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SUPPLY-DEMAND BALANCE IN AN AUTONOMOUS MICRO GRID BY DISTRIBUTED SUB-GRADIENT BASED COORDINATION

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ABSTRACT

Islanding operation of micro grid offers high reliability power supply to the critical loads within its distribution networks. For an autonomous or islanding micro grid with high renewable energy penetration it has to maintain its own supply demand balance of active and reactive power. One of the issues is power reference control of distributed renewable generators (RGs) under the conditions of dynamic load and weather. The maximum peak power tracking (MPPT) algorithms emphasize high energy usage efficiency but may cause a supply-demand imbalance when the maximum available renewable generations are more than demanded for islanding micro grids. Some of the centralized algorithms have been proposed to rectify these problems, but they are limited with their applications, droop control is the most frequently used one, however it poses some issues like oscillating responses. To reduce these problems, this paper proposes a distributed sub gradient-based coordination solution by coordinating the operations of different types of distributed renewable generators in a micro grid. By controlling the amount of utilization of renewable generators the supply-demand balance can be well maintained and the dynamic performance of the system can be improved. Simulation results will show the effectiveness of this method.

Key Words: Distributed Cooperative Control, Distribution Generator, Micro grid, Multi-Agent System, Renewable Generator

I. INTRODUCTION

A micro grid can be defined as a cluster of loads, distributed generators (DGs) and energy storage systems that is serviced by a distribution network and can operate in both grid connected and islanded modes [1]. The micro grid has following advantages much lesser environmental impact than the large conventional thermal power stations, power quality and reliability is achieved, cost savings are achieved and more.

Wind and solar power are renewable power supply alternatives due to their abundance, cleanness and low production cost/unit. However, the incorporation of wind and solar power causes new disturbances in the operation and control of micro grids, especially under high renewable energy penetration. One issue is the reference power control of distributed renewable generators (RGs) under dynamic weather and load conditions. The usage of MPPT (maximum peak power tracking algorithms) [2] may provide high energy usage efficiency but lead to supply demand imbalance, particularly for micro grids operating autonomously under the condition of high penetration of renewable energy. These problems can be rectified by using energy storage devices like batteries, flywheels, super-capacitors etc to absorb excess energy [3]. Even if sufficient energy storage devices are available, their effectiveness is limited by the maximum charging and discharging rate and charging level. The control issues for an autonomous micro grid are very similar to those of large-scale power systems, such as frequency regulation and supply-demand balance.

The previous proposed methods are two-level control scheme for a wind farm [4], optimal dispatch control strategy for a wind farm in [5], and coordinated control method [6] for leveling photovoltaic (PV) generation.

All of the above methods are centralized, requiring complicated communication networks to collect information globally and a central controller to process huge amounts of data. So, these solutions are costly to implement and susceptible to single-point failures. The centralized solutions may not be able to respond in a timely fashion if operating conditions change rapidly and unexpectedly. Since well-designed distributed control solutions can be reliable, flexible, scalable, and low-cost to implement they are good choice for the control and operation of micro grids.

Multi-agent system (MAS) is one of the most popular distributed control approaches [7] & [8]. Existing MAS based applications in power systems are usually rule-based and lacked rigorous stability analysis. Recent developments in consensus and cooperative control have been successfully applied [9] & [10], which can improve the stability and applicability of MAS-based solutions.

In this paper, the coordination of multiple RGs in a micro grid is formulated as a convex optimization problem that can be solved using the distributed sub gradient algorithm introduced in [11].

II. PROPOSED SUBGRADIENT-BASED SOLUTION

2.1 Utilization Level Based Coordination

The total active power demand (P_D) of a micro grid can be calculated as:

$$P_D = \sum_{i=1}^{n} P_{L,i} + P_{Loss} \qquad (1)$$

Where *n* is the number of buses in the micro grid, $P_{L,i}$ is the demand of load at bus *i*, and P_{Loss} is the active power loss in the micro grid.

The total available renewable power generation in the micro grid can be calculated as:

$$P_G^{max} = \sum_{i=1}^{m} P_{G,i}^{max} \qquad (2)$$

Where *m* is the number of RGs, and $P_{G,i}^{max}$ is the maximum power generation of RG*i*. In autonomous micro grid, if P_G^{max} is less than P_D, all RGs can operate in MPPT mode, and the SG's should compensate the generation deficiency. On the other hand, if P_G^{max} is larger as P_D, MPPT control strategies no longer apply. A suitable reloading strategy is required to share the load demands among the RGs, which can be accomplished by controlling the utilization levels of RGs to a common value

$$u^* = \min\left\{\frac{P_D}{P_G^{max}}, 1\right\} \qquad (3)$$

Where u^* is the common utilization level for all RGs.

The active power generation reference of RG*i* is calculated as:

$$P_{G,i}^{ref} = u^*.P_{G,i}^{max} \qquad (4)$$

2.2 Distributed Generation Coordination Algorithm

The objective for multiple RGs coordination is to minimize the function formulated as:

$$Min\ H(u_i[k]) = \frac{1}{2}\left(\sum_{i=1}^{m} u_i[k] P_{G,i}^{max} - P_D\right)^2 \qquad (5)$$

Where k is discrete time step, $u_i[k]$ is utilization level of RG i at step k.

The equation (5) is a loss function = $(utilization * generation - loss)^2$ the equation (5) represents the utilization level at one instant, it has to be updated for next step based on the communication coefficients from another agents in the network. This can be done from the equation (6) taken from [11] called subgradient algorithm**:**

$$x^i(k+1) = \sum_{j=1}^{m} a_j^i(k) x^j(k) - \propto^i (k) d_i(k) \qquad (6)$$

Where $a^i{}_j$ is communication coefficient, $\alpha^i(k)$ is step size, and $d_i(k)$ is the subgradient.

So the equation (5) can be updates as**:**

$$u_i[k+1] = \sum_{j=1}^{m} a_{ij}\, u_j[k] - d_i \frac{\partial H(u_i[k])}{\partial u_i[k]} \qquad (7)$$

Where a_{ij} is communication coefficient, d_i is step size, and $\frac{\partial H(u_i[k])}{\partial u_i[k]}$ is sub gradient.

$$\frac{\partial H(u_i[k])}{\partial u_i[k]} = P_{G,i}^{max}\left(\sum_{i=1}^{m} u_i[k] P_{G,i}^{max} - P_D\right) \qquad (8)$$

The speed of convergence depends on the transfer of communication coefficients. Since the mean metropolis algorithm as shown in equation (9) is fully distributed adaptive to changes in communication network topology and able to provide convergence guarantee, it is adopted in the paper.

$$a_{ij} = \begin{cases} \frac{2}{(n_i+n_j+1)} & j \epsilon N_i \\ 1 - \sum_{j \epsilon N_i} \frac{2}{(n_i+n_j+1)} & i = j \\ 0 & otherwise \end{cases} \qquad (9)$$

Where n_i and n_j are numbers of agents connected to agents *i* and *j*, and N_i indicates indices of agents that communicate with agent *i.*

Substituting equation (7) in equation (6) we get

$$u_i[k+1] = \sum_{j=1}^{m} a_{ij}\, u_j[k] - P_{G,i}^{max} d_i\left(\sum_{i=1}^{m} u_i[k] P_{G,i}^{max} - P_D\right) \qquad (10)$$

$$U[k+1] = A.U[k] - \left(\sum_{i=1}^{m} u_i[k] P_{G,i}^{max} - P_D\right).D \qquad (11)$$

$$U[k] = [u_1[k], \ldots, u_i[k], \ldots, u_m[k]]^T$$

$$D = [P_{G,1}^{max} d_1, \ldots, P_{G,i}^{max} d_i, \ldots, P_{G,m}^{max} d_m]^T$$

According to mean metropolis algorithm, the transition matrix A is a doubly stochastic matrix, which has the following properties:

1) All the eigenvalues of A are less or equal to 1.

2) A vector $a \in R^m$ is said to be stochastic vector when its components $a_i, i = 1, \ldots \ldots, m.$ are non negative and their sum is equal to 1.

i.e $\sum_{i=1}^{m} a_i = 1$

The equilibrium of the system described by equation (10) can be obtained by summing up both sides of equation (9) and letting.

$$\sum_{i=1}^{m} u_i^* = \sum_{i=1}^{m} \sum_{j=1}^{m} (a_{ij} u_j^*) - \left(\sum_{i=1}^{m} u_i^* P_{G,i}^{max} - P_D\right) \sum_{i=1}^{m} \left(P_{G,i}^{max} d_i\right) \qquad (12)$$

According to equation (9), A is a symmetric matrix with the sums of each equals 1.

i.e $\sum_{i=1}^{m} a_{ji} = 1$

$$\sum_{i=1}^{m}\sum_{j=1}^{m}(a_{ij}u_j^*) = \sum_{i=1}^{m}\sum_{j=1}^{m}(a_{ji}u_i^*) = \sum_{i=1}^{m}\left(u_i^*\sum_{j=1}^{m}a_{ji}\right) = \sum_{i=1}^{m}u_i^* \qquad (13)$$

Since $\sum_{i=1}^{m}(P_{G,i}^{max}d_i) \neq 0$ thus

$$\sum_{i=1}^{m}u_i^* P_{G,i}^{max} - P_D = 0 \qquad (14)$$

From equation (13) we get

$$u^* = \frac{P_D}{\sum_{i=1}^{m}(P_{G,i}^{max})} = \frac{P_D}{P_G^{max}} \qquad (15)$$

Therefore, the proposed control law can achieve the supply demand balance within the micro grid according to equation (2).

Measuring the total load and estimating power loss accurately in a distributed way are difficult. Since supply-demand imbalance will cause changes in system frequency, it is better to use frequency deviation to overcome the difficulty.

The model for dynamic frequency response is proposed in [12] as given below:

$$\frac{df}{dt} = \frac{f_0}{2\omega_{kin0}}\left(\sum_{i=1}^{m}u_i P_{G,i}^{max} - P_D\right) \qquad (16)$$

The equation (16) can be written as:

$$\frac{df}{dt} \approx \frac{f[k]-f[k-1]}{\Delta t} = \frac{\Delta f[k]}{\Delta t}$$

From this

$$\Delta f[k] = \frac{f_0\Delta t}{2\omega_{kin0}}\left(\sum_{i=1}^{m}u_i[k]P_{G,i}^{max} - P_D\right) \qquad (17)$$

Where Δt is the time step for utilization level update.

Therefore

$$\sum_{i=1}^{m}u_i[k]P_{G,i}^{max} - P_D = \frac{2\omega_{kin0}}{f_0\Delta t}\Delta f[k] \qquad (18)$$

By substituting equation (18) in equation (10), finally the proposed updating law for utilization level of RG*i* can be represented as:

$$u_i[k+1] = \sum_{j=1}^{m}a_{ij}u_j[k] - \propto_i \Delta f[k] \qquad (19)$$

Where $\propto_i = 2P_{G,i}^{max}\omega_{kin0}d_i/f_0\Delta t$

It should be noted that it is unnecessary to estimate ω_{kin0}, which changes with operating conditions and is hard to accurately estimate. Since its impact on control update has been combined with the other parameters and absorbed into $\propto_i$. Thus, it is preferable and reasonable to tune $\propto_i$ directly.

2.3 Proposed Control Topology

The proposed control topology mainly composed of Renewable generators (RGs), a SG and loads as shown in Fig. 1,

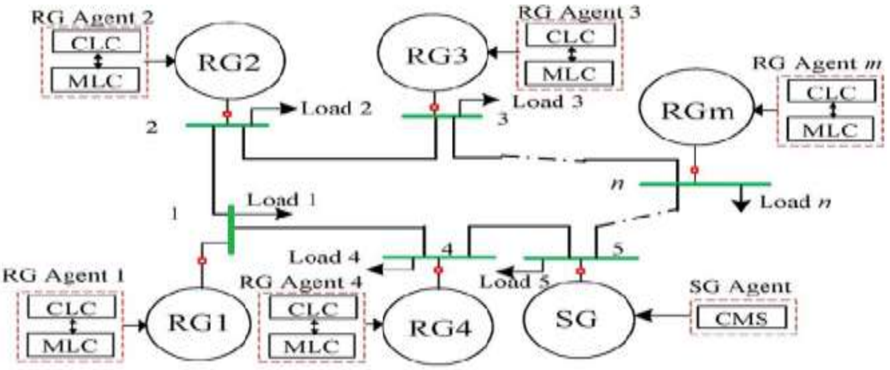

Fig.1. Illustration of Control Topology of a Micro grid

2.3.1 Rg Agent

The RG agent implements a two level control operation. Each generator agent implements a two-level control strategy as shown in Fig. 2.The upper cooperative level control, and the lower Machine level control**.** The upper cooperative level control (CLC) discovers the desired utilization level and decides the reference of active power generation. The CLC consists of four function modules. Measurement and prediction module measures the system's frequency and predicts the maximum available renewable generation. Communication module exchanges

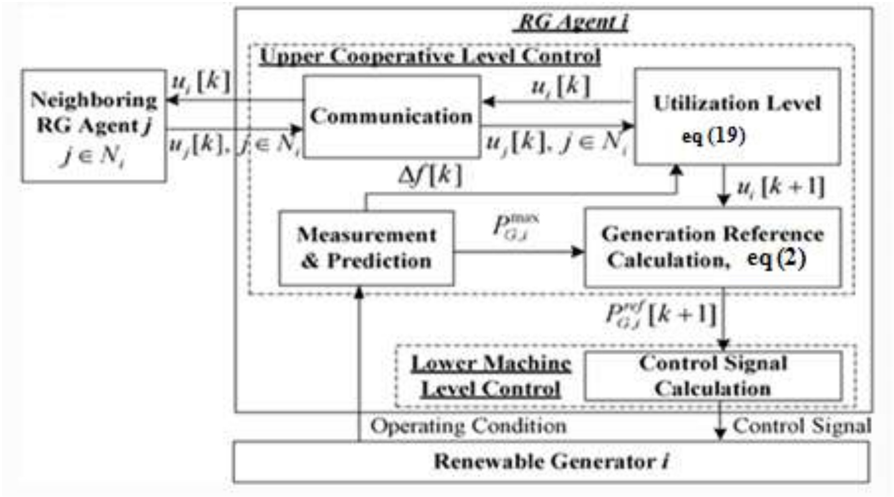

Fig.2. Block Diagram of an RG Agent

utilization level information with its neighboring RG agents. Based on local frequency deviation measurements and received utilization levels. Utilization level module calculates the common utilization level that all the RG's have to be maintained. The utilization level will be updated according to equation (20). The equation is calculated based on distributed sub-gradient based coordination algorithm [11]. Generation reference module calculates the active power generation reference based on the utilization level and the predicted maximum renewable power. This is updated by equation (4).

III. MACHINE LEVEL CONTROL

The machine level control includes the control of different types of DG's in a micro grid.

3.1 Control of DFIG

The machine-level control of each DFIG manages active power reference tracking, as well as reactive power or

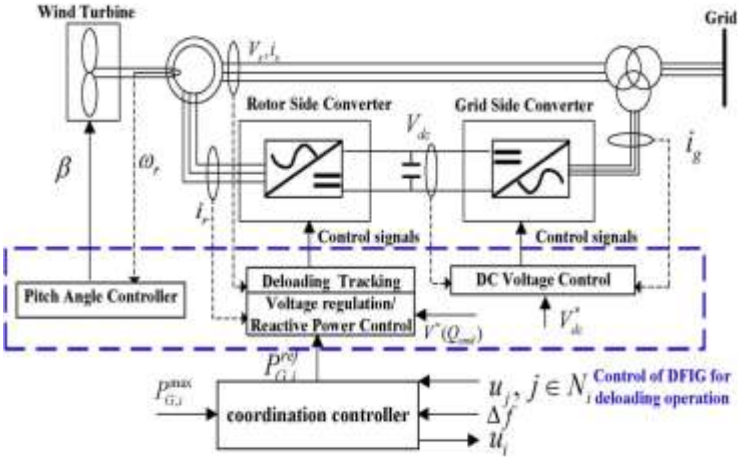

Fig.3. Machine-level control of DFIG in Deloading Mode

terminal voltage regulation and DC-link voltage regulation. As illustrated in Fig. 3, the machine-level control consists of the electrical control of two converters and the mechanical control of pitch angle.

3.2 PV Control

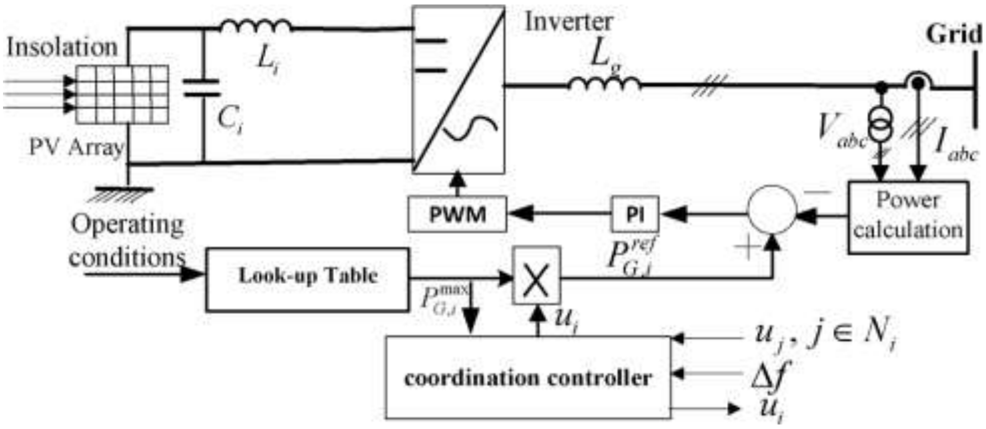

Fig.5. Control Strategy for PV System

The PV system model described in [13] is adopted in this paper. *V* and *I* are the solar array voltage and current, respectively, and *Vabc* and *Iabc* are the local bus voltage and current. In this paper, PV is controlled in unit power factor mode. If a PV system is equipped with insolation and temperature sensors, the following method introduced in [14] can be used to estimate the maximum generation of $P^{max}_{G,i}$.

$$P^{max}_{G,i} = P_{STC}\frac{G_{INC}}{G_{STC}}\left[1 + k_{pv}(T_c - T_r)\right] \tag{20}$$

Where P_{STC} is Module maximum power at standard test condition (STC), G_{INC} is Incident irradiance, G_{STC} is Irradiance at STC 1000W/m^2, k_{pv} is Temperature coefficient of power, T_c is Cell temperature, T_r is Reference temperature. Once $P^{max}_{G,i}$ and u_i have been calculated, the generation reference can be updated according to (2). After that, simple PI control can be used to control the inverters for active power tracking, as shown in Fig. 5.

3.3 Control of SG

In this project, the SG in the renewable micro grid has two functions. If the renewable generation is sufficient to power all loads, SG is just used for voltage regulation. If the renewable generation is insufficient, in addition to voltage regulation, the SG also generates active power to compensate the deficiency as shown in fig.6.

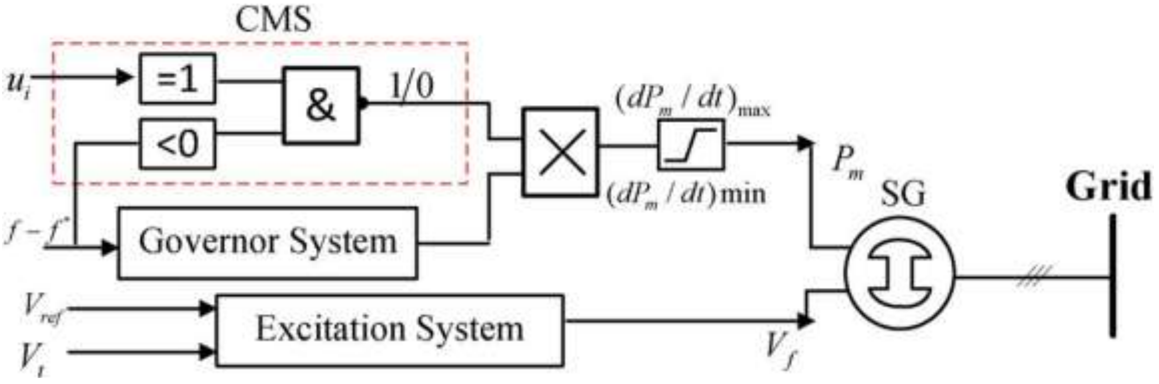

Fig.6. Control Logic of Synchronous Machine

IV. SIMULATION RESULTS

The proposed fully-distributed cooperative control algorithm is tested with a 6-bus micro grid model using MATLAB/SIMULINK software, as shown in Fig.7. The simulink control circuits for PV and DFIG are shown in Fig.8.and Fig.9.

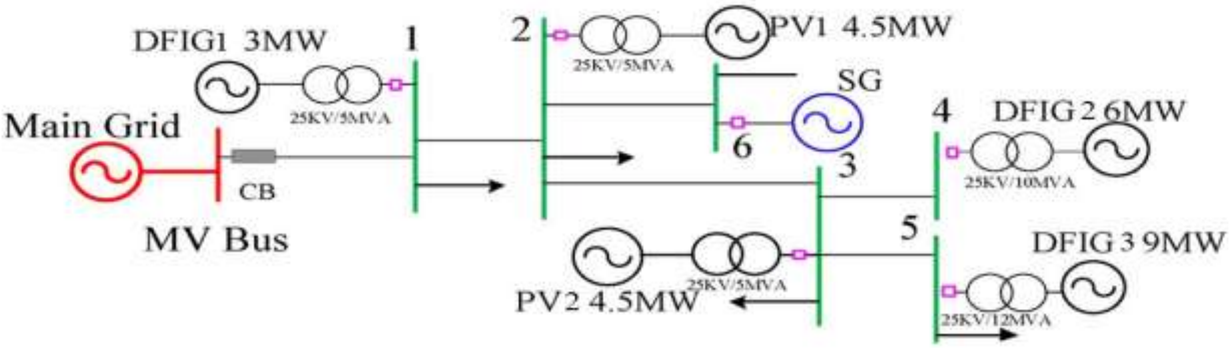

Fig.7. Configuration of a 6-bus Micro grid

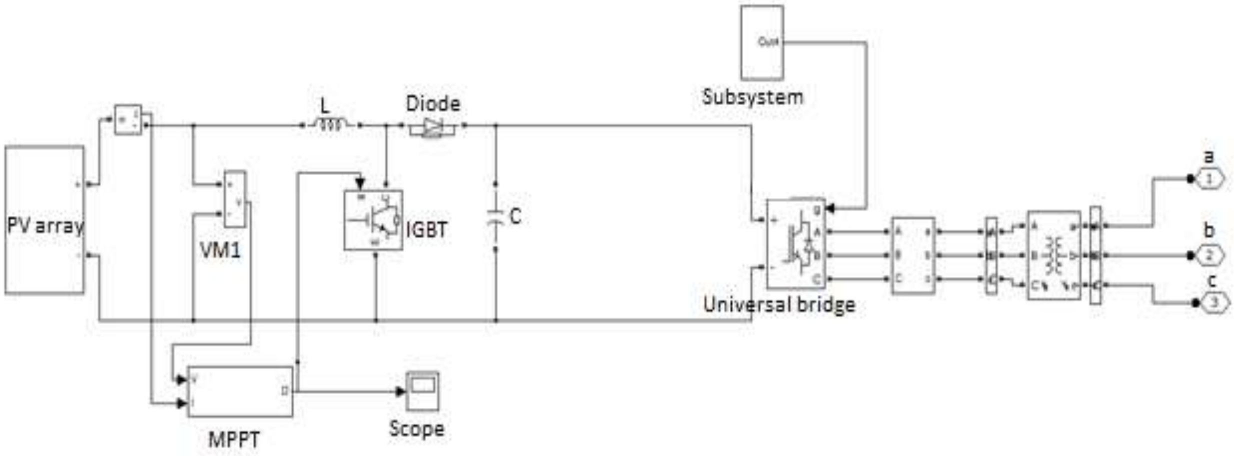

Fig.8.Simulink Model of PV Control System

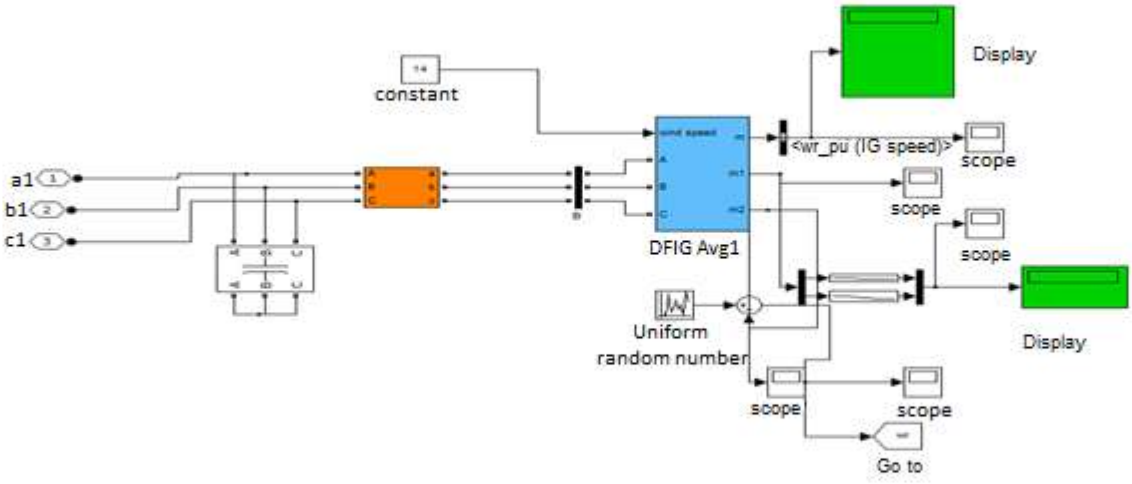

Fig.9.Simulink Model of DFIG Control

The demands of the loads remain constant. The wind speeds of the DFIGs 1, 4, 5 are constant at 11 m/s, 14 m/s, and 14 m/s. The solar irradiation of PVs at bus-2 and bus-3 are 900 and 1000w/m^2, respectively. An islanding event at 20 s is simulated to test the performance of the proposed control scheme. Fig.10. shows the utilization level profiles of 5 RG's and frequency response. All RGs are controlled using the MPPT algorithm before islanding, and initially the output of the SG is set to 2 MW to create enough disturbances to test the performance of the proposed control algorithm.

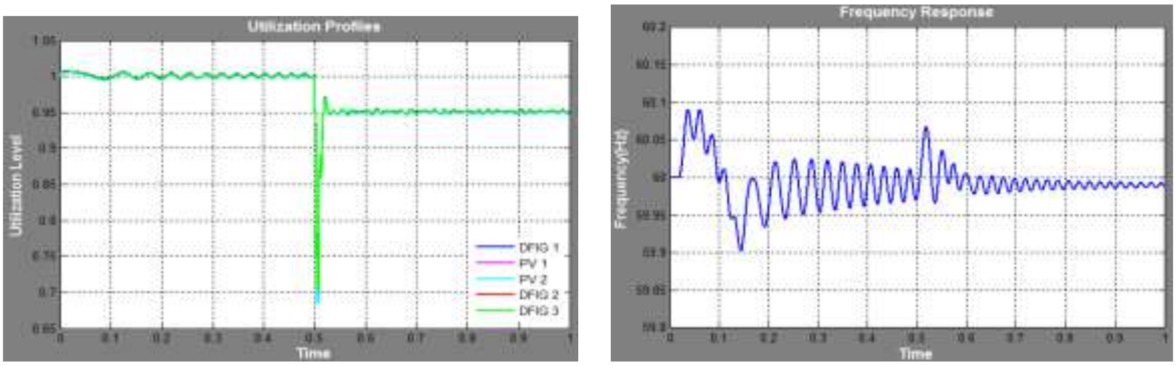

Fig.10.a) Utilization profiles of 5RG's

b) System Frequency response under the proposed solution

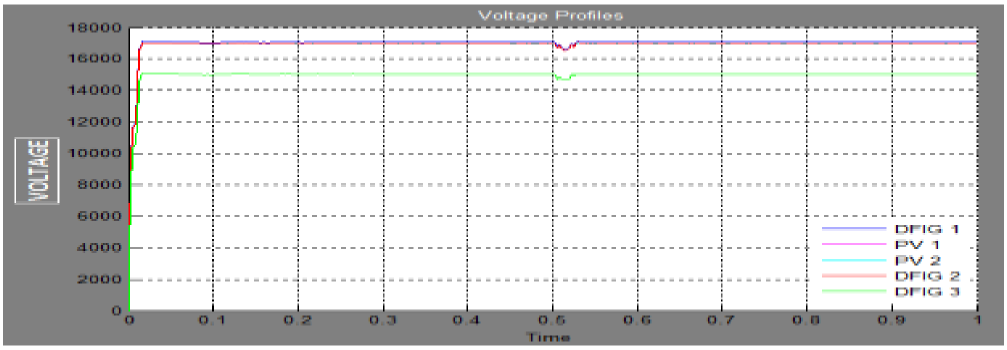

Fig.11.Voltage profiles of DG's

At the instant of islanding, the available renewable power is more than the load demand, the frequency of system increases at this moment as shown in Fig. 10. The proposed algorithm controls the utilization level to drop in order to allow the RGs to dump excessive renewable power. At this instant the voltage profiles are as Shown in Fig.11.

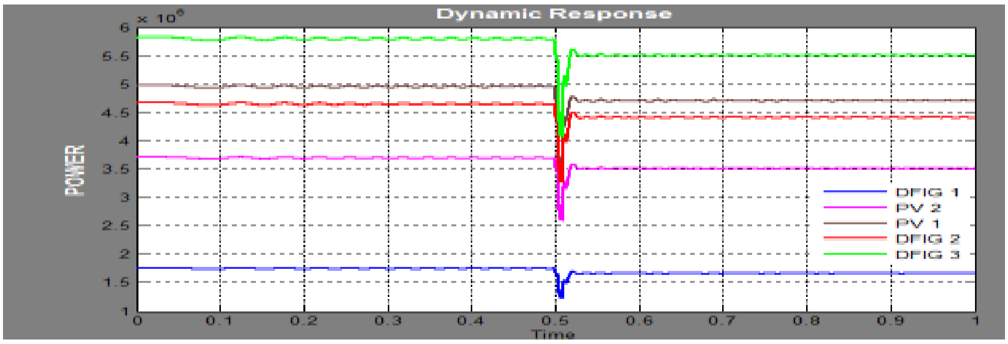

Fig.12.Dynamic Response of 5DG's

Fig.12. shows the dynamic responses of the RGs. The active power generations of the DGs converge to a value below the maximum available power after islanding. The utilization levels, if calculated, are the same as the ratio of actual output power to MPPT power.

V. CONCLUSION

By synchronizing the utilization levels of the RGs to a common value. The proposed control scheme has the following advantages, The cost of the communication network will be much lesser than that of a centralized solution due to the introduction of a simple MAS-based fully distributed method, avoidance of the direct loading condition measurements, coordination of different types of DGs at distributed level, improvement in system's dynamic performance due to introduction of the subgradient optimization method.

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