast inner current loop and a slow outer voltage loop is adopted for microgrid power converters (MPC) [4]. The large bandwidth current loop regulates the current (and hence the power flow) while simultaneously providing the over current protection.

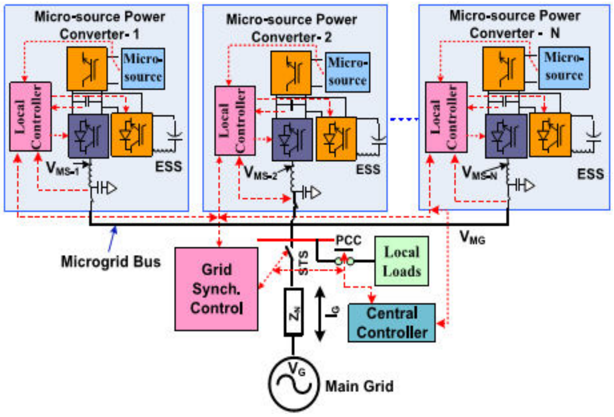

Fig.1. Schematic of a typical microgrid interface with the main grid

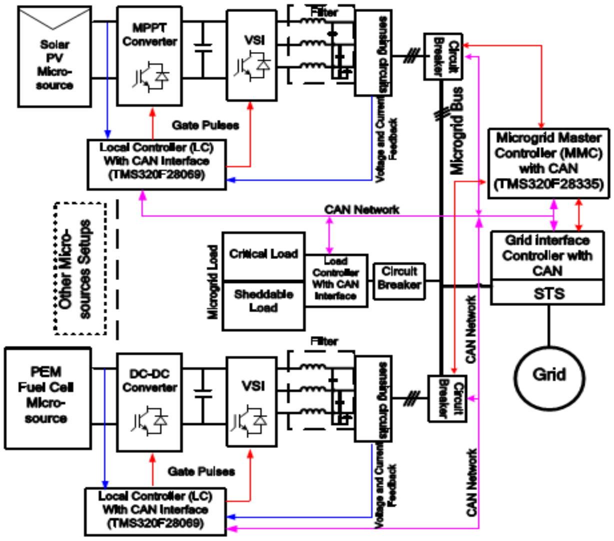

Fig.2. Microgrid configuration with CAN communication interfaces between MMC, LC, load controller and grid synchronizer

Fig.2.The figure shows the block diagram representation of the laboratory prototype microgrid based on MS like solar PV, proton exchange membrane fuel cell, wind turbine, etc. The MMC is responsible mainly for the

overall supervisory system monitoring and control.

In the microgrid scenario, the grid synchronization becomes essential under two operating conditions [13]–[29].

1. After the microgrid is energized (black-started) to operate in autonomous mode, it must get connected to the grid, once the stable grid is restored.
2. When microgrid gets intentionally islanded due to some transient or fault on the main grid, it needs to transit back to grid connected mode when the stable grid is restored.

Under both these conditions, the microgrid sources operate in such a way that both voltage and frequency are maintained with in permissible limits. As the MS are usually small (and with low or zero inertia) [1], [4] any rapid changes in operating conditions can lead to instability. It is generally expected that whenever the main grid restores or stabilizes, the microgrid should transit to grid connected mode in a seamless manner. The stiff main power grid enables the microgrid to retain stability under most operating conditions.

For the 3-φ VSI-based distributed generation system, the commonly investigated and implemented GS methods [4], [8], [28] can be broadly classified. The methods presented in suitable to be used to control one MS with VSI to achieve the grid synchronization. ZCD is a simple but low-quality grid voltage makes it an inconsistent and inaccurate method of GS. Most of the other methods require significant and complex calculations/transformations, which demand high speed digital signal processors (DSP) for implementation. This adds to the cost and complexity of implementation [4]. These methods primarily use the frequency and phase information of the sensed utility grid voltage vector. The problem arises when microgrids with multiple MS with different dynamical characteristics (e.g. solar PV, fuel cell, wind, etc.) need to be grid synchronized. The MS need to be synchronized with each other first to form the microgrid bus, and then this microgrid is synchronized and connected to the main grid.

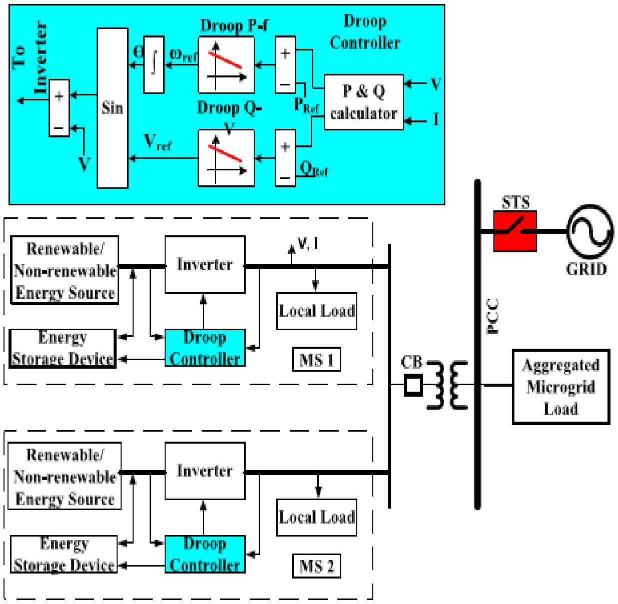

Fig.3. Droop controlled microgrid in islanded mode

In the microgrids with decentralized control without any supporting communication architecture, droop control is used during this situation where more than one MS is active and grid is not connected. Droop rates for all the sources are assumed to be different due to their dynamics and power rating capacities. Fig.3 shows an example of a microgrid with two sources supported by an energy storage system (ESS) for transient and steady state back up. The controllers used for both MS are based on droop control. The droop controller based on feedback of microgrid bus voltage and current (V/I) and the droop characteristics, decides the new operating condition interms of the angle ø (time integral of angular frequency ω) and Vref which is then used for generating the pulse width modulation (PWM) control signal for inverter. This is the classic droop control. Leeet al.[5] proposed GS scheme which facilitate multiple droop controlled power converters to provide the grid synchronized output voltage allowing grid connectivity with the help of low-bandwidth communication link. The droop control even though simple for implementation, it inherently lacks in providing accurate control and has poor dynamic response due to poor band width. In microgrids with centralized control supported with suitable communication architecture, the real and reactive power control during the island mode of operation is generally managed through the master–slave configuration. In such microgrids which are well equipped with high speed communication network, the communication assisted GS (CAGS) methods can be preferred.

They either use real-time grid voltage template acquisition or time synchronization mechanism for enabling the synchronization process. Any form of CAGS method uses one of the method or derived method out of one listed. In conventional CAGS, time synchronization of various microgrid resources is achieved, which further enables easy grid synchronization. The typically adopted mechanisms are high resolution timer, GPS timer, and NTP [11]. High resolution timer and GPS timer are expensive and hence result in increased system cost. They are also dependent on external commercial communication networks whose availability under certain situations is not guaranteed. NTP, on the other hand, performs poorly in wireless network due to unpredictable transmission delays. As sis and Taranto [29] have presented an automatic reconnection scheme for an intentionally islanded microgrid with two hydro generators.

The proposed scheme utilizes remote sensing of voltage with the help of communication system. Gallina et al. [27] proposed the power line communication (PLC) assisted microgrid synchronization. But PLC has a poor bandwidth which restricts its use in control implementations of microgrids. Takei et al. [11] have proposed a real-time Ethernet-based phasor monitoring system enabling different microgrid tasks including GS. There al-time Ethernet broadcasts the information about V/I phasors, and equipment status to all the nodes in a predictive manner at high speed. This time-deterministic transmitted information enables the realization of various protection and control applications in the microgrid scenario [12]. But security of such data within the communication network is a major concern. Zhang et al. [12] discussed the time synchronization attacks, mainly on GPS data, which forge the time stamp causing significant operational issues in control and protection system.

Chen et al. [30] presented a CAN-based control scheme for paralleling the single phase inverters with smooth mode transition scheme. The elegant work, however, limits itself to microgrids comprising of similar MS with single phase inverters with similar power capacities. The scheme is based on configuring one of the MS in voltage mode control and the rest in current mode control, which results in an increase in the mode transition time as simultaneous synchronization of loads and MS is not feasible. Cho et al. [31] proposed a communication network coordinated active synchronization control scheme for a microgrid.

The communication network with RS485 serial interface with proprietary Korea Electro technology Research Institute protocol was used for real-time communication. The presented scheme allows the microgrid bus synchronization under various operating conditions of the MS, while also accounting for the impact of the network delay on the synchronization process. However, this otherwise very useful paper, does not adequately address the requirement of a fast and optimized synchronization process which is essential for enhancing microgrid reliability. Lee et al. [32] described the use of CAN in dc microgrid control. Thale and Agarwal [33] have presented the use of the CAN communication for protection system of an ac microgrid.

Performance of all methods including CAGS methods presented is characterized by various factors. Implementation complexity, tracking accuracy of frequency and phase angle of the grid voltage, response time of the grid synchronization become critical factors to be taken into account. As a microgrid comprises of various different types of MS, which are dynamically very different in nature, synchronization of all the sources to the grid becomes a difficult task especially when they are sparsely located.

The proposed CAN CAGS (CCAGS) method offers significant advantages over the existing CAGS methods. CCAGS method enables the microgrid to carry out frequent grid synchronization, which is especially important under weak grid conditions. A robust and fault tolerant CAN communication being a much cheaper option compared to a network timer protocol or GPS system, it can be the preferred choice in a majority of centrally or hierarchically controlled microgrid installations, especially where MS are dispersed. The main contribution of the proposed research work can be summarized as below.

1. The proposed CCAGS scheme provides smooth transition of MS control from voltage mode to current mode control.
2. It minimizes the synchronization time while switching from islanded mode of operation to grid connected mode.
3. It facilitates three modes of grid synchronization:
   a) Simultaneous synchronization of all the MS with the main grid;
   b) Synchronization of all MS to form microgrid bus followed by main GS;
   c) Synchronizing one MS with main grid acting as a black-start generator followed by rest of the MS to synchronize in current mode control, which enables minimizing the total time required for the microgrid for mode transition.
4. It provides a simple and a low cost scheme for implementation of CAGS. The following sections provide details of this simple and novel grid synchronization scheme supported by analytical and hardware implementation details.

III. PROPOSED GRID SYNCHRONIZATION METHOD

As shown in Fig.2, the LCs corresponding to various MS, the MMC, the load controller, and the grid synchronizer are all interconnected with each other through a CAN bus.CAN is a message broadcast communication with nondestructive bus arbitration. CAN provides a robust communication due to its multi method error detection feature. In this paper, an isolated CAN bus used for the microgrid control operation is built around CAN trans-receiver ISO1050.The CAN data is broadcasted to all nodes simultaneously.

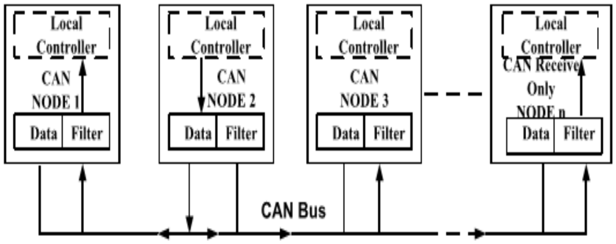

Fig.4. CAN nodes transmission and reception of data

Fig.4 shows how a CAN node can broadcast or receive the data to or from the CAN bus. All receiving nodes have the flexibility to accept or ignore the received message. This allows the grid synchronizer to make a data streaming available to all LCs. This feature is a big advantage that allows the scheme to facilitate simultaneous excitation of MS using the commonly received grid template from the grid synchronizer.

The detailed scheme of the proposed control and communication interface for the fuel cell MS is shown in Fig.5. Similar interface is available with other MS. To synchronize multiple MS with each other to form the microgrid bus and then to connect the same to the main grid, it is necessary that each of the MS acquires or receives the grid voltage template ata fast rate.

In the proposed scheme, the grid synchronizer block is designed to implement the synchronously rotating frame PLL (SRF-PLL) with capability to adopt unbalanced grid voltage and harmonic contamination. The instantaneous phase angle information of the grid voltage which is the output of the SRF-PLL and the voltage amplitude of the grid supply is communicated on the CAN network to all the LCs simultaneously.

In smaller networks, the network time delays are in significant and can be neglected. Hence, each of the LC is in a position to generate the reference grid voltage template to drive the VSI to get grid synchronized voltage output. The outer voltage control loop implementation makes sure to maintain the operating voltage same for each of the MS. Thus the voltage, frequency, and phase synchronized MS are ready to be connected with the grid. The grid synchronizer block continues data broadcasting on CAN bus during the synchronization process, thus enabling each of the sources to accurately track the grid voltage and phase changes. The communication interface designed with the CAN plays a vital role in switching the control between standalone and grid connected modes, allowing smooth synchronization as well as islanding of the microgrid.

The flowchart for CAN-based GS method is shown in Fig.6.The control loop is designed in such a way that it allows each MS to get energized in voltage mode control to operate in standalone mode but synchronized with grid voltage, based on information received through CAN communication from grid synchronizer. The load controller ensures the balance between the generated power and the load on the microgrid bus, there by maintaining the stability of the system during islanded mode of operation.

After closing STS, on receiving confirmed message from the CAN interface, it is switched over to current control mode allowing export or import of the power to or from the main grid. This allows easy GS of all the MS, minimizing the time required for GS of the microgrid. To understand the proposed control scheme with SRF-PLL and its modeling, basic details are provided next. The proposed control scheme implementation allows the MS power to be modulated by VSI to regulate the microgrid bus voltage and frequency (v, f) during standalone mode of operation, which exists between the formation of the microgrid bus and its synchronization with the main grid. In the grid connected mode, the real and reactive power (P, Q) is controlled.Fig.7 shows the equivalent circuit of a MS interconnected with the main grid through a power conditioning unit followed by an LC filter. Here the MS is represented as a controlled current source, I (ms) which supplies the real power Pms into the dc link capacitor at voltage V_{DC}. LC filter comprising L_{fl}-C_{fl} is used to filter out the high frequency switching components and microgrid line inductance (Lmg) is neglected being very small [30].

The local controller senses the VSI side and MG bus side parameters like i_{abc}, v_{abc}_MS, iabc-MS, V_{DC}, etc., to modulate the VSI to control the real power P, reactive power Q or microgrid bus voltage and frequency depending on the operational mode. Synchronously rotating reference frame transformation is used to realize the VSI control. Model of VSI can then be expressed as [30]

$$L_{fl}\frac{di_d}{dt} = -r_l i_d + L_{fl}\omega i_q + e_d - v_d$$

$$L_{fl}\frac{di_q}{dt} = -L_{fl}\omega i_d - r_l i_q + e_q - v_q \quad (1)$$

Wher ei$_d$, i$_q$, v$_d$, vq and ed, eq are the transformed variables of voltages and currents. Fig.8 shows the block diagram of the VSIs inner current control strategy for PQ control while microgrid is in grid connected mode.

The transfer function of the inner current control loop of the VSI is given by

$$G_{ims}(s) = \frac{I_d(s)}{U_d(s)} = \frac{I_q(s)}{U_q(s)} = \frac{1}{L_{fl}s + r_l} \quad (2)$$

Where modulation indices, m$_{dms}$ and m$_{qms}$ are derived from the new set of variables u$_d$ and u$_q$ as

$$m_{dms} = \frac{2}{v_{DC}}(u_d - L_{fl}\omega_o\, i_q + v_d)$$
$$m_{qms} = \frac{2}{v_{DC}}(u_q + L_{fl}\omega_o\, i_d + v_q) \quad (3)$$

Where ωo is the micro grid's angular frequency. Transfer function (2) consists of a pole at s=−rl/L$_{fl}$. PI controller with a zero, GCi [= (Kps + Ki)/s] is used with Ki/Kp =rl/Lfl to cancel out this pole [34].

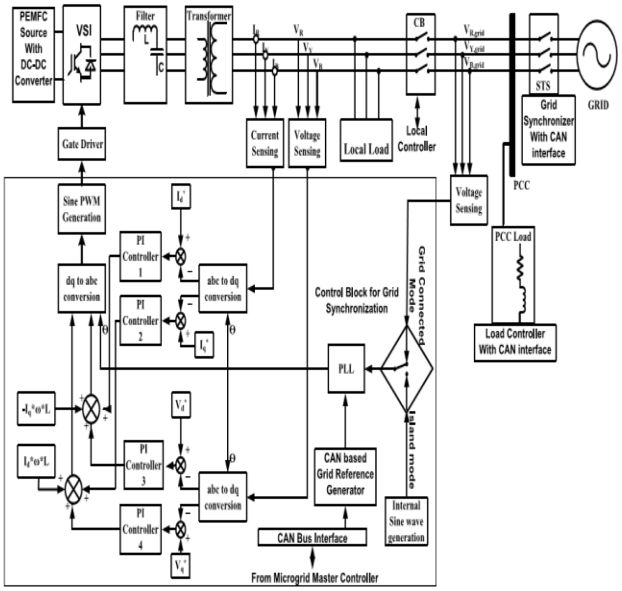

Fig.5. Detailed MPC control implementation with power topology and CAN communication interfaces

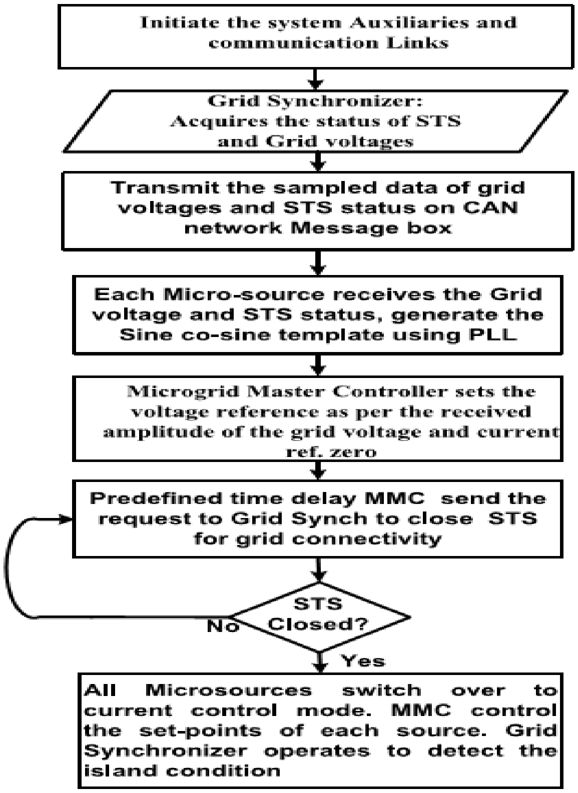

Fig.6. Algorithm for CAN-based GS

During the autonomous mode of operation, the VSI is controlled to maintain the voltage and frequency at PCC in tight limits. The MS coupled with ESS can regulate the common dc link voltage in order to regulate the ac bus voltage. The microgrid's ac voltage regulation model is given as

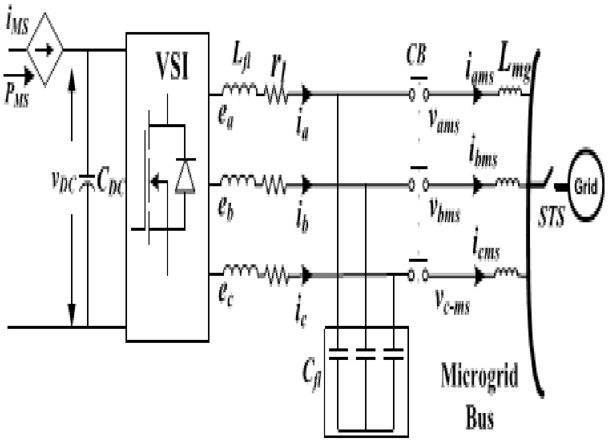

Fig.7. Equivalent circuit model representing the power electronic interface with LC filter between an MS and the main grid

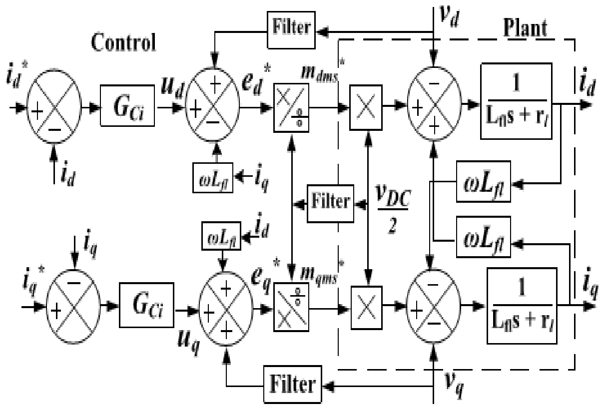

Fig.8. VSIs inner current control loop for PQ control in grid connected mode

$$C_{fl}\frac{dv_d}{dt} = C_{fl}\omega\ v_q + i_d - i_{Ld}$$

$$C_{fl}\frac{dv_q}{dt} = -C_{fl}\omega\ v_d + i_q - i_{Lq}$$

(4)

Similarly all other MS power electronic interfaces are modeled. In standalone mode, the outer voltage mode control is dominantly active as the MMC controls the i_d and i_q reference values.

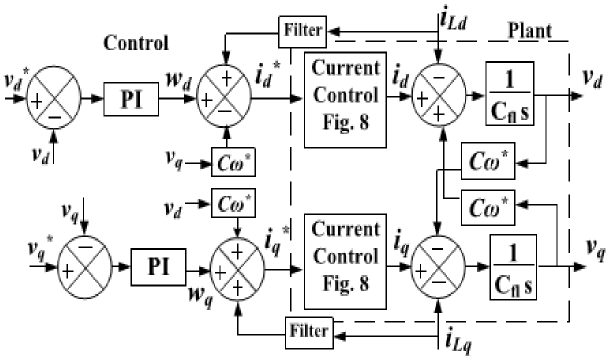

Fig.9. VSIs outer voltage control loop for the microgrid bus voltage regulation in standalone mode

Fig.9 shows the block diagram of outer voltage control loop for the microgrid bus voltage regulation during standalone mode of operation. The VSC parameters for one such interface are given in Table 3.2 along with the designed values of controller parameters. The inner current control loop and outer voltage control loop activation is coordinated with the STS status, i.e., close or open indicating the grid connectivity of the microgrid. This guarantees a seamless transition from standalone mode to grid connected mode or vice versa. This simple but robust method offers the following advantages.

1. Simultaneous synchronization of all MS of microgrid, which minimizes the time required for transition from i_{sl} and or black-start mode to grid connected mode.
2. Smooth transition from voltage mode control to current mode control or vice versa.
3. Easy and simple implementation of GS procedure. No additional cost of implementation as CAN is commonly available feature on most of the DSP processors, which are used as LC for inverter control.
4. CAN provides fault tolerant, robust and fast communication, ensuring appropriate execution of the algorithm.
5. Uses single message box transmission method for CAN network which minimizes the time latencies in data communication. Therefore, time synchronization of all the MS becomes easy.

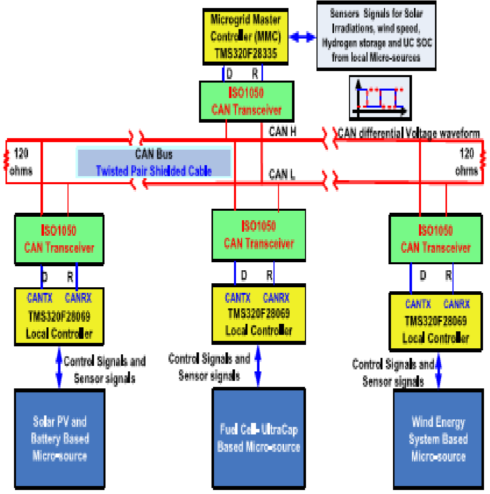

Fig.10. Schematic of CAN communication network implementation for the microgrid under study

A. CAN Network Implementation

The proposed control strategy works in co-ordination with CAN interface between the grid synchronizer, MMC, and LCs.Fig.10 shows the schematic of the CAN-based communication network for the microgrid under study. The LC are interfaced with Texas Instrument's ISO1050 CAN transceiver through a twisted pair cable with 120termination resistors [33]. The functionality of grid synchronizer, LC and MMC are realized on DSP with built-in CAN modules. These controllers support 1 Mb/s data speed on CAN bus, facilitating high speed and robust communication within the microgrid. CAN protocol comes with a high immunity to electrical interference and ability to self-diagnose and repair data errors. The software for CAN protocol is developed on Texas Instrument's Code Composer Studio (CCS 4.2.1) platform. The software code is optimized to minimize effective time for transmission and reception of data across all the LCs, grid synchronizer, and MMC.

IV. DESIGN OF A FUZZY CONTROLLER

The Fuzzy control is a methodology to represent and implement a (smart) human's knowledge about how to control a system. A fuzzy controller is shown in Figure.11. The fuzzy controller has several components:

- A rule base that determines on how to perform control
- Fuzzification that transforms the numeric inputs so that the inference mechanisms can understand.
- The inference mechanism uses information about the current inputs and decides the rules that are suitable in the current situation and can form conclusion about system input.
- Defuzzification is opposite of Fuzzification which converts the conclusions reached by inference mechanism into numeric input for the plant.

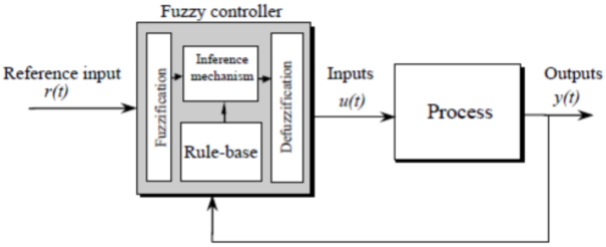

Fig.11 Fuzzy Control System

Fuzzy logic is a form of logic that is the extension of boolean logic, which incorporates partial values of truth. Instead of sentences being "completely true" or "completely false," they are assigned a value that represents their degree of truth. In fuzzy systems, values are indicated by a number (called a truth value) in the range from 0 to 1, where 0.0 represents absolute false and 1.0 represents absolute truth. Fuzzification is the generalization of any theory from discrete to continuous. Fuzzy logic is important to artificial intelligence because they allow computers to answer 'to a certain degree' as opposed to in one extreme or the other. In this sense, computers are allowed to think more 'human-like' since almost nothing in our perception is extreme, but is true only to a certain degree.

Table 1: IF-THEN rules for fuzzy inference system

u(t)		**e(t)**						
		NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
Δe(t)	**NB**	NB	NB	NB	NB	NM	NS	ZO
	NM	NB	NB	NB	NM	NS	ZO	PS
	NS	NB	NB	NM	NS	NS	PS	PS
	ZO	NB	NM	NS	ZO	ZO	PM	PM
	PS	NM	NS	ZO	PS	PS	PB	PB
	PM	NS	ZO	PS	PM	PM	PB	PB
	PB	ZO	PS	PM	PB	PB	PB	PB

The fuzzy rule base can be read as follows
IF e(t) is NB and Δe(t) is NB **THEN** u(t) is NB
IF e(t) is <negative big> and Δe(t) is <negative big>**THEN** u(t) is <negative big>

V. MATLAB/SIMULINK RESULTS

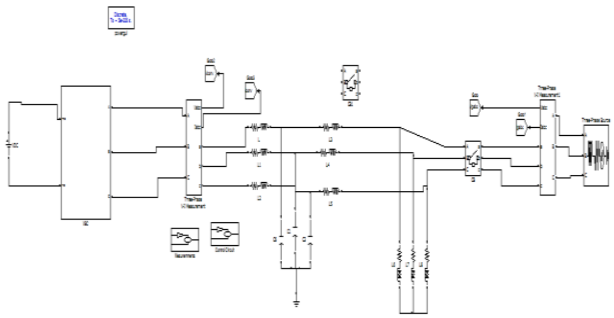

Fig.12 Matlab/Simulink model of CAN assisted GS system

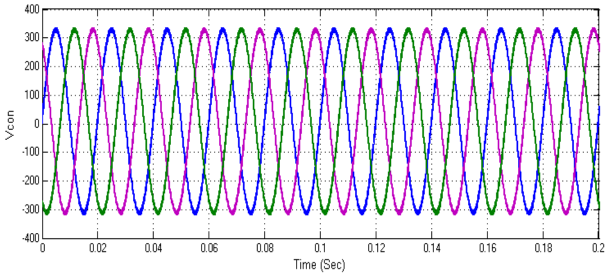

Fig.13 Converter Voltage (V)

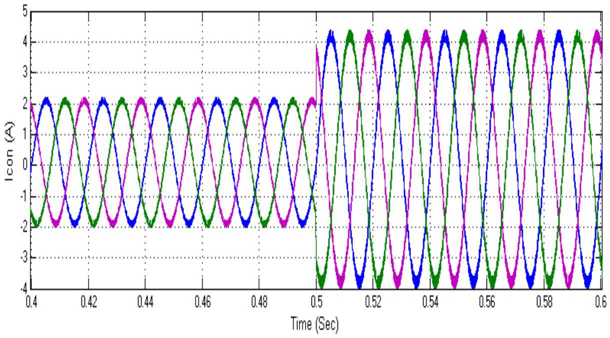

Fig.14 Converter Current (A)

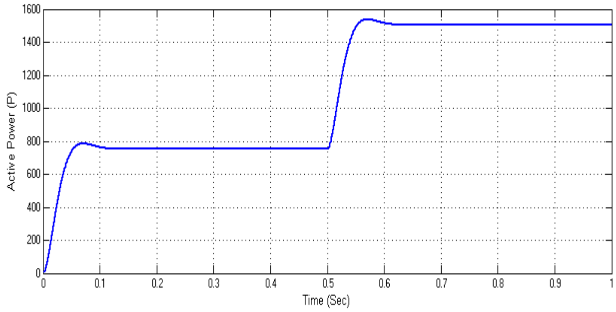

Fig.15 Active Power

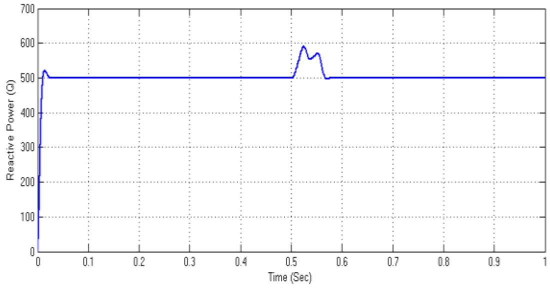

Fig.16 Reactive Power

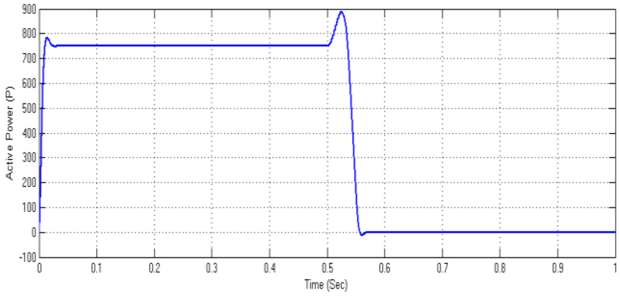

Fig.17 Grid Active Power

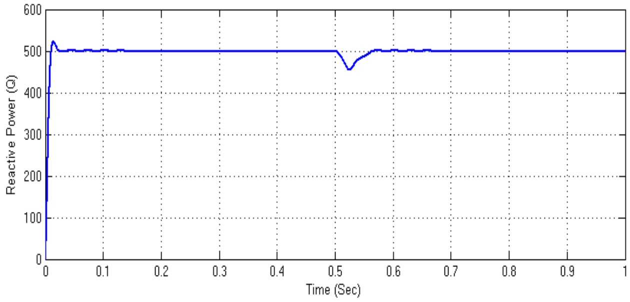

Fig.18 Grid Reactive Power

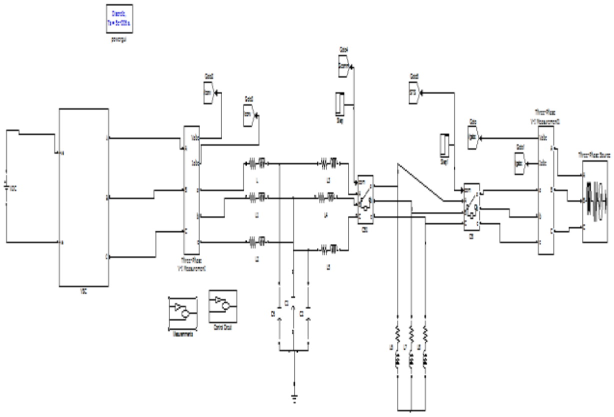

Fig.19 Matlab/Simulink model of CAN assisted GS system

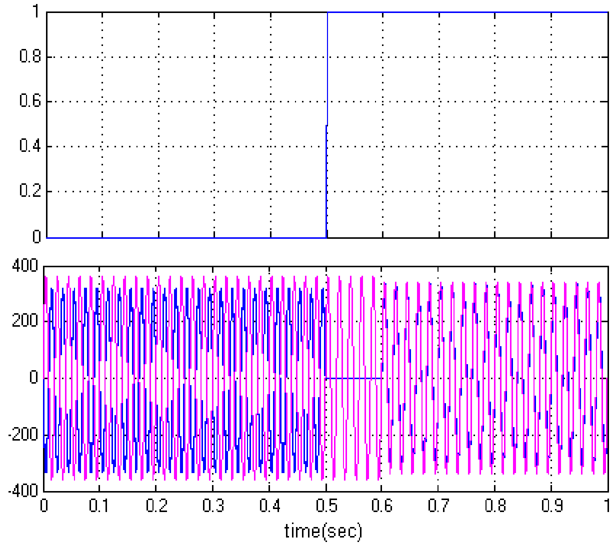

Fig.20 Smooth transition from standalone mode to grid connected mode: Output Voltage

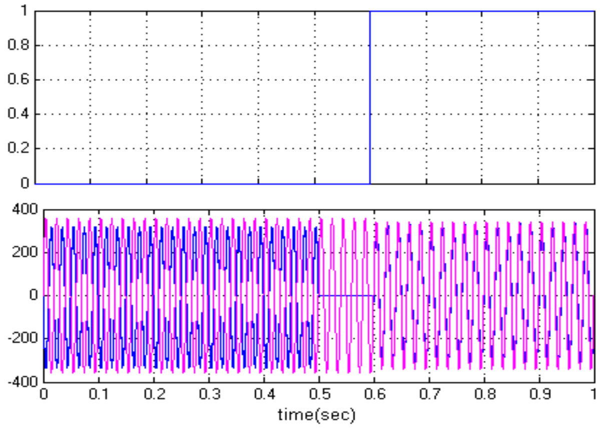

Fig.21 Smooth transition from standalone mode to grid connected mode: Output Voltage

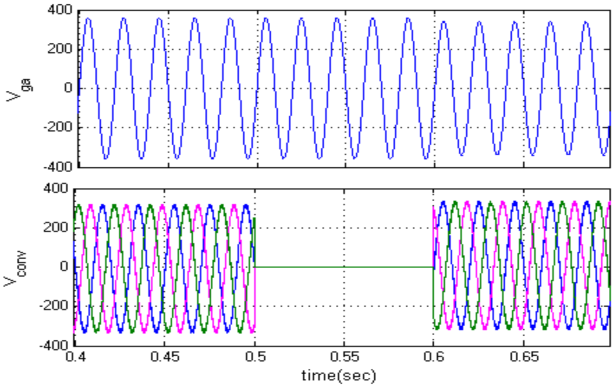

Fig.22 Grid Voltage and Converter Voltage

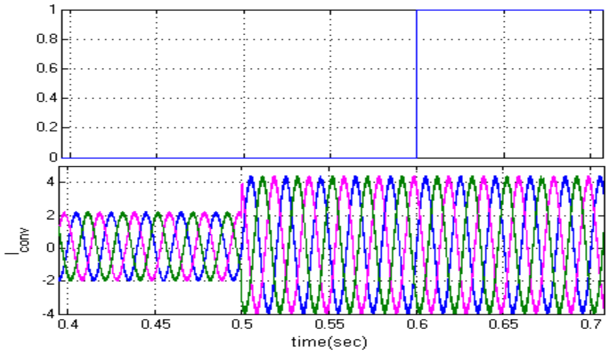

Fig.23 smooth transition from standalone mode to grid connected mode: Converter Current

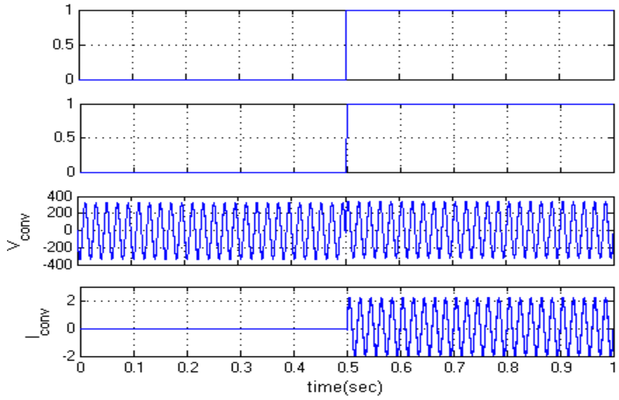

Fig.24 smooth transition from standalone mode to grid connected mode: Converter Voltage and Current

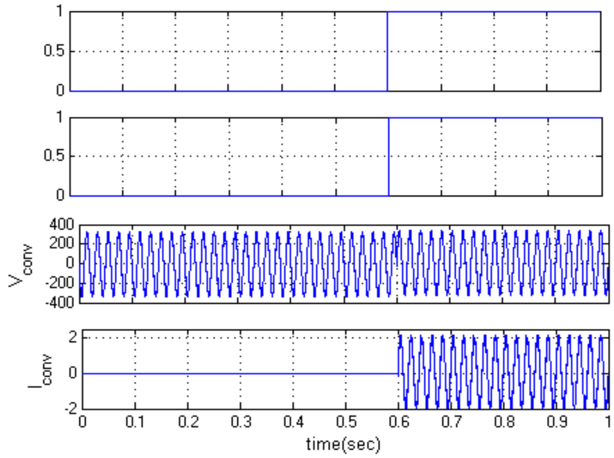

Fig.25 smooth transition from standalone mode to grid connected mode: Converter Voltage and Current

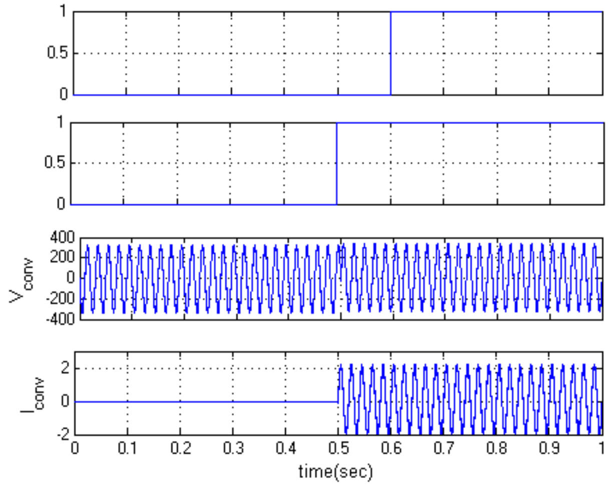

Fig.26 smooth transition from standalone mode to grid connected mode: Converter Voltage and Current

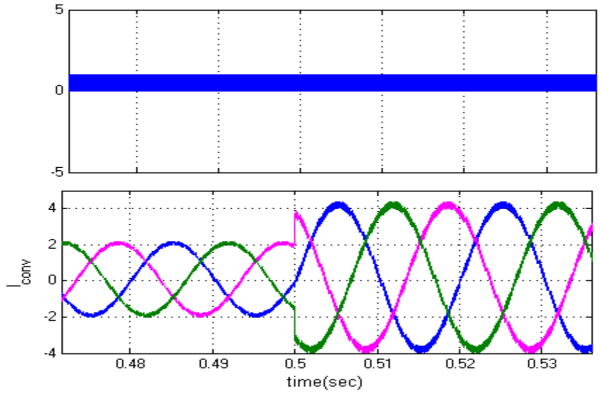

Fig.27 Converter Current before and after grid connection

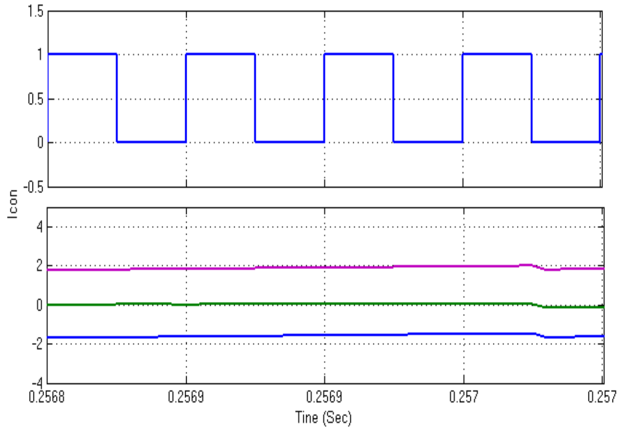

Fig.28 Expanded view of Converter Current before and after grid connection

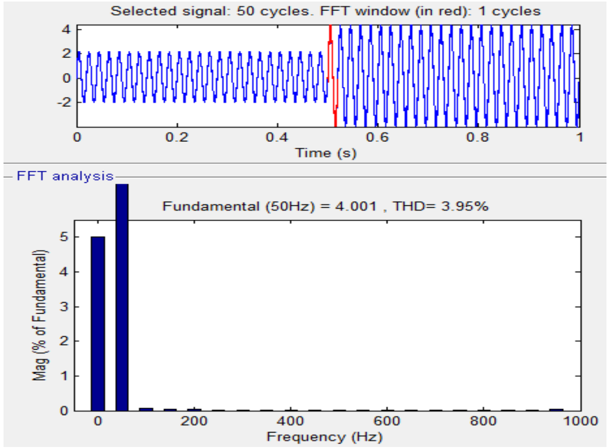

Fig.29 THD Analysis of Current with PI controller

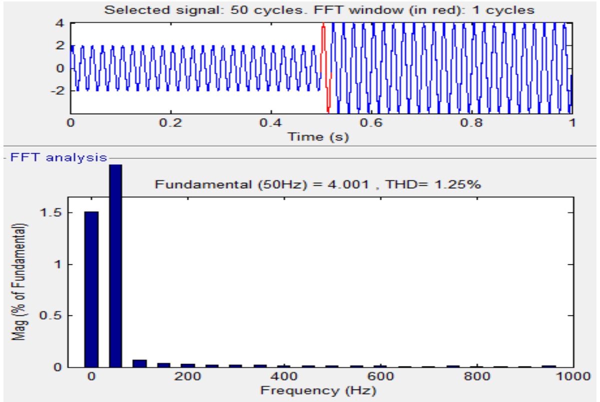

Fig.30 THD analysis of Current with Fuzzy logic controller

VI. CONCLUSION

A fuzzy logic based secondary controller is used for achieving the grid synchronization by integrating the renewable energy resource converters to microgrid. The simulation results with fuzzy logic controller helps in obtaining the quick response, low steady state error and reduces the harmonics with low ripple content. The power factor is also improved near PCC and power quality has been increased by the influence of multiple types of DG sources in distribution generation system. Hence, the proposed fuzzy logic system has better performance for achieving grid synchronization than existed conventional PI controller.

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