Noiseless Consensus Based Algorithm for Economic Dispatch problem in Grid-connected Microgrids to Enhance Stability among Distributed Generators

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***Abstract*—Economic Dispatch is an important problem in the operation of microgrids. It aims to minimize the total cost of operation/generation of microgrids while meeting all the defined constraints. Since microgrids consist of distributed generators, it is imperative for these generators to communicate seamlessly with each other without any losses and to ensure secure operation of the microgrid. With use of distributed generators, noise is inherent in the system. Most of the economic dispatch problems do not include noise in their analysis while finding a relevant solution. This paper focuses on including noises as a constraint in grid connected mode microgrids to find a better economic dispatch solution. This will enhance the microgrid's performance and make it a more resilient system.**

***Keywords*—Microgrids, consensus based algorithm, economic dispatch, distributed generators.**

I. INTRODUCTION

Economic Dispatch is an optimization problem used to minimize the cost of the system. It is one of the important problem in the field of power systems. While finding minimum cost of the system, all the constraints (both equality constraints and inequality constraints) of the system are taken into consideration. Many methods have been used to solve economic dispatch problem, most commonly by quadratic convex function [1], [2]. In [3] and [4] Lagrangian relaxation technique and quadratic programming has been used respectively. Consensus based algorithms have been studied widely by ensuring the equal increment cost criterion [5]-[8]. To minimize the total cost, both economic dispatch and demand side management problems were solved [9]-[15]. The conventional economic dispatch problem assumes that the system/microgrids are noiseless. In real-time, noises are present in the system (from components as well as surroundings). This affects the performance and resilience of the microgrids. It also limits their stability. Hence, it is necessary to include noise in consensus-based algorithm economic dispatch problem, to stabilize the microgrids and enhance their resiliency and performance.

Some publications have included noise in their analysis [16]-[18]. They developed noiseless control algorithm for voltage and frequency synchronization in microgrids as well as power sharing approach which is independent of its parameters. But not much research has been carried out in this area and therefore, this paper will explore towards this approach. [19] has discussed this strategy for islanded microgrids but did not include grid connected microgrids. This paper represents the noiseless economic dispatch problem for grid-connected microgrids. Also, in this approach there is no need of central controller, hence the system is more cyber secure and less expensive. Since a distributed approach is utilized, it eliminates the need of central controller and reduces communication complexity [20]-[25].

Microgrids are defined as a group of interconnected distributed energy (renewable and conventional) resources and loads which acts as a whole controllable entity when compared to a grid. It can be either connected (grid-connected mode) or disconnected (islanded mode) to the grid. In this paper, grid-connected mode is under analysis. In order to minimize the total generation cost, the incremental costs of all the distributed generators must be equal to each other. Incremental cost of each generator is defined as the derivative of its cost function with respect to its power output. This paper is divided into the following sections: Section II and III defines the economic dispatch problem and microgrid system, Section IV discusses the distributed noise-resilient economic dispatch approach [19]. Section V includes results and discussion and Section VI provides conclusions.

II. ECONOMIC DISPATCH FORMULATON

The Langrangian method is used to define the economic dispatch problem for grid-connected microgrid. First, the objective function of the microgrid is defined. This function is most commonly used in solving economic dispatch problems. Considering i (1, 2, 3,…, n) units of generation in a microgrid system, the cost of a generator can be defined in terms of the following quadratic equation:

$$\sum_{i=1}^{n} C_i P_i = \sum_{i=1}^{n} a_i P_i^2 + b_i P_i + c_i \quad (1a)$$

Where, $C_i P_i$ is the cost of generator i
a_i, b_i, c_i are the cost co-efficient
P_i is the total power output of the generator

For economic dispatch problem, we want to minimize the generation cost of the microgrid. Equation (1a) becomes:

$$\min \sum_{i=1}^{n} C_i P_i = \min \sum_{i=1}^{n} a_i P_i^2 + b_i P_i + c_i \quad (1b)$$

Also, total power output of generator can be defined as:

$$\sum_{i=1}^{n} P_i = P_D + P_{loss} \text{ , for } P_i^{min} < P_i < P_i^{max} \quad (2)$$

Where, P_D is the total load and P_{loss} are the losses incurred during transmission of power from generation units to the loads. P_i^{min} is the minimum generation limit of generator i and P_i^{max} is the maximum generation limit of generator i.

To formulate the Lagrangian function, equation (1a), (1b) and (2) becomes:

$$L(P_1, P_2, \ldots P_n) = \sum_{i=1}^{n} C_i P_i + \lambda\left(P_D + P_{loss} - \sum_{i=1}^{n} P_i\right) + \sum_{i=1}^{n} u_x\left(P_i - P_i^{max}\right) + \sum_{i=1}^{n} u_y\left(P_i^{min} - P_i\right) \quad (3)$$

Where, λ, u_x, u_y are Lagrange multipliers.

To find solution of the above economic dispatch problem, incremental cost ($IC_1, IC_2, \ldots, IC_n$) for each generator should be calculated. To find the minimized cost of the microgrid, these incremental cost for different generators should be equal to each other, i.e.,

$IC_1 = IC_2 = \ldots = IC_n$
where, n = number of generation units

Solution to this problem, is most commonly used solution:

$$\lambda_i = \frac{\partial C_i P_i}{\partial P_i} = 2a_i P_i + b_i = \lambda^* \qquad P_i^{min} < P_i < P_i^{max}$$

$$\lambda_i = \frac{\partial C_i P_i}{\partial P_i} = 2a_i P_i + b_i < \lambda^* \qquad P_i = P_i^{max}$$

$$\lambda_i = \frac{\partial C_i P_i}{\partial P_i} = 2a_i P_i + b_i > \lambda^* \qquad P_i = P_i^{min} \quad (4)$$

Where, λ_i and λ^* are incremental cost and optimal incremental cost respectively.

So, the economic dispatch problem has to take into account generation limits for each generator to find economic dispatch schedule for the microgrid. If there are no equality or inequality constraints to be considered for the generators, then it is fairly easy to solve economic dispatch problem. However, most of the problems have some constraints which need to be considered while solving economic dispatch problem for microgrids. The above equations provided are the basic problem formulation for any economic dispatch related problems.

III. MICROGRID STRUCTURE

The microgrid under analysis for this paper consists of 4 generator units. It is in grid-connected mode and has a solar/Photovoltaic (PV) generator, wind generator and 2 coal-based generator units. The units' cost function is described in the quadratic equation (1a). P_{loss} has been assumed as 7% of the total load. Cost-coefficients, minimum and maximum power generation limits of the units are provided in the table below.

TABLE I. List of parameters for generators

Unit	P_{min}(kW)	P_{max}(kW)	a	b	c
1	4	18	0.070	2.15	56
2	8	40	0.080	1.15	50
3	5	25	0.070	3.3	41
4	5	40	0.056	3.4	36

IV. CONSENSUS-BASED ECONOMIC DISPATCH APPROACH FOR NOISELESS COMMUNICATION [19]

In this section, the approach introduced in [19] is explained. The communication link for the microgrid is defined. There is an agent corresponding to each generator unit, which collects information from their respective units. This information is processed by a specific agent. All the agents in the communication system are also connected to each other. Since, our grid-connected mode microgrid has 4 generation units, we have 4 agents in total, and each connected to their specified unit. The information collected and processed by the agents is exchanged between each other. This exchange helps provide information regarding the present status of each unit. This information is used to change the output power from each unit (while keeping their constraints in check), to minimize the total cost of the microgrid system. Noise from the components, surroundings, electric/magnetic interference are some of the reasons assumed in this analysis. Noise accumulated due to communication between units as well as between units and agents have been included in this approach. They have been modeled as Gaussian noise [16]. Communication links can be selected as c_{12}, c_{21}, c_{23}, c_{32}, c_{34}, c_{43}.

Corresponding incremental cost of each unit is calculated by their respective agent and then exchanged with each other. Set point of output power is calculated based on the information and is sent to their respective generation units. Accordingly, the units change their power generation to have equal incremental cost to solve the economic dispatch problem. This leads to overall minimization of microgrid cost.

[19] has formulated this approach as follows:

$$X[k+1] = X[k] + \mu[k][M\,x[k] + WD[k]]$$

$$M = -H'GH$$

$$W = H'G$$

$$H = H_2 - H_1 \quad (5)$$

Where,

X[k] is the incremental cost of units at kth iteration

X[k+1] is the incremental cost of units at (k+1)th iteration

μ[k] is recursive step size

G is r×r diagonal matrix with link control gain as its diagonal elements

H_1 and H_2 are r×n matrix in which rows are elementary vectors.

D[k] is the noise in the communication link

$$H_1 = \begin{vmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{vmatrix}$$

$$H_2 = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} ; H = \begin{vmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & -1 & 1 \end{vmatrix} = H_2 - H_1$$

G (small noise) = diag [0.2 0.2 0.2 0.2 0.2 0.2]

Similarly, M and W can be calculated using the formula given above.

Next step is to average the incremental costs of all the units in order to reduce the effects of noise. This will result in a more resilient and stable microgrid devoid of any (lesser) communication noise.

$$X_{avg}[k+1] = \frac{1}{k+1} \sum_{j=1}^{k+1} X[j]$$
$$= \frac{1}{k+1} \sum_{j=1}^{k} x[j] + X[k+1]$$
$$= X_{avg}[k] - \frac{1}{k+1} X_{avg}[k] + \frac{1}{k+1} X[k+1] \quad (6)$$

From (5) and (6), the noiseless economic dispatch approach is concluded as [19]:

$$X[k+1] = X[k] + \mu[k][M\,x[k] + WD[k]]$$

$$X_{avg}[k+1] = X_{avg}[k] + \frac{1}{k+1}[X[k+1] - X_{avg}[k]] \quad (7)$$

where, $X_{avg}[k+1]$ are set points for incremental costs of units.

This method is iterative in nature and an estimate is made using the step size, which is then averaged in later stages to reduce the effect of noise. The consensus problem is solved iteratively for each step size.

V. RESULTS AND DISCUSSIONS

The grid-connected microgrid is analyzed under 4 different conditions. Initially the microgrid is studied when there is no noise in the system. The economic dispatch algorithm provided in the previous section is tested to see the performance of the system in absence of noise. In the second condition, noise of variance 0.2 is introduced in the system, and the performance is observed. During the third condition, noise variance is increased to 0.5 and for the final condition, the noise variance is set to 0.8. The performance of the microgrid under different noise conditions has been analyzed using MATLAB. In all the cases, power output of the 4 generator units tries to maintain its optimal dispatch schedule with the introduction of different noise levels. In the end, a comparison has been made to show how the system stabilizes the incremental cost under various noise conditions. Fig. (1) shows varying power output of the 4 generator units under 60 sec period. This case is simulated under noise free conditions. It takes around 15 sec for the system to reach a constant generating power output for high noise variance. Fig. (2), (3) and (4) shows output during some noise variance. In this study, we have considered small (variance of 0.2), medium (variance of 0.5) and large (variance of 0.8) noise levels to simulate the system and observe its behavioral pattern for the chosen consensus-based algorithm. Due to less stability of the system for higher noise levels, the economic dispatch solution changes and is not as stable as observed for lesser noise levels. In all the figures below, it is visible that the system takes a couple of seconds to reach a constant value.

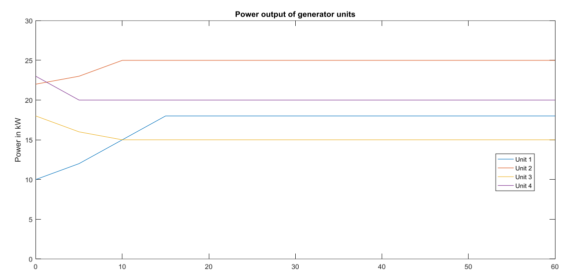

Fig. 1 Output power of generator units in kW without noise

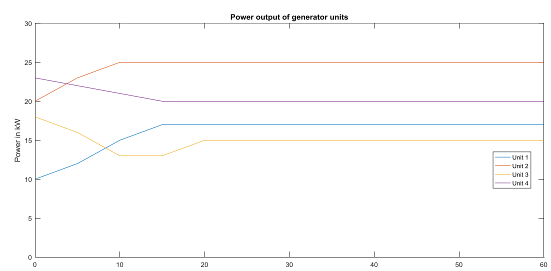

Fig. 2 Output power of generator units in kW with 0.2 noise variance

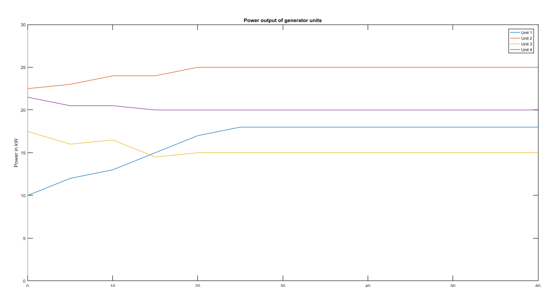

Fig. 3 Output power of generator units in kW with 0.5 noise variance

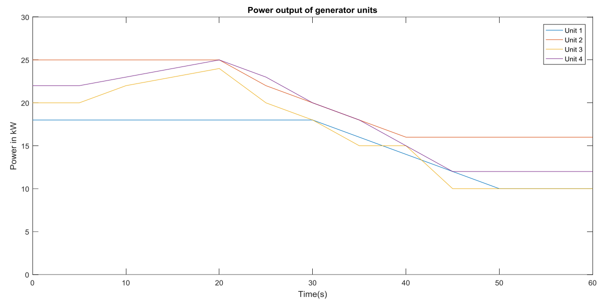

Fig. 4 Output power of generator units in kW with 0.8 noise variance

The higher the noise, the more time it is taken by the system to reach to the desired value. For noise variance of 0.2, the system takes about 20 sec to reach its desired output. For 0.5 noise variance, it takes around 25 sec and 45 sec for 0.8 noise variance.

Fig. (5), (6), (7) and (8) shows incremental costs of the 4 generator units for no noise condition, noise variance of 0.2, 0.5, and 0.8 respectively. During no noise condition, the algorithm helps set the incremental cost of all the generator units at a faster pace. With increase in noise variance, it takes time to reach to consensus. For higher noise levels, as seen in Fig. (8), it was difficult to achieve consensus and the system still has some instability. But for smaller and medium noise levels, the algorithm worked effectively in weeding out noise in the system. The average incremental cost ($/kWh) comes out to be around 6 as seen from the graphs, which is close to the values calculated manually.

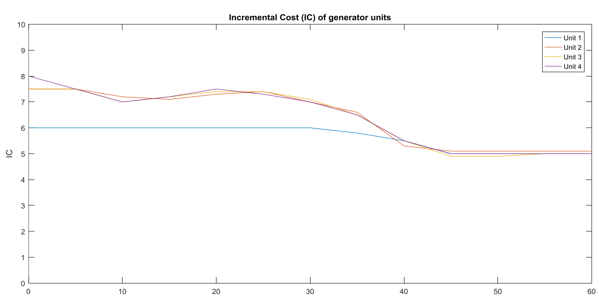

Fig. 5 Incremental Cost (IC) of generator units without noise

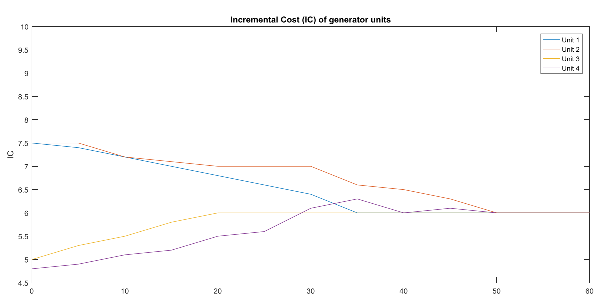

Fig. 6 Incremental Cost (IC) of generator units with 0.2 noise variance

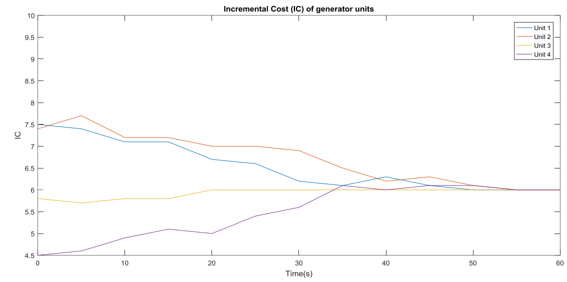

Fig. 7 Incremental Cost (IC) of generator units with 0.5 noise variance

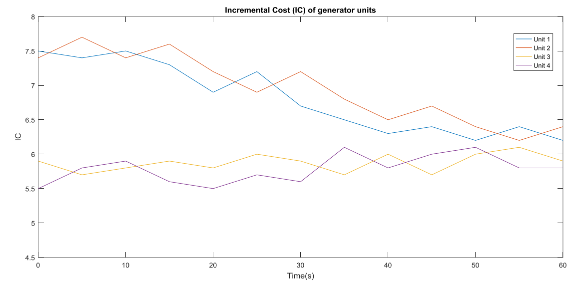

Fig. 8 Incremental Cost (IC) of generator units with 0.8 noise variance

Fig. (9) shows comparison between incremental costs of all the generator units with respect to time under different noise conditions. As seen from the graph, higher noise variance (green legend) is not easy to stabilize the microgrid during grid-connected mode. However, it works perfectly fine for low to medium level noise. This can be also be concluded from the graph by looking at the black and red legends with correspond to low and medium noise variance respectively.

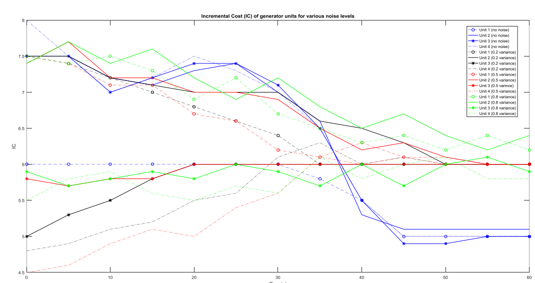

Fig. 9 Comparison of Incremental Cost (IC) of generator units for all conditions

VI. Conclusions

The proposed consensus based algorithm for economic dispatch works well for islanded microgrids [19]. In this paper, this proposed algorithm was used to analyze the behavior of microgrid during grid-connected mode. The microgrid shows good response during less and medium noise level. It brings the system close to its set point for incremental cost in less time. However, it was observed that it took longer for the system to reach its set point for noise levels higher than 0.8 variance. The system oscillated around the set point value for a longer time and hence can be concluded that it was not stable to the desired level. Thus, this economic dispatch algorithm is very good for small and medium noises as it brings stability to the system in a short span of time based on the case study.

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The noiseless consensus based algorithm for economic dispatch has been developed in [19] and analyzed for islanded microgrid performance. This paper analyzes the effect of this algorithm on grid connected microgrids which has not been carried out by other researchers to the best of authors' knowledge.

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