

Droop Control for Micro-grid Operations Including Generation Cost and Demand Side Management

Dulal Manna, Swapan K. Goswami and Pranab K. Chattopadhyay

Abstract—A new cost-based droop control method based upon generation cost and demand side cost management of the micro-grid is proposed in this paper. At present, many droop control methods have been developed based on either the power rating or the generation cost of the distributed generation (DG) unit, without consideration of the demand side participation in the operation and control. This exclusion might not be appropriate, if different types of consumers are connected in the micro-grid systems. This study proposes a droop control method considering both DG and load operating cost characteristics in order to minimize the generation cost of the micro-grid.

Index Terms—Distributed generation, droop control, generation cost, micro-grid operation, optimization of demand cost function.

NOMENCLATURE

P_{Gi}	Active power of the i^{th} generating unit.
Q_{Gi}	Reactive power of the i^{th} generating unit.
P_L	Active power component of the load.
Q_L	Reactive power component of the load.
P_D	Total Active power Demand of the system.
Q_D	Total Reactive power Demand of the system.
V	Bus voltage.
f	System frequency.
m_i	Frequency droop coefficients of the i^{th} generating unit.
n_i	Voltage droop coefficients of the i^{th} generating unit.
f_{0i}	Nominal frequency of the i^{th} generating unit.
$ V_0 $	Nominal phase voltage magnitude.
$K_{mi}, K_{fi}, K_{\xi i}, K_{oi}, K_{li}$	Conversion factors of the cost function of the i^{th} generating unit.
$a_i, b_i, c_i, \alpha_i, \beta_i, \gamma_i, \varepsilon_i, \rho_i$	Cost coefficients of the i^{th} generator.
v_i, u_i, ω_i	Coefficient for characterizing the loss model of the i^{th} converter.

m_{PG}	Active power stiffness factors of the micro grid.
n_{QG}	Reactive power stiffness factors of the micro grid.
K_{cPi}, K_{cQi}	Scaling factors of the i^{th} generator.
mC_{PG}	Active power cost-based stiffness factors of the micro-grid.
nC_{QG}	Reactive power cost-based stiffness factors of the micro-grid.
α	Active power exponent.
β	Reactive power exponent.
N_G	Number of generating unit bus.
N	Number of bus.

I. INTRODUCTION

MICRO-GRID systems, which are clusters of loads and distributed micro generators at the distribution level, can bring about potential benefits to the consumers such as improved supply reliability, quality and better utilization of resources [1] compared with conventional power systems.

Control and management of micro-grid systems can be achieved both by centralized and decentralized techniques [2]. However, the centralized control systems have some disadvantages too. For widely dispersed DGs, where communication links are not viable, autonomous droop schemes might be more appropriate compared with centralized control systems. Centralized schemes are generally favorable where micro-grid needs fulfill control flexibility requirements. Centralized schemes require fast communication links that might not be economically viable for an islanded micro-grid system. Stability and reliability of the micro-grid are also dependent on these communication links. If the links fail then the total system might collapse, such vulnerabilities cannot be tolerated.

For a decentralized scheme, a multi-agent approach [3] can be one possibility where the individual distributed energy resource (DER) units are controlled by local agents. These agents exchange data, and eventually make control decisions for their accompanied DER to determine their buying and selling bids. Multiple DERs with their own agents can, therefore, be connected together to form a micro-grid with plug-n-play flexibility [4]. However, data exchange among agents of different DGs will still require high-speed links, which when included, make this approach not fully autonomous [5]. The droop control scheme is very popular in isolated micro-grid systems as it only depends on locally measured variables and some predefined parameter ranges and does not require any communication links. The main drawback of a droop scheme

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is that it is only appropriate for normal steady-state operating conditions. Under fault conditions bus voltages and frequency of the system can dip appreciably in the droop control method. Some droop methods recommend [6], [7] inclusion of inductive virtual impedances with DERs bus.

The common objective of the traditional control schemes has been to share power among the DGs in proportion to their respective ratings. This objective is correct only if the DGs connected in the micro-grid are of the same type. But when different types of DGs, having different cost functions and emission characteristics are connected in the micro-grid, this scheme might not be appropriate based on economic considerations. New droop control strategies, based on a weighted combination of generation costs and some other factors, have been prescribed [1], [8]. Two cost-prioritized droop schemes 1) linear technique and 2) nonlinear technique have been proposed in [1].

To improve energy efficiency, supply reliability and operational flexibility of a micro-grid, demand-side participation in the operation and control of the micro-grid is being increasingly advocated [9]–[12]. Demand side management has the potential to reduce the overall cost of generation, as the occurrences of the loads can be shifted at convenient times, thus making the load curve flat. A technical challenge is that the operation and control of micro-grids rests on determining a rational method for allocating generation among different types of DG units.

To address this concern, a new droop scheme with due consideration to generation cost with demand-side participation is developed and presented in this paper.

The main goal and contributions of this paper include: 1) Development of an optimum droop scheme based on generation cost and the load-cost curve, 2) determination of the load sharing by the generators based on cost and 3) determination of the optimal value of the slope of the load-cost curve.

The optimization problem for realizing the issues mentioned above is solved using the Artificial Bee Colony algorithm (ABC). Interaction between the demand and the supply side cost of the micro-grid has been given due consideration in order to minimize the total generation costs.

II. COSTS ASSOCIATED WITH THE POWER GENERATION IN THE MICRO-GRID

A. Active Power Generation Cost

Active power generation by Distributed energy resources (DER) involves some generation costs, which when summed up for all DGs, gives the total cost for active generation.

Generation costs $\{CP_i(P_{Gi})\}$ of an engine-driven DG unit, in general, can be grouped under two broad categories, viz, 1) operating costs $\{CP_{Oi}(P_{Gi})\}$ and 2) emission penalties or incentives $\{CP_{\xi i}(P_{Gi})\}$ and can be represented as,

$$CP_i(P_{Gi}) = CP_{Oi}(P_{Gi}) + CP_{\xi i}(P_{Gi}). \quad (1)$$

The function commonly quoted for representing operational costs (covering maintenance and fuel costs) and a penalty function associated with greenhouse gas emission incurred by

generators driven by internal combustion engines or micro-turbines [1], [13], has the form:

$$\begin{aligned} CP_i(P_{Gi}) &= \text{maintenance cost} + \text{fuel cost} \\ &\quad + \text{emission penalty} \\ &= K_{mi} \times P_{Gi} + K_{fi}(a_i + b_i \times P_{Gi} + c_i \times P_{Gi}^2) \\ &\quad + K_{\xi i}\{\alpha_i + \beta_i \times P_{Gi} + \gamma_i \times P_{Gi}^2 \\ &\quad + \varepsilon_i \times \exp(\rho_i \times P_{Gi})\}. \end{aligned} \quad (2)$$

The power output of renewable sources is dependent on climatic conditions. A dispatchable and renewable DG is one with storage included to allow for flexible generation control. Cost functions of the renewable DG would include relevant costs incurred by the storage and can be represented as [8],

$$CP_i(P_{Gi}) = K_{oi} \{P_{Gi} + K_{li}(v_i + u_i \times P_{Gi} + \omega_i \times P_{Gi}^2)\}. \quad (3)$$

B. Reactive Power Generation Cost

Though generation of reactive power does not require any direct fuel consumption, the cost of reactive power generation, $CQ_i(Q_{Gi})$ of a DG can be primarily linked to the accompanied active power losses and imposed penalty to reactive power production. The reactive power cost can be calculated as [8],

$$CQ_i(Q_{Gi}) = CP_i(P_{Gi} + \Psi \times Q_{Gi}) - CP_i(P_{Gi}) \quad (4)$$

where the value of Ψ are nearly 3% and 5% for engine-driven DGs and renewable DGs respectively [8].

Total generation cost (TGC) of the micro-grid can be calculated as,

$$TGC = TAGC + TRGC$$

where $TAGC = \sum_{i=1}^n CP_i(P_{Gi})$ is the total active power generation cost and $TRGC = \sum_{i=1}^n CQ_i(Q_{Gi})$ is the total reactive power generation cost.

III. GENERATION ALLOCATION—EXISTING SOLUTION TECHNIQUE

A. Traditional Droop Based Method

P - f droop and Q - V droop controls used in conventional grids have been successfully adopted in the micro-grid environment [14], [15]. In conventional P - f droop and Q - V droop control, the operating frequency f_i^* and voltage V_i^* are given as,

$$f_i^* = f_{0i} - m_i \times P_{Gi} \quad (5)$$

$$|V_i^*| = |V_{0i}| - n_i \times Q_{Gi}. \quad (6)$$

The droop gain m_i and n_i can be defined as [16],

$$m_i = \frac{f_{i,\max} - f_{i,\min}}{P_{gi,\max}} \quad \text{and} \quad n_i = \frac{|V|_{i,\max} - |V|_{i,\min}}{Q_{gi,\max}}.$$

Realization of the droop control would then involve measurement of the DG terminal voltages and currents for computing its active and reactive power outputs. These P_{Gi} and Q_{Gi} should next be substituted into (5) and (6) to obtain the frequency f_i^* and voltage magnitude $|V_i^*|$. This will ensure sharing of active and reactive power in proportion to machine

ratings as long as the droop coefficients of (5) and (6) are tuned according to the equations:

$$m_i \times P_{Gi} = \text{constant} \\ \text{and } n_i \times Q_{Gi} = \text{constant}$$

where, $i = 1, 2, \dots, n_d$; n_d being the number of droop controlled DG buses.

$$\text{e.g. } m_1 \times P_{G1} = m_2 \times P_{G2} = \dots = m_{n_d} \times P_{G_{n_d}} \quad (7)$$

$$\text{and, } n_1 \times Q_{G1} = n_2 \times Q_{G2} = \dots = n_{n_d} \times Q_{G_{n_d}} \quad (8)$$

So, power sharing by each DG unit can be regulated as follows:

Power balance equation of the power system considered as,

$$\sum_{i=1}^{n_d} P_{Gi} = P_D \text{ and } \sum_{i=1}^{n_d} Q_{Gi} = Q_D$$

where, P_D = (total active power demand + active power loss) and, Q_D = (total reactive power demand + reactive power loss)

$$\text{e.g. } P_{G1} + P_{G2} + \dots + P_{G_{n_d}} = P_D \quad (9)$$

$$\text{and, } Q_{G1} + Q_{G2} + \dots + Q_{G_{n_d}} = Q_D \quad (10)$$

From (7), (9) can be expressed as,

$$\begin{aligned} \therefore P_{G1} + \frac{m_1}{m_2} \times P_{G1} + \frac{m_1}{m_3} \times P_{G1} + \dots + \frac{m_1}{m_{n_d}} \times P_{G1} &= P_D \\ \Rightarrow P_{G1} \times m_1 \times \left(\frac{1}{m_1} + \frac{1}{m_2} + \frac{1}{m_3} + \dots + \frac{1}{m_{n_d}} \right) &= P_D \\ \Rightarrow P_{G1} = \frac{m_{PG}}{m_1} \times P_D \end{aligned}$$

$$\text{where } m_{PG} = \left(\frac{1}{m_1} + \frac{1}{m_2} + \frac{1}{m_3} + \dots + \frac{1}{m_{n_d}} \right)^{-1}.$$

So, for the i^{th} DG unit, active power generation can be formulated as,

$$P_{Gi} = \frac{m_{PG}}{m_i} \times P_D$$

Similarly, reactive power generation of the i^{th} DG unit can be formulated as,

$$Q_{Gi} = \frac{n_{QG}}{n_i} \times Q_D$$

$$\text{where } n_{QG} = \left(\frac{1}{n_1} + \frac{1}{n_2} + \frac{1}{n_3} + \dots + \frac{1}{n_{n_d}} \right)^{-1}.$$

B. Cost-based Droop Model

Nutkani *et al.* [1] developed a new droop model based on generation cost of the DG units for islanded micro-grid systems, where different types of DG units are integrated.

The droop equations based on cost function can be written as,

$$|V_{d,i}| = |V_{\max,i}| - nQ_i \times CQ_i(Q_{Gi})' \quad (11)$$

$$f_i = f_{\max,i} - mP_i \times CP_i(P_{Gi})' \quad (12)$$

where $|V_{d,i}|$ and f_i are the voltage magnitude and frequency of the droop controlled bus at the point of connection (PC) in

Fig. 1) with the micro-grid. The cost functions $CQ_i(Q_{Gi})'$ and $CP_i(P_{Gi})'$ are defined as [13],

$$CP_i(P_{Gi})' = \frac{CP_i(P_{Gi}) - CP_i(P_{Gi} = 0)}{P_{Gi,\max}} \quad (13)$$

and,

$$CQ_i(Q_{Gi})' = \frac{CQ_i(Q_{Gi}) - CQ_i(Q_{Gi} = 0)}{Q_{Gi,\max}} \quad (14)$$

where mP_i and nQ_i are active and reactive power generation coefficients, which can be represented as,

$$mP_i = \frac{f_{\max,i} - f_{\min,i}}{K_{cP_i}} \quad (15)$$

and,

$$nQ_i = \frac{|V|_{\max,i} - |V|_{\min,i}}{K_{cQ_i}}. \quad (16)$$

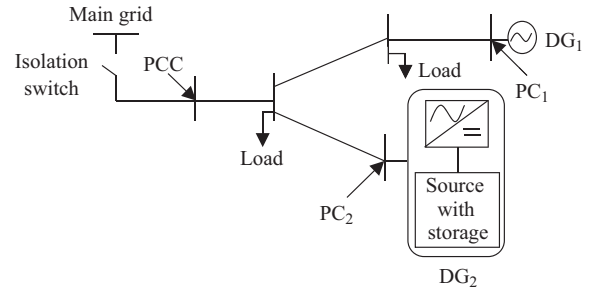


Fig. 1. Schematic diagram of a generic two-DER micro-grid.

The mathematical expressions for maximum and minimum frequency and voltage of the i^{th} DG unit can be expressed as [1],

$$\begin{aligned} f_{\max,i} &= f_{\max} - \frac{f_{\max} - f_{\min}}{2} \\ &\times \frac{CP_i(P_{Gi} = 0) - CP_{\min}(P_{Gi} = 0)}{CP_{\max}(P_{Gi} = 0) - CP_{\min}(P_{Gi} = 0)}; \\ f_{\min,i} &= \frac{f_{\max} + f_{\min}}{2} - \left\{ \frac{f_{\max} - f_{\min}}{2} \right. \\ &\times \left. \frac{CP_i(P_{Gi} = P_{Gi,\max}) - CP_{\min}(P_{Gi} = P_{G,\max})}{CP_{\max}(P_{Gi} = P_{G,\max}) - CP_{\min}(P_{Gi} = P_{G,\max})} \right\}; \\ |V|_{\max,i} &= |V|_{\max}; \end{aligned} \quad (17)$$

and

$$\begin{aligned} |V|_{\min,i} &= \frac{|V|_{\max} + |V|_{\min}}{2} - \left\{ \frac{|V|_{\max} - |V|_{\min}}{2} \right. \\ &\times \left. \frac{CQ_i(Q_{Gi} = Q_{Gi,\max}) - CQ_{\min}(Q_{Gi} = Q_{G,\max})}{CQ_{\max}(Q_{Gi} = Q_{G,\max}) - CQ_{\min}(Q_{Gi} = Q_{G,\max})} \right\} \end{aligned}$$

where $f_{\max}$, $f_{\min}$ and $|V|_{\max}$, $|V|_{\min}$ are the maximum and minimum value of the frequency and voltage of the system respectively.

In (14), if the reactive power cost is considered as $CQ_i(Q_{Gi} = 0) \approx 0$ when $Q_{Gi} = 0$, the equation reduces to,

$$CQ_i(Q_{Gi})' = \frac{CQ_i(Q_{Gi})}{Q_{Gi,\max}} \quad (18)$$

In (15) and (16) the scaling factor are needed for normalizing the active and reactive generation costs as the dimensions of the equations remain Hz and Volt respectively. One possibility is to set the scaling factors as the maximum costs of the individual DGs such as proportional power sharing based on ratings. That means,

$$K_{cP_i} = CP_i (P_{Gi} = P_{Gi,max})'$$

$$K_{cQ_i} = CQ_i (Q_{Gi} = Q_{Gi,max})'.$$

At a steady state condition the frequency of the micro-grid must be constant. e.g., the frequency of each DG unit at point of connection (PC) must be the same, i.e.,

$$f_1 = f_2 = \dots = f_{nd}. \quad (19)$$

Voltage magnitude at PC of DG units can be considered as,

$$V_1 \approx V_2 \approx \dots \approx V_{nd}. \quad (20)$$

For steady state operations of the system, the relationship (21) and (22) can be obtained from (11) and (12), if the maximum and minimum limits of the voltage magnitude and frequency of all DG units are considered to be the same. e.g. $f_{max,i} - f_{min,i} = \text{constant}$ and $|V|_{max,i} - |V|_{min,i} = \text{constant}$ for all DGs.

$$\frac{CP_1 (P_{G1})'}{CP_1 (P_{G1} = P_{G1,max})'} = \frac{CP_2 (P_{G2})'}{CP_2 (P_{G2} = P_{G2,max})'}$$

$$= \dots = \frac{CP_{nd} (P_{Gnd})'}{CP_{nd} (P_{Gnd} = P_{Gnd,max})'} \quad (21)$$

$$\frac{CQ_1 (Q_{G1})'}{CQ_1 (Q_{G1} = Q_{G1,max})'} = \frac{CQ_2 (Q_{G2})'}{CQ_2 (Q_{G2} = Q_{G2,max})'}$$

$$= \dots = \frac{CQ_{nd} (Q_{Gnd})'}{CQ_{nd} (Q_{Gnd} = Q_{Gnd,max})'} \quad (22)$$

The DG with the lowest maximum cost $CP_i (P_{Gi} = P_{Gi,max})'$ must also operate at the lowest actual cost $CP_i (P_{Gi})'$ in order to satisfy the equality of (21) and (22), e.g. the scaling factor can be set as the maximum costs of the most expensive DG instead of the maximum costs of the individual DGs as in equation (17),

$$K_{cP_i} = \max \left\{ \begin{array}{l} CP_1 (P_{G1} = P_{G1,max})', \\ CP_2 (P_{G2} = P_{G2,max})', \dots, \\ CP_{nd} (P_{Gnd} = P_{Gnd,max})' \end{array} \right\}$$

$$K_{cQ_i} = \max \left\{ \begin{array}{l} CQ_1 (Q_{G1} = Q_{G1,max})', \\ CQ_2 (Q_{G2} = Q_{G2,max})', \dots, \\ CQ_{nd} (Q_{Gnd} = Q_{Gnd,max})' \end{array} \right\}.$$

Then the equality equations (21) and (22) become,

$$CP_1 (P_{G1})' = CP_2 (P_{G2})' = \dots = CP_{nd} (P_{Gnd})' \quad (23)$$

$$CQ_1 (Q_{G1})' = CQ_2 (Q_{G2})' = \dots = CQ_{nd} (Q_{Gnd})' \quad (24)$$

C. Power Sharing Method Based on the Cost Function

The power flow equality constraint of the system can be written as,

$$\sum_{i=1}^{nd} P_{Gi} = P_D \quad \text{and} \quad \sum_{i=1}^{nd} Q_{Gi} = Q_D$$

To satisfy the equality of (23) and (24), P_{Gi} and Q_{Gi} can be adjusted to,

$$P_{Gi} = \frac{mC_{PG}}{CP_i (P_{Gi})} \times P_D \quad (25)$$

$$\text{and, } Q_{Gi} = \frac{nC_{QG}}{CQ_i (Q_{Gi})} \times Q_D \quad (26)$$

where

$$mC_{PG} = \left(\frac{1}{CP_1 (P_{G1})} + \frac{1}{CP_2 (P_{G2})} + \frac{1}{CP_3 (P_{G3})} + \dots + \frac{1}{CP_{nd} (P_{Gnd})} \right)^{-1}$$

$$nC_{QG} = \left(\frac{1}{CQ_1 (Q_{G1})} + \frac{1}{CQ_2 (Q_{G2})} + \frac{1}{CQ_3 (Q_{G3})} + \dots + \frac{1}{CQ_{nd} (Q_{Gnd})} \right)^{-1}.$$

IV. PROBLEM FORMULATION FOR THE PROPOSED SOLUTION

To minimize the total operating cost of the micro-grid, the objective function of this work is to consider various DG operating characteristics as follows:

The first part of the objective function represents frequency deviation as in (27).

$$F_1 = \left\{ \begin{array}{l} (CP_1 (P_{G1})' - CP_2 (P_{G2})')^2 \\ + (CP_2 (P_{G2})' - CP_3 (P_{G3})')^2 + \dots + \\ (CP_{nd-1} (P_{Gnd-1})' - CP_{nd} (P_{Gnd})')^2 \end{array} \right\} \quad (27)$$

where nd is the number of droop controlled DG buses.

The second part of the objective function represents voltage deviation of the droop controlled buses, as in (28).

$$F_2 = \left\{ \begin{array}{l} (CQ_1 (Q_{G1})' - CQ_2 (Q_{G2})')^2 \\ + (CQ_2 (Q_{G2})' - CQ_3 (Q_{G3})')^2 + \dots + \\ (CQ_{nd-1} (Q_{Gnd-1})' - CQ_{nd} (Q_{Gnd})')^2 \end{array} \right\} \quad (28)$$

So, the objective function of the system is,

$$F = F_1 + F_2. \quad (29)$$

The equality constraints are the power balance equations of the system (as in (30)) and the inequality constraints are the generation and voltage limit constraints (as in (31)).

Power flow equalities in the system are given as follows:

$$\sum P_G = P_D \quad \text{and} \quad \sum Q_G = Q_D. \quad (30)$$

Active and reactive power output and voltage magnitudes restricted by their generation limit constraints are given as follows:

$$\left. \begin{array}{l} P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max}; \quad i = 1, \dots, N_G \\ Q_{Gi,min} \leq Q_{Gi} \leq Q_{Gi,max}; \quad i = 1, \dots, N_G \\ \text{and, } V_{i,min} \leq V_i \leq V_{i,max}; \quad i = 1, \dots, N \end{array} \right\}. \quad (31)$$

The vector x of the dependent variables is given as follows:

$$x^T = [P_L, Q_L, f, V].$$

P_L , Q_L are the active and reactive power components of the load, “V” is the bus voltage and “f” is the steady state frequency of the system.

The vector u of the control variables is chosen as,

$$u = [P_G, Q_G]^T$$

where P_G, Q_G are the active and reactive power generation of the DG units.

V. PROPOSED SOLUTION TECHNIQUE

A. Modified Cost Function

Participation of the demand side in the micro-grid operation can contribute positively to settle the market clearing price (MCP). The main idea is to determine the MCP for the dispatch of an aggregate of different types of DGs to an aggregate of different types of consumers.

Sellers (generating unit in this case) would receive the MCP for their electricity and all consumers would pay the MCP.

If $TAGC$ denotes the total active power generation cost of the system, then this cost must be contributed by the total demand. Let P_D be the active power demand at cost $TAGC$ obtained from the “n” number of consumers connected in the micro-grid. According to [18], P_D can be expressed as,

$$P_D = \left(\sum_{j=1}^n \frac{cP_{D,j}}{m_{D,j}} - \sum_{j=1}^n \frac{TAGC}{m_{D,j}} \right) \quad (32)$$

Fig. 2 shows the demand and generation cost curves. Here $cP_{D,j}$ is the cost axis intercept of the demand curve that varies with the type of consumer and $m_{D,j}$ is the slope of the active power of the load.

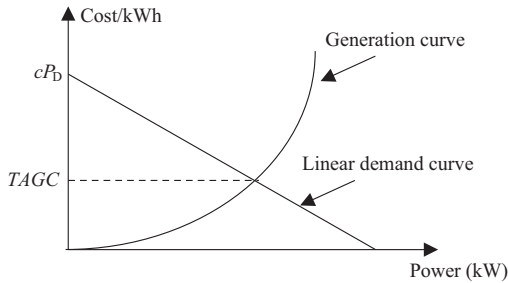


Fig. 2. Demand and Generation curves.

From (25), generation cost can be calculated as,

$$CP_i(P_{Gi}) = \frac{mC_{PG}}{P_{Gi}} \times P_D$$

Now considering the demand side cost curve as in (32), the generation cost function can be expressed as,

$$CP_i(P_{Gi}, P_D) = \frac{mC_{PG}}{P_{Gi}} \times \left(\sum_{j=1}^n \frac{cP_{D,j}}{m_{D,j}} - \sum_{j=1}^n \frac{TAGC}{m_{D,j}} \right) \quad (33)$$

Similarly, $CQ_i(Q_{Gi}, Q_D)$ can be formulated as,

$$CQ_i(Q_{Gi}, Q_D) = \frac{nC_{QG}}{Q_{Gi}} \times \left(\sum_{j=1}^n \frac{cQ_{D,j}}{n_{D,j}} - \sum_{j=1}^n \frac{TRGC}{n_{D,j}} \right) \quad (34)$$

where $cP_{D,j}$ and $cQ_{D,j}$ are the active and reactive power cost axis intercept of the demand curve, $m_{D,j}$ and $n_{D,j}$ are the slopes of the active and reactive power of the load, $TAGC$ and $TRGC$ are the total active power generation cost and total reactive power generation cost respectively.

From (33) and (34) $TAGC$ and $TRGC$ can be calculated as,

$$TAGC = \frac{\sum_{j=1}^n (cP_{D,j}/m_{D,j})}{\sum_{j=1}^n (1/m_{D,j})} - \frac{CP_i(P_{Gi}, P_D) \times P_{Gi}}{mC_{PG} \times \sum_{j=1}^n (1/m_{D,j})}$$

$$TRGC = \frac{\sum_{j=1}^n (cQ_{D,j}/n_{D,j})}{\sum_{j=1}^n (1/n_{D,j})} - \frac{CQ_i(Q_{Gi}, Q_D) \times Q_{Gi}}{nC_{QG} \times \sum_{j=1}^n (1/n_{D,j})}$$

The $MCP (= TGC)$ can be calculated as,

$$MCP = TAGC + TRGC$$

The demand cost curve slope (m_D and n_D) can be formulated using (32) (as in Appendix A).

B. Proposed Droop Scheme with Demand Cost Slope and Generation Cost

In the present work a new cost-based droop control scheme has been proposed, where both generation cost and demand side cost are considered.

The proposed droop equations based on both of these cost characteristics are represented as,

$$|V_{d,i}| = |V_{\max,i}| - n_d Q_i \times CQ_{Di}(Q_{Gi}, Q_D)' \times Q'_{Gi} \quad (35)$$

$$f_i = f_{\max,i} - m_d P_i \times CP_{Di}(P_{Gi}, P_D)' \times P'_{Gi} \quad (36)$$

The cost functions $CQ_{Di}(Q_{Gi}, Q_D)'$ and $CP_{Di}(P_{Gi}, P_D)'$ are set as,

$$CQ_{Di}(Q_{Gi}, Q_D)' = \frac{CQ_i(Q_{Gi}, Q_D)}{Q_{Gi,\max}} \quad (37)$$

and,

$$CP_{Di}(P_{Gi}, P_D)' = \frac{CP_i(P_{Gi}, P_D) - CP_i(P_{Gi} = 0)}{P_{Gi,\max}} \quad (38)$$

where $CQ_i(Q_{Gi}, Q_D)$ and $CP_i(P_{Gi}, P_D)$ are the reactive and active power cost functions respectively which are dependent on both generation and demand cost curves. It can be formulated as (33) and (34).

In (35) and (36), $Q'_{Gi} = \frac{Q_{Gi}}{Q_{G\max,i}}$ and $P'_{Gi} = \frac{P_{Gi}}{P_{G\max,i}}$, $n_d Q_i$ and $m_d P_i$ are the cost-based droop coefficients, which can be represented as,

$$m_d P_i = \frac{f_{\max,i} - f_{\min,i}}{CP_{D\max}(P_{Gi}, P_D)'} \quad (39)$$

$$n_d Q_i = \frac{|V|_{\max,i} - |V|_{\min,i}}{CQ_{D\max}(Q_{Gi}, Q_D)'} \quad (40)$$

where, $CQ_{D\max}(Q_{Gi}, Q_D)'$ and $CP_{D\max}(P_{Gi}, P_D)'$ can be formulated as,

$$CQ_{D\max}(Q_{Gi}, Q_D)' = \max \left\{ \begin{array}{l} CQ_{D\max,1}(Q_{G1}, Q_D)', \\ CQ_{D\max,2}(Q_{G2}, Q_D)', \dots, \\ CQ_{D\max,nd}(Q_{Gnd}, Q_D)' \end{array} \right\}$$

and,

$$CP_{D\max}(P_{Gi}, P_D)' = \max \left\{ \begin{array}{l} CP_{D\max,1}(P_{G1}, P_D)', \\ CP_{D\max,2}(P_{G2}, P_D)', \dots, \\ CP_{D\max,nd}(P_{Gnd}, P_D)' \end{array} \right\}$$

where

$$CQ_{D\max,i}(Q_{Gi}, Q_D)' = CQ_{Di} \left(Q_{Gi} = Q_{G\max,i}, Q_D = \sum_{i=1}^n Q_{L,i}^{\text{nominal}} \right)'$$

and, $CP_{D\max,i}(P_{Gi}, P_D)' = CP_{Di} \left(P_{Gi} = P_{G\max,i}, P_D = \sum_{i=1}^n P_{L,i}^{\text{nominal}} \right)'$.

It should be mentioned here that, as the DGs will share the loads on the basis of the costs, it could result into a low duty cycle of the DGs resulting in expensive operations. However, once the capacity of the low cost DGs are exhausted, the capacity of the higher cost DGs has to be explored for catering the loads. Thus, overall system efficiency will not be hampered. In fact, this operational strategy is followed for large fossil fueled power stations as well.

VI. SOLUTION ALGORITHM

In this work the generation cost has been optimized using the ABC algorithm as follows:

Step 1: Input bus and line data and $V_{\max}$, $V_{\min}$, $f_{\max}$, $f_{\min}$, $PG_{\max}$, $PG_{\min}$, $QG_{\max}$ and $QG_{\min}$;

Step 2: Input for ABC:

$UB = [PG_{\max}; QG_{\max}]$ and $LB = [PG_{\min}; QG_{\min}]$ where UB and LB are the upper and the lower bound of PG and QG . Initialize $V = V_{\max}$, $f = f_{\max}$;

Step 3: Calculate the generation cost using (2)–(4);

Step 4: Calculate the voltage and frequency dependent static load using appropriate multiplication factors as follows [14]:

$$P_{Li} = P_{0i} \times |V_i|^\alpha \times (1 + K_{pf} \times \Delta f)$$

$$Q_{Li} = Q_{0i} \times |V_i|^\beta \times (1 + K_{qf} \times \Delta f)$$

where Δf is the frequency deviation, $\Delta f = f - f_0$, α is active power exponent, β is reactive power exponent, P_0 is initial load active power, Q_0 is initial load reactive power, K_{pf} and K_{qf} are the constants;

Step 5: Total demand, $P_D = \sum_{i=1}^N P_{Li}$ + active power loss, and, $Q_D = \sum_{i=1}^N Q_{Li}$ + reactive power loss;

Step 6: Total generation, $P_{Gn} = \sum_{i=1}^{nd} P_{Gi}$; $Q_{Gn} = \sum_{i=1}^{nd} Q_{Gi}$; nd is the total number of the droop bus bar.

Step 7: Find load flow solution;

Step 8: Calculate the value of the objective function for ABC using (29);

Step 9: Advance the number of the cycle by 1;

Step 10: If the number of the cycle is less than the maximum number of cycles, go to step 3, otherwise stop.

VII. RESULT AND DISCUSSION:

As discussed in Section II, generation cost depends on the type of the DER. In the present work three types of cost functions are considered [13], [17].

$$^1CP(P_G) = 0.04P_G + 0.01(1 + 6P_G + 14P_G^2) + 0.02 \left\{ 2.5 - 6.047P_G + 5.638P_G^2 \right\} + 25 \times 10^{-3} \exp(3.33P_G)$$

$$^2CP(P_G) = 0.04P_G + 0.01(4 + 12P_G + 2P_G^2) + 0.02 \left\{ 4.09 - 5.554P_G + 6.49P_G^2 \right\} + 10 \times 10^{-3} \exp(2.857P_G)$$

$$^3CP(P_G) = 0.05\{P_G + 0.1(0.02 - 0.1P_G + 0.1P_G^2)\}$$

In the prefix of the cost function $\{CP(P_G)\}$ in (41), 1 and 2 represent the cost functions of the Engine Driven DG units and 3 represents the cost function of the dispatchable renewable type DG unit.

To test and verify the effectiveness of the proposed algorithm, a 38 bus balanced test system is chosen with five DG units placed at bus 1, 35, 36, 37 and 38 as shown in Fig. 3. The nominal value of the frequency, voltage magnitude and ratings of the DG units are given in Table I. The bus and the line data of the system and the value of constants K_{pf} , K_{qf} , the nominal load power is as in [19]. Load type, the active and reactive power exponents (α and β) and active and reactive power cost axis intercepts (cP_D and cQ_D) are given in Table II.

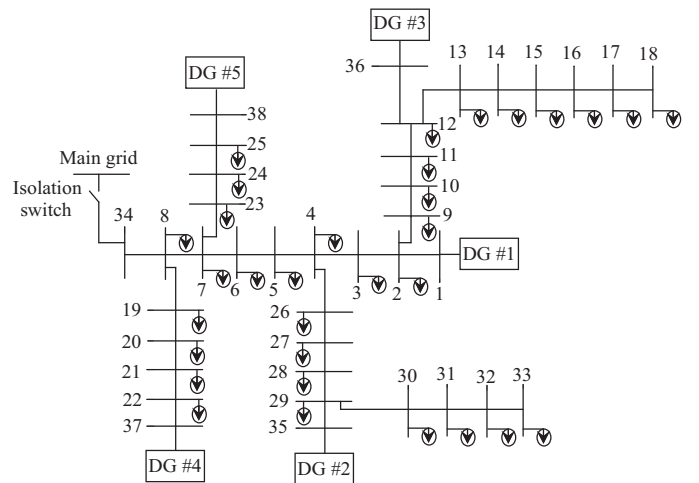


Fig. 3. 38-bus distribution system.

Two cases were considered to compare the proposed droop scheme with the non-linear (or cost-based droop method [1]) and traditional droop schemes [14] in terms of load sharing

TABLE I
DGs LOCATION, NOMINAL SETTING AND RATINGS

DG #	Location (Bus Number)	f^* (PU)	V^* (p.u.)	$P_{\max}$	$Q_{\max}$
1	1	1	1.01	1.0	0.6
2	35	1	1.01	3.0	1.8
3	36	1	1.01	1.5	0.9
4	37	1	1.01	1.5	1.5
5	38	1	1.01	1.0	0.9

TABLE II
LOAD TYPES AND COST DATA

Bus	cP_D	cQ_D	α	β	Load Type ^a	Bus	cP_D	cQ_D	α	β	Load Type ^a
1	0	0	0	0	—	20	6	4.1	1.51	3.4	C
2	6	4.1	1.51	3.4	C	21	8	9.1	0.18	6.0	I
3	6	4.1	1.51	3.4	C	22	7	7.7	0.92	4.04	R
4	8	9.1	0.18	6.0	I	23	6	4.1	1.51	3.4	C
5	7	7.7	0.92	4.04	R	24	6	4.1	1.51	3.4	C
6	6	4.1	1.51	3.4	C	25	6	4.1	1.51	3.4	C
7	8	9.1	0.18	6.0	I	26	6	4.1	1.51	3.4	C
8	7	7.7	0.92	4.04	R	27	8	9.1	0.18	6.0	I
9	8	9.1	0.18	6.0	I	28	6	4.1	1.51	3.4	C
10	6	4.1	1.51	3.4	C	29	6	4.1	1.51	3.4	C
11	6	4.1	1.51	3.4	C	30	6	4.1	1.51	3.4	C
12	7	7.7	0.92	4.04	R	31	7	7.7	0.92	4.04	R
13	6	4.1	1.51	3.4	C	32	7	7.7	0.92	4.04	R
14	7	7.7	0.92	4.04	R	33	6	4.1	1.51	3.4	C
15	6	4.1	1.51	3.4	C	34	0	0	0	0	—
16	8	9.1	0.18	6.0	I	35	0	0	0	0	—
17	6	4.1	1.51	3.4	C	36	0	0	0	0	—
18	8	9.1	0.18	6.0	I	37	0	0	0	0	—
19	7	7.7	0.92	4.04	R	38	0	0	0	0	—

^aC—Commercial; R—Residential; I—Industrial

by DG units, total generation cost, and voltage and frequency regulation. Results obtained from all the cases are discussed in the following.

A. Case I: Similar Type of DGs with Different Cost Co-efficient

In Case I, the nature of the cost function of all DGs in the micro-grid are of a similar type (Engine Driven DG unit), but with different cost coefficients. The cost functions of DG #1, DG #2, DG #3 and DG #5 are considered as type 1, DG #4 is considered to have a cost function of type 2 (as in (41)). With this operating condition, the output power and generation costs as calculated by the proposed method, along with non-linear and traditional droop schemes are given in Table III for the sake of comparison.

From Table III, it can be seen that the optimal values of the

total generation cost of the system obtained by the proposed and the non-linear method are less compared to traditional methods. The total generation cost is slightly less in the proposed method compared with the non-linear method for the same type DG units connected in the micro-grid.

Fig. 4 shows graphically a comparison of bus voltage corresponding to the power output obtained under different methods. It can be observed that the voltage profile is better in the proposed method as compared to the other two methods.

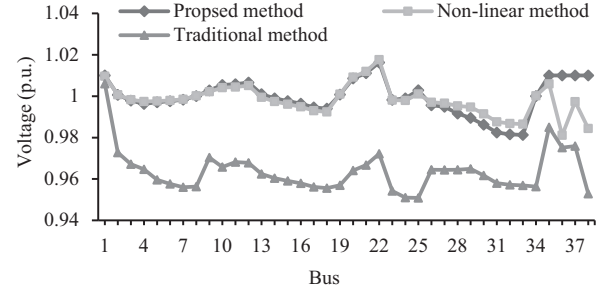


Fig. 4. Comparison of voltage magnitudes (Case I).

In Table IV, the output bus voltage and angle from the load flow solution and the optimal value of the slope (m_D and n_D) of load curve are given.

Table V shows the optimal values of the generation cost co-efficient obtain from the proposed and nonlinear methods.

The power among all the DG units shared proportionally (K_{cost}) based on their cost co-efficient are shown in Fig. 5.

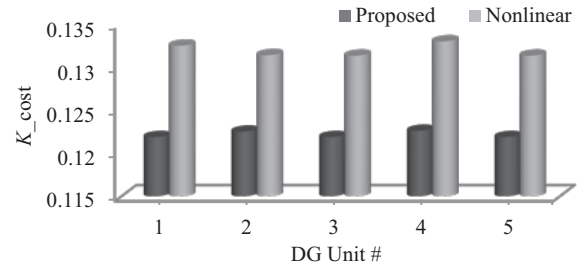


Fig. 5. Comparison of K_{cost} (Case I).

The maximum error in proportional power sharing is 0.597535% by the proposed method whereas the value is 0.938882524% by the nonlinear method. The expression of K_{cost} is given in Appendix B. It is also observed that

TABLE III
OPTIMAL VALUE OF GENERATION COST, DG'S OUTPUT POWER AND FREQUENCY OF THE SYSTEM

DG Bus	Non-linear Method				Traditional Method				Proposed Method			
	P_G (p.u.)	Q_G (p.u.)	$APGC$	$RPGC$	P_G (p.u.)	Q_G (p.u.)	$APGC$	$RPGC$	P_G (p.u.)	Q_G (p.u.)	$APGC$	$RPGC$
Bus #1	0.72156	0.135337	0.1820	0.0015	1.681	0.563	0.8739	0.0219	0.6996	0.0779	0.1742	0.0008
Bus #35	0.72156	0.761529	0.1820	0.0084	0.841	0.751	0.2294	0.0099	0.6755	0.4469	0.1659	0.0046
Bus #36	0.72156	0.618777	0.1820	0.0068	0.38	0.3	0.0752	0.0011	0.6996	0.8052	0.1742	0.0086
Bus #37	0.970243	0.378002	0.2903	0.0058	0.56	0.6	0.1308	0.0050	1.0370	0.2354	0.3259	0.0039
Bus #38	0.72156	0.553278	0.1820	0.0061	0.38	0.3	0.0752	0.0011	0.6996	0.8090	0.1742	0.0087
Total	3.8565	2.4469	1.0183	0.0287	3.842	2.514	1.3845	0.0390	3.8114	2.3744	1.0145	0.0266
			$TGC = 1.047$				$TGC = 1.424$				$TGC = 1.041$	
Frequency (p.u.)	0.9900				0.9987				0.999884			

$APGC = \{C P_i(P_{Gi})\}$ —Active power generation cost; $RPGC = \{C Q_i(Q_{Gi})\}$ —Reactive power generation cost; P_G —Active power generation; Q_G —Reactive power generation.

TABLE IV
VOLTAGE AND ANGLE FROM THE LOAD FLOW SOLUTION AND VALUES OF THE LOAD COST CURVE SLOPE (m_D AND n_D)

Bus	Voltage Magnitude (p.u.)	Voltage Angle ($^\circ$)	m_D	n_D	Bus	Voltage Magnitude (p.u.)	Voltage Angle ($^\circ$)	m_D	n_D
1	1.01	0	0	0	20	1.008545	-0.05865	54.75496	96.76939
2	1.000642	-0.41619	24.91219	39.89763	21	1.011091	0.062335	75.94541	215.9826
3	0.997899	-0.34337	24.90199	40.54985	22	1.01625	0.321718	64.7056	180.3394
4	0.996258	-0.38064	116.4919	454.2513	23	0.998238	-0.52951	54.77084	79.41616
5	0.9971	-0.41482	99.70618	251.3031	24	0.998952	-0.68573	11.65552	19.54649
6	0.997546	-0.43246	41.3854	50.05801	25	1.002913	-0.801	11.8281	18.08521
7	0.998342	-0.45195	77.53614	219.0779	26	0.99564	-0.35554	83.25818	163.6694
8	1.000034	-0.40036	59.2401	124.9489	27	0.994902	-0.31974	116.8684	366.0508
9	1.002805	-0.58513	115.2952	443.8116	28	0.991597	-0.20178	84.16124	209.6172
10	1.005462	-0.7472	82.33494	195.643	29	0.989496	-0.10178	42.02924	61.22183
11	1.005821	-0.7794	109.05	131.0264	30	0.986252	-0.01841	25.2932	7.237128
12	1.006635	-0.84273	98.69855	209.1888	31	0.982431	-0.09406	41.11063	117.2279
13	1.001037	-0.92007	82.33292	114.0017	32	0.981579	-0.11458	28.50258	76.73407
14	0.998965	-0.9864	49.84337	93.62784	33	0.981315	-0.12145	83.09235	101.8352
15	0.997678	-1.0184	82.74828	403.5526	34	1.000034	-0.40036	0	0
16	0.996433	-1.03826	116.3941	449.5856	35	1.01	0.07389	0	0
17	0.994592	-1.10356	83.11725	203.9385	36	1.01	-0.90762	0	0
18	0.99404	-1.11176	77.71991	227.5121	37	1.01	0.459506	0	0
19	1.000755	-0.36676	66.41876	183.622	38	1.01	-0.8208	0	0

TABLE V
OPTIMAL VALUE OF THE GENERATION COST CO-EFFICIENT FOR CASE I

DG	Proposed Method		Non-linear Method	
Bus	$CP_{Di}(P_{Gi}, P_D)'$	$CQ_{Di}(Q_{Gi}, Q_D)'$	$CP_i(P_{Gi})'$	$CQ_i(Q_{Gi})'$
Bus #1	0.174196972	0.089033902	0.727955376	0.13533694
Bus #35	0.181335024	0.01552372	0.721911973	0.761528509
Bus #36	0.174196972	0.008615034	0.721559738	0.618777085
Bus #37	0.181220308	0.029514122	0.758185047	0.378002061
Bus #38	0.174196972	0.008656152	0.721559738	0.553278146

the most expensive DG units are sharing minimum power as shown in Table III.

B. Case II: Different Types of DGs

In this case different types of DG's are considered in the micro-grid system. DG #1 and DG #3 are considered to be of type 1, DG #2 is considered to have the cost function of type 3, DG #4 and DG #5 are considered to have the cost functions of type 2. Though three types of DGs are only considered in the example, the method proposed is applicable to any number of different types of DGs.

Optimal generation costs and output generation powers are given in Table VI. From Table VI, total generation costs are reduced in the proposed method compared to that in the traditional and non-linear methods. A comparison of the bus voltage profile for the proposed and non-linear methods can be found in Fig. 6. It can be observed that the voltage profile

is better in many buses, whereas voltage is slightly lower in a few buses by the proposed method as compared with the nonlinear method. This happens due to the proposed method of reactive power sharing of the DGs.

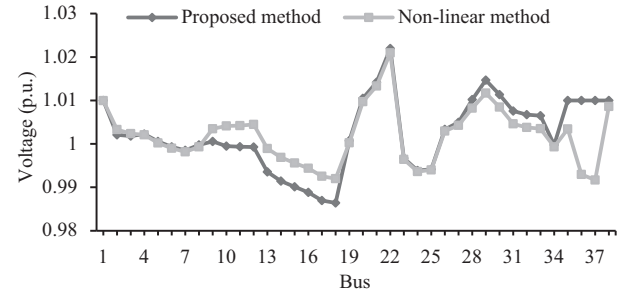


Fig. 6. Comparison of voltage magnitudes (Case II).

The bus voltage and angle from the load flow solution and the optimal value of the slope (m_D and n_D) of the load curve are given in Table VII.

Output active and reactive load power in p.u. from the load flow solutions using the proposed droop method for Case I and Case II are given in Table VIII.

For a demonstration of the effectiveness of the proposed method, full day load and generation variation are considered as in Fig. 7.

TABLE VI
GENERATION COST, DG'S OUTPUT POWER AND FREQUENCY OF THE SYSTEM

DG Bus	Non-linear Method				Traditional Method				Proposed Method			
	P_G (p.u.)	Q_G (p.u.)	$APGC$	$RPGC$	P_G (p.u.)	Q_G (p.u.)	$APGC$	$RPGC$	P_G (p.u.)	Q_G (p.u.)	$APGC$	$RPGC$
Bus #1	0.533778	0.039766	0.1212	0.0003	1.681	0.563	0.8739	0.0219	0.4815	0.2151	0.1110	0.0015
Bus #35	1.993692	0.295539	0.0999	0.0007	0.841	0.751	0.0421	0.0159	2.2143	0.4317	0.1109	0.0011
Bus #36	0.553778	0.578999	0.1212	0.0045	0.38	0.3	0.0752	0.0011	0.4815	0.3250	0.1110	0.0023
Bus #37	0.401681	1.170383	0.1663	0.0062	0.56	0.6	0.1972	0.0040	0.3693	1.1319	0.1609	0.0056
Bus #38	0.3931	0.36489	0.1615	0.0018	0.38	0.3	0.1477	0.0012	0.3010	0.4055	0.1506	0.0017
Total	3.85603	2.449577	0.670091	0.013516	3.842	2.514	1.336163	0.044168	3.847598	2.509154	0.644403	0.012238
			$TGC = 0.683607$				$TGC = 1.38033$				$TGC = 0.656641$	
Frequency (p.u.)	0.98976				0.9987				0.999846			

TABLE VII
VOLTAGE MAGNITUDE AND ANGLE FROM THE LOAD FLOW SOLUTION AND OPTIMAL VALUE OF LOAD COST CURVE SLOPE (m_D AND n_D)

Bus	Voltage Magnitude (p.u.)	Voltage Angle ($^{\circ}$)	m_D	n_D	Bus	Voltage Magnitude (p.u.)	Voltage Angle ($^{\circ}$)	m_D	n_D
1	1.01	0	0	0	20	1.0105	-1.70764	59.94782	105.5633
2	1.0021	-0.22542	26.73306	38.6525	21	1.0142	-1.82194	82.67264	233.1442
3	1.0018	-0.2231	26.60111	39.70514	22	1.0219	-1.98837	71.27591	196.2509
4	1.0022	-0.19621	121.9762	449.2547	23	0.9967	-1.06763	60.29391	84.21087
5	1.0005	-0.66392	105.9775	260.3926	24	0.9938	-1.21445	12.96182	21.20603
6	0.9993	-0.83474	44.84334	52.17846	25	0.9942	-1.31462	12.77371	21.66386
7	0.9985	-1.00111	81.83539	237.2764	26	1.0033	-0.10494	88.68007	161.1284
8	0.9997	-1.17023	64.32973	131.6685	27	1.0050	0.023069	121.5215	356.3938
9	1.0005	-0.27437	119.5522	429.4011	28	1.0102	0.682102	87.92915	197.5906
10	0.9995	-0.31516	87.27641	185.1815	29	1.0147	1.183124	44.07417	55.26978
11	0.9994	-0.31873	114.5344	124.9836	30	1.0114	1.272608	26.52338	6.533031
12	0.9993	-0.32786	103.2905	196.6397	31	1.0076	1.199819	41.95062	107.389
13	0.9936	-0.39303	86.34506	108.3803	32	1.0067	1.180109	30.26475	76.87762
14	0.9914	-0.45517	52.77304	85.23339	33	1.0065	1.173513	89.25995	102.194
15	0.9901	-0.48516	86.76865	383.5342	34	0.9997	-1.17023	0	0
16	0.9888	-0.5027	122.207	409.0127	35	1.01	2.412468	0	0
17	0.9870	-0.56578	87.97566	191.7857	36	1.01	-0.23351	0	0
18	0.9864	-0.57321	79.87249	215.7394	37	1.01	-2.11262	0	0
19	1.0007	-1.22589	70.7212	201.8055	38	1.01	-1.33148	0	0

TABLE VIII
ACTIVE AND REACTIVE LOAD POWER FROM THE LOAD FLOW SOLUTION (P.U.)

Bus	Case I		Case II		Bus	Case I		Case II	
	P_L	Q_L	P_L	Q_L		P_L	Q_L	P_L	Q_L
1	0	0	0	0	20	0.091052	0.042094	0.089338	0.038723
2	0.200125	0.102096	0.200336	0.105757	21	0.091981	0.04201	0.088973	0.038979
3	0.200207	0.100454	0.20133	0.102953	22	0.092504	0.04255	0.089169	0.039173
4	0.059966	0.019974	0.060304	0.020229	23	0.091025	0.051292	0.088825	0.048542
5	0.060032	0.030534	0.059971	0.029524	24	0.427741	0.208396	0.413182	0.192764
6	0.120466	0.081374	0.119429	0.078342	25	0.4215	0.225234	0.419267	0.18869
7	0.090094	0.041416	0.089883	0.0383	26	0.05988	0.024888	0.060392	0.02537
8	0.101039	0.061412	0.098797	0.058387	27	0.059773	0.024787	0.060529	0.025499
9	0.060588	0.020444	0.061526	0.021164	28	0.059238	0.019433	0.060908	0.020688
10	0.060552	0.020821	0.061364	0.022074	29	0.118621	0.066535	0.121513	0.07396
11	0.045718	0.031088	0.04676	0.032706	30	0.19711	0.562849	0.20192	0.625707
12	0.060645	0.036682	0.061531	0.039096	31	0.145596	0.065457	0.151502	0.071588
13	0.060553	0.035731	0.062026	0.037717	32	0.21	0.1	0.21	0.1
14	0.120087	0.081956	0.120433	0.090197	33	0.06	0.04	0.06	0.04
15	0.060249	0.010094	0.061723	0.010658	34	0	0	0	0
16	0.060016	0.020182	0.06019	0.022219	35	0	0	0	0
17	0.059982	0.019974	0.060876	0.021314	36	0	0	0	0
18	0.089881	0.039881	0.092092	0.042124	37	0	0	0	0
19	0.090118	0.041789	0.089868	0.038095	38	0	0	0	0

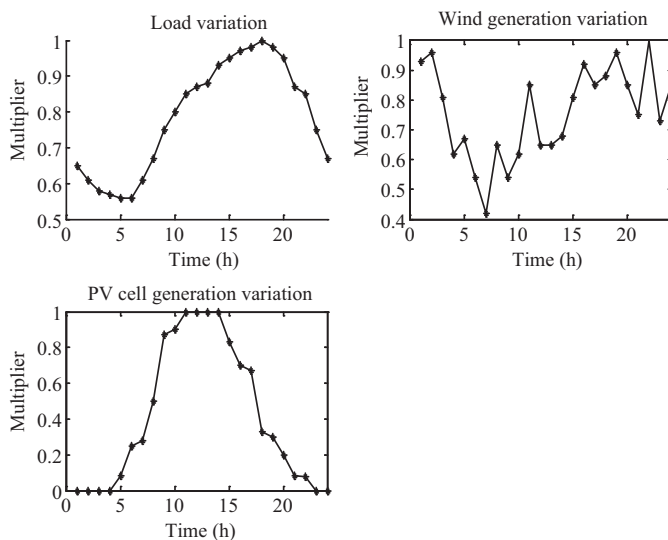


Fig. 7. Load and DG output shape multiplier.

Figs. 8 and 9 show the bus voltages with the variation of generation and load demand by the proposed and non-linear methods respectively for a full day (24 hours).

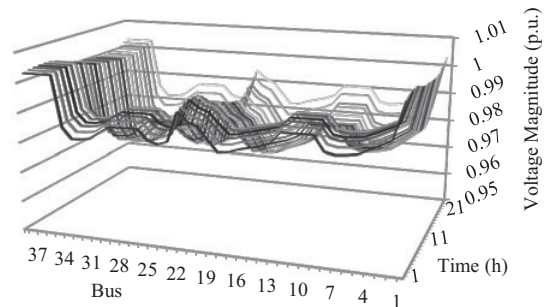


Fig. 8. Voltage Magnitudes by the proposed method.

Table IX shows the total generation costs by the non-linear and proposed methods for 24 hours including the variations of demand and DG output.

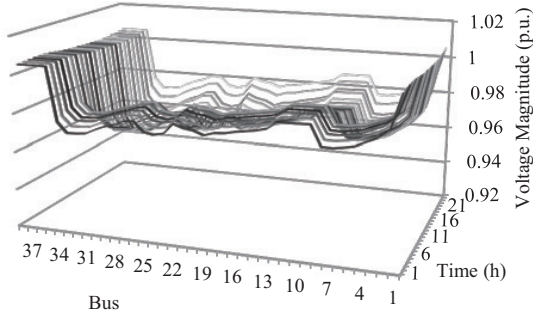


Fig. 9. Voltage magnitudes by the non-linear method.

TABLE IX
GENERATION COST FOR 24 HOURS (P.U.)

Method	APGC (p.u.)	RPGC (p.u.)	TGC (p.u.)
Non-linear	15.93541	0.376119	16.311529
Proposed	14.8192	0.375025	15.194225

VIII. CONCLUSION

A new droop control method based on generation cost and demand side management issues has been presented in this paper. The results from the proposed method have been compared with the non-linear and traditional cost-based droop schemes, whose common objective is to autonomously minimize the total generation cost (TGC) of the micro-grid system. In case-I, the TGC of the micro-grid from the proposed method and the non-linear method are less than that of the traditional method. The optimum TGC by the proposed method is slightly less than in the non-linear method when same type DG units are connected in the system with different types of load. In case-II, TGC is less than the non-linear and traditional droop method when different types of DG units are connected in the micro-grid with different types of load. The TGC obtained by the proposed method is 3.945% less than the non-linear method. The cost reduction ability of the proposed method without affecting the simplicity of the droop scheme is confirmed from the results.

APPENDIX A

From (32), the i^{th} bus load can be formulated as,

$$P_{L,j} = \left(\frac{cP_{D,j}}{m_{D,j}} - \frac{TAGC}{m_{D,j}} \right) \quad (A1)$$

Proof: now consider that three loads are connected in the micro-grid at bus 1, 2 and 3. So from (A1),

$$P_{L,1} = \left(\frac{cP_{D,1}}{m_{D,1}} - \frac{TAGC}{m_{D,1}} \right) \quad (A2)$$

$$P_{L,2} = \left(\frac{cP_{D,2}}{m_{D,2}} - \frac{TAGC}{m_{D,2}} \right) \quad (A3)$$

$$\text{and } P_{L,3} = \left(\frac{cP_{D,3}}{m_{D,3}} - \frac{TAGC}{m_{D,3}} \right) \quad (A4)$$

Now add (A2), (A3) and (A4),

$$P_{L,1} + P_{L,2} + P_{L,3} = \left(\frac{cP_{D,1}}{m_{D,1}} - \frac{TAGC}{m_{D,1}} \right)$$

$$+ \left(\frac{cP_{D,2}}{m_{D,2}} - \frac{TAGC}{m_{D,2}} \right) + \dots + \left(\frac{cP_{D,3}}{m_{D,3}} - \frac{TAGC}{m_{D,3}} \right)$$

$$\Rightarrow P_{L,1} + P_{L,2} + P_{L,3} = \left(\frac{cP_{D,1}}{m_{D,1}} + \frac{cP_{D,2}}{m_{D,2}} + \frac{cP_{D,3}}{m_{D,3}} \right)$$

$$- \dots - \left(\frac{TAGC}{m_{D,1}} + \frac{TAGC}{m_{D,2}} + \frac{TAGC}{m_{D,3}} \right)$$

$$\Rightarrow \sum_{j=1}^3 P_{L,j} = \sum_{j=1}^3 \frac{cP_{D,j}}{m_{D,j}} - \sum_{j=1}^3 \frac{TAGC}{m_{D,j}}$$

Now, if “ n ” numbers are the load bus in the micro-grid,

$$\Rightarrow \sum_{j=1}^n P_{L,j} = \sum_{j=1}^n \frac{cP_{D,j}}{m_{D,j}} - \sum_{j=1}^n \frac{TAGC}{m_{D,j}}$$

Whereas, $\sum_{j=1}^n P_{L,j} = P_D$, total demand of the system.

$$\therefore P_D = \sum_{j=1}^n \frac{cP_{D,j}}{m_{D,j}} - \sum_{j=1}^n \frac{TAGC}{m_{D,j}} \quad (\text{Prove})$$

From (A1), the active power demand slope can be calculated as,

$$\therefore m_{D,j} = \left(\frac{cP_{D,j} - TAGC}{P_{L,j}} \right)$$

Similarly the reactive power demand slope can be calculated as,

$$\therefore n_{D,j} = \left(\frac{cQ_{D,j} - TRGC}{Q_{L,j}} \right)$$

APPENDIX B

For proportional power sharing K_{cost} can be formulated for the nonlinear method from (25) as,

$$P_{G1} \times CP_1 (P_{G1}) = P_{G2} \times CP_2 (P_{G2}) = \dots$$

$$\dots = P_{Gi} \times CP_i (P_{Gi}) = K_{\text{cost}}(B1)$$

Similarly, for the proportional power sharing K_{cost} can be formulated for the proposed method as,

$$P_{G1} \times CP_{D1} (P_{G1}, P_D) = P_{G2} \times CP_{D2} (P_{G2}, P_D) = \dots$$

$$\dots = P_{Gi} \times CP_{Di} (P_{Gi}, P_D) = K_{\text{cost}}(B2)$$

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