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Optimum Economic Scheduling Strategy of Islanded Multi-Microgrid

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Abstract *– The paper presents a new methodology of the multi-microgrid (MMG) system is developed for large-scale integration of microgrids (MGs) and distribution generation (DG) units. The different controllable MGs, DG units and loads for MMGs system requires an efficient dispatch strategy in order to balance supply demand for optimizing the total cost of the integrated system. This paper described an optimum economic dispatch strategy of islanded MMGs. To optimize the system operating and running cost, genetic algorithm have been used and searches the optimum value of the output parameters like power produced by the controllable DG. The objective function comprises input fuel cost, operation cost, as well as the cost of emissions subject to various system constraints. The proposed optimization process is applied to a newly designed MMG system that has been operated under various constraints. Simulation results guaranteed the validity the proposed optimization method.*

Keywords*: Multi-microgrid, Distributed Generation, Cost Function, Economic Dispatch, Genetic Algorithm.*

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INTRODUCTION

Microgrid (MG) is a low voltage grid that integrates various distributed generation (DG) unit and energy storage devices for supplying power to load at distribution level. It can be operated both in on-grid or islanding mode. In islanding mode, MGs have restricted energy handling capability. A single MG can supply only a highest load capacity of approximately 10 MVA. However several MGs can be interconnected together to form larger power pool to meet the greater power demands. It also has more redundancy and ensures better supply reliability [1]. The interconnected MGs are generally called multi-microgrid (MMG) or integrated MG; it is a relatively new concept [2]. MMG system not only connect several individual MGs and but also other distributed generations to a medium voltage distribution grid. Normally, an MMG is operated to the high-voltage grid and for emergency purpose it may also be operated in islanded mode that is completely isolated from grid [3]. Several researches have been studied about the MMG system.

Gil and Pecas Lopes [2] proposed a robust frequency control methods for an MMG in islanded operation. Wang et al. [4] studied optimizing the operation cost of each individual MGs in a real grid. In Rua et al. [5] work, communications uncertainty is considered isolated mode in a MMGs operation. A novel methodology to implement a telephone line for communication and reliable control is presented in Arefifar et al. [6] study, considering the MGs building block methodology. The bi-level programming has been used for analysing the competitive state of major decision making among an energy services providers representing various MGs is presented in Georgia et al. [7]. The paper of Rua et al. [8] analysis the impact of liaison in frequency and power control in multi-MGs systems in islanded mode. The allocation problem of numerous MGs by considering installation investment, optimal design and operation, and power losses is elaborately explained and suggest some way to improve those problems in Yang et al. [9] work. The technical and commercial management strategy and state calculation has been developed for MMGs in Madureira [10]. The paper of Li et al. [11] describes an energy return plan methodology between a power grid and MMGs system. A multiobjective algorithm for improving the power flow controller performance of MMGs which minimizes MMGs operating cost, power loss, and all buses voltage profile fluctuation have been discussed in Kargarian et al. [12] work. In Gregoratti et al. [13] study, an arbitrary topology has been used in a distributed convex MGs optimization network for energy exchanging between islanded MGs that exchanged energy flows. An advanced control system can be used at medium to high voltage grid substations and can be used to manage micro-generation with load parameters in Vasiljevska et al. [14] study.

Optimal sizing estimation of distributed energy storage devices for integrated MGs is discussed in Logenthiran et al. [15]. For better utilization of renewable energy, to reduce production cost (30%) a new algorithm

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for smart intelligent home energy management system with consumption shifting in demand response program considering various constraints has been proposed in Moghaddam et al. [16] study, at a islanded mode. But the optimum sizes of energy storage system and real time implementations are not mentioned. In a MG, renewable sources, generators heat and output powers optimum combination is a major problem. To overcome multi-objectives optimization problems, the modified particle swarm optimization (PSO) called as neighbourhood re-dispatch PSO algorithm has been proposed in Si1 et al. [17] work. The major objectives were to reduce electricity cost with minimum costs avoiding other parameters. In Chen et al. [18] research, a matrix perturbation theory based distributed optimization dispatch algorithm has been proposed to determine the optimal DG outputs and that also satisfied the supply, consumer demand constraints.

However, the researchers don't sufficiently studied about the optimum economic dispatch strategy of islanded MMGs. In this paper genetic algorithm searches the optimum magnitude of the outturn power produced by the dispatchable distributed generator subject to minimization of operating cost. The objective function formulated the input fuel cost, operation cost, and emissions cost subject to various system constraints. The proposed optimization process is implemented on a typical MMG system.

CONTROL STRATEGY

There is no fixed or predefined structure of MGs control system; it depends on the types of configuration and MGs architecture [19]. Furthermore, the MMG system increases the system complexity. The centralized control architecture is discussed [2, 10, 14, 19] with few modifications. The hierarchical control architecture comprises the following controller as shown in Fig.1: (i) Central power monitoring system (CPMS), (ii) Power management controller (PMC), (iii) Load management controller (LMC), and (iv) Microgrid controller (MGC).

The central power monitoring system (CPMS) is the decision maker and responsible for the economical optimization of the integrated system. It globally minimizes the total operating cost. It is aware about the characteristics of all the micro sources with their respective operational limits, controllable load and state of charge (SOC) of energy storage system (EES). The total load is observed and the supply demand is balanced according to operating strategy of the system.

The CPMS globally runs and sends the control signal to MGC, PMC and LMC for changing the power level under their controlling devices to balance the supply demand. PMC and LMC operate at medium voltage level. PMC controls the power of distributed generation units and EES. LMC monitors the controllable load by load shedding. Each of the MGCs will share out the power changes among its DG units and controllable loads at each MG.

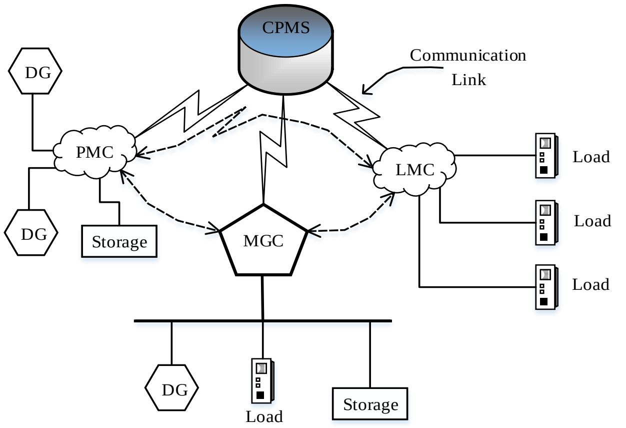

Fig 1. Hierarchical control structure of integrated microgrid

MODEL OF THE STUDIED SYSTEM

The schematic diagram of the studied MMGs system is shown in Fig.2. The adopted test network represents the architecture of a MV grid containing three MGs, several kinds of larger DGs and controllable loads. The MG1 consists with WTG, FC, ESS, MG2 with FC, DG, and MG3 with MTG and FC. Each MG has controllable load. MTG, WTG, ESS and some controllable loads is connected at medium voltage level. Two wind turbine generators is connected at MG1. At medium voltage level three wind turbine generators delivers power. The capacity and operational limits of distribution energy resources is given in Table 1. The supply demand balance can be written by the following eq.(1) from Fig.2.

$$\sum P_L - \sum\left(P_{DEG} + P_{MTG} + P_{FC} + P_{WTG} + P_{PV} \pm P_{ESS}\right) = 0 \quad (1)$$

Table 1.
Capacity and Limits of Microsources

Position	Micro-sources	Capacity (kW)	Lower Limit (kW)	Upper Limit (kW)
MG1	WTG	200	0	200
	FC	200	40	200
	ESS	50	-	-
MG2	FC	200	40	200
	DEG	250	45	250
MG3	MTG	200	30	200
	PV	300	0	300
MV	MTG	200	30	200
	WTG	300	0	300
	ESS	100	-	-

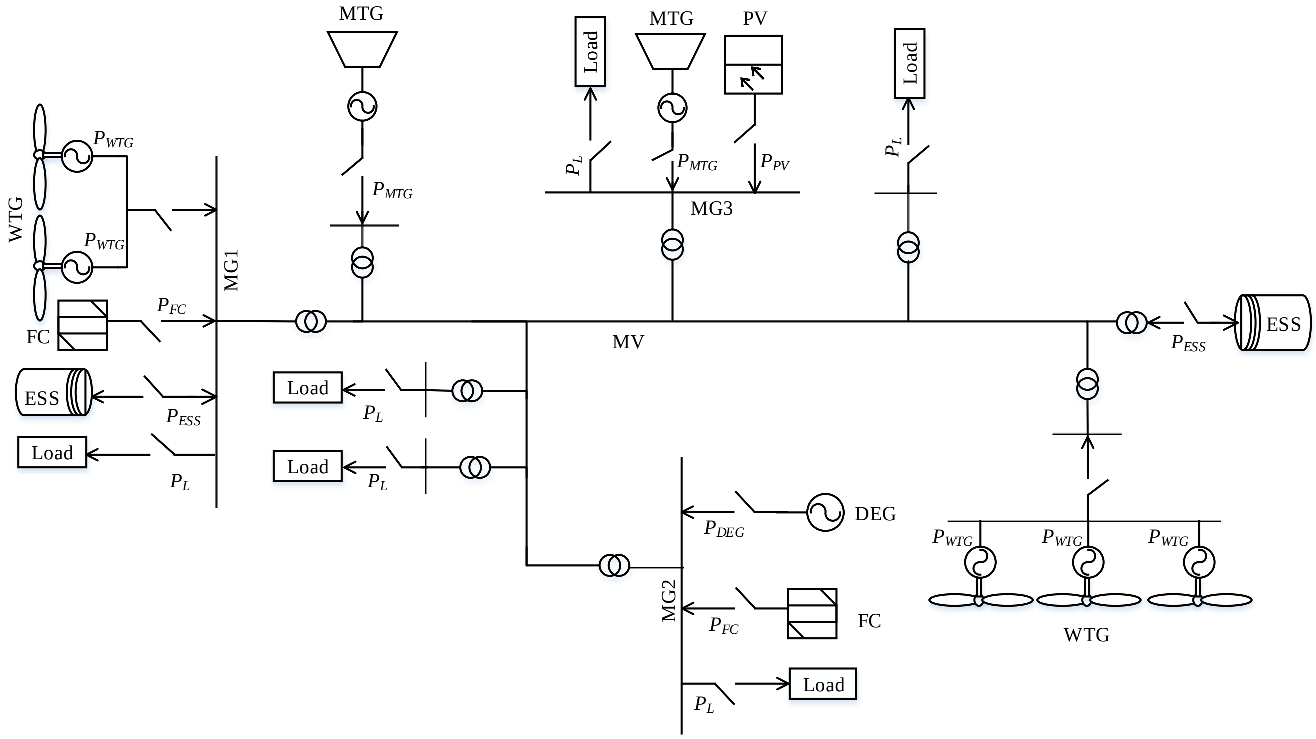

Fig 2. Schematic diagram of integrated microgrid

SYSTEM MODELLING

The modelling of different parts of the integrated MG system is presented in this section. The fuel input is provided only for the DEG, MTG and FC as PV energy comes from the nature. The energy storage system can be charged by producing electrical power from PV and WTG. Each part of the integrated system is designed separately based on its properties. The features of some equipment's are available from the manufacturer.

*A. **Diesel Engine Generator(DEG)***

The diesel engine generator efficiency decreases at light load condition, and the fuel expenditure is almost full. Therefore, it is needed to fix up the minimum output power magnitude of DG [20]. The minimum loading capacity of a DG is limited to 30-50% [21] and the optimum operating scale is 70-89% from the rated power [22]. The fuel consumption rate (litre/hour) of a 250 kW DEG shown in Fig.3 is used for simulation [23].

$$F_{DEG} = \alpha P_{DEG}^2 + \beta P_{DEG} + \gamma \qquad (2)$$

The DEG should be operated economically to control the governing system so that the generation costs will be lower.

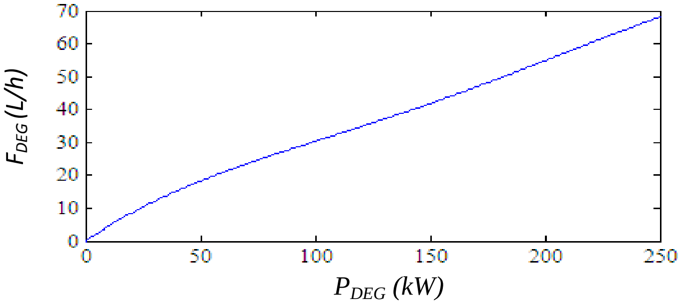

Fig 3. Output power vs. fuel consumption rate of DEG

*B. **Microturbine Generator (MTG)***

The efficiency of the MTG increases with the increase of the supplied power. The typical efficiency curve of a 200 kW micro turbine is modelled as shown in Fig.4 [24].

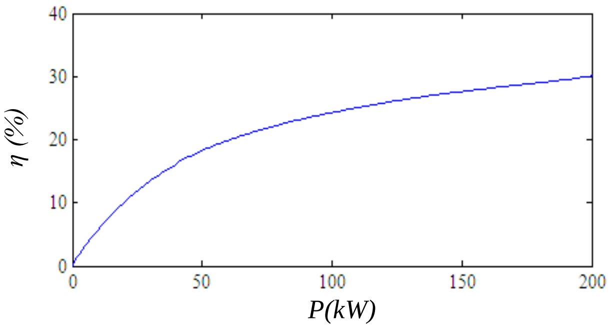

Fig 4. Output power vs. efficiency curve of MTG

The fuel input for a microturbine can be expressed as [25],

$$F_{MTG} = \sum_{J} \frac{P_J}{\eta_J} \qquad (3)$$

P_J = Net power generated at interval *J* (kW).

η = Microturbine avail at interval *J*.

The minimum and maximum loading constraint of MTG is given by eq.(4).

$$P_{MTG}^{Min} \leq P_{MTG} \leq P_{MTG}^{Max} \qquad (4)$$

C. *Fuel Cell (FC)*

The competency of any fuel cell can be described as follows [26] where all unit must be in the same scale.

$$\eta_{FC} = \frac{Electrical\ Power\ Output\ \ (P_{FC})}{Fuel\ Input\ \ (F_{FC})} \qquad (5)$$

The typical output power versus efficiency curve of a typical 200 kW fuel cells is shown in Fig.5.

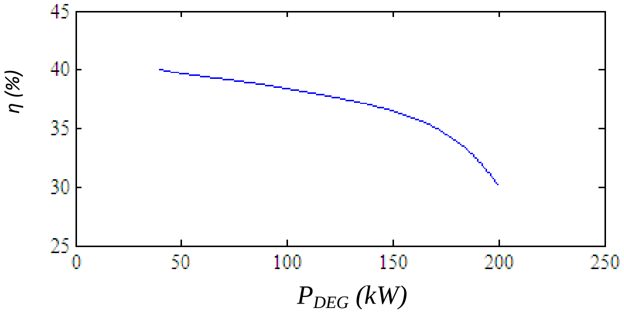

Fig.5. Fuel cell output power vs efficiency curve

The fuel input for the cell can be expressed as [25]:

$$F_{FC} = \sum_{J} \frac{P_J}{\eta_J} \qquad (6)$$

Where the symbols represents their usual meaning

The minimum and maximum loading constraint of FC is given by eq.(7).

$$P_{FC}^{Min} \leq P_{FC} \leq P_{FC}^{Max} \qquad (7)$$

D. *Wind Turbine Generator (WTG)*

It is very common things that the speed of wind changes in every hours, days and seasons. For planning long term the wind distribution can be represents by by Weibull distribution functions as follows [27]:

$$f_v(v) = \begin{cases} \dfrac{\beta}{\alpha} \times \left(\dfrac{v}{\beta}\right)^{\rho-1} \times e^{\left(\frac{\gamma}{\alpha}\right)^{\beta}} & v \geq 0 \\ 0 & Otherwise \end{cases} \qquad (8)$$

Where, $\alpha, \beta \;\&\; v$ are the shape parameter, scale parameters of Weibull function and wind speed, respectively.

The output of WTG The performance curve of WTG can be approximated as a function of wind speed (V_w). A third order polynomial function is used to fit the parameters on wind speed and wind turbine performance curve. By using the following expression, the generated output power of WTG can be determined.

$$P_{WTG} = \begin{cases} 0, & V_w < V_{Cut-in} \\ aV_w^3 + bV_w^2 + cV_w + d, & V_{cut-in} \leq V_w < V_r \\ P_{Rated}, & V_r \leq V_w \leq V_{cut-out} \end{cases} \qquad (9)$$

Where V_{cut-in}= Cut in speed, V_r=Rated speed and $V_{cut-out}$=Cut out speed.

The power curve of a 100kW turbine is shown in Fig.6 is used in this model [28]. The input wind speed is considered for this model is shown in Fig.7.

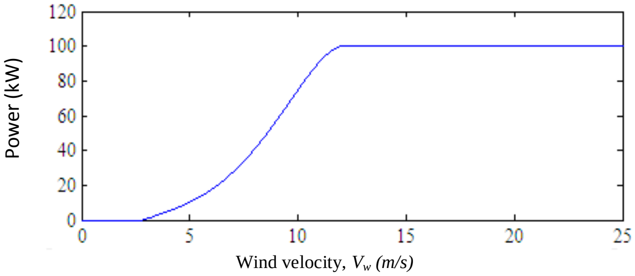

Fig.6. Power curve of a *100 kW* turbine

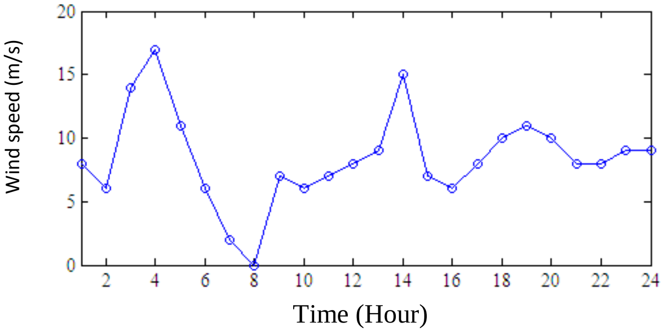

Fig.7. The input wind speed as used in the model

E. *Solar Photovoltaic (PV) System*

The output power of solar photovoltaic depends on environmental conditions, such as solar radiation and temperature, resulting in a non-linear and time-variant power source. Depending in the solar radiation and load current, the output power of the PV module will be changed that follows the equation (10) [29],

$$P_{PV} = \eta A\phi[1 - 0.005(T_a + 25)] \qquad (10)$$

Where, *S* is the area of PV array (m^2), *φ* presents the solar irradiation *(W/m²)* and T_a is ambient temperature (^0C). Our

Studied system has the following parameters: $A=2000m^{2,}$ $\eta=20\%$ and we assume temperature is constant $(T_a=25^0C)$. The solar irradiation data for 24 hour period used in this model is given in Fig.8.

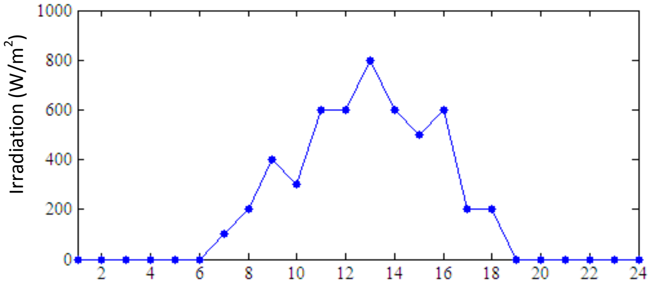

Fig 8. The input irradiation data for simulated model

F. *Energy Storage System (ESS)*

Energy storage systems are an important part for the hybrid power system and effectively supply deficit power to maintain the system stability [29]. Energy can be stored in many ways like use of electro-chemical battery, super-capacitors, super conducting magnetic energy storage, flywheel storage system and many more. The state of charge (*SOC*) of ESS should be monitored and kept in acceptable ranges so that it will not be overcharged the battery [30]. The minimum and maximum *SOC* of ESS should be limited by eq. (11).

$$SOC_{ESS}^{Min} \le SOC_{ESS} \le SOC_{ESS}^{Max} \tag{11}$$

For safety operation of ESSs, battery management system can be applied. In this system, batteries voltage, current and temperature is controlled from centrally. To reduce the cost of output energies, proper allocation of EES batteries is an important factor. To design a smart MG, to keep balance or optimization between source & load demand, to maintain the limit of SOC and to design an optimum sizing of EESs are an important consideration.

OBJECTIVE FUNCTION FORMULATION

The main objective function includes operating fuel cost, maintenance cost and cost of emission released from each microsource [31].

$$CF = \sum_{i=1}^{N} (C_i F_i + OM_i) + \sum_{i=1}^{N} \sum_{j=1}^{M} \alpha_i EF_{ij} P_i \tag{12}$$

Where,

C_i	Fuel costs, i in \$/L for the diesel, and \$/kWh for the gas.
F_i	Rate of fuel expense, i in L/h for DG, and kW/h for the FC and MT.
OM_i	Operation cost, i in \$/h
α_j	Cost of emission, j
EF_{ij}	Emission factor i, emission type j
M	Emission types (NO_x or CO_2 or SO_2)
N	Number of generating units i

Diesel is used in DEG but the fuel used in MTG and FC is natural gas. No fuel is required for WTG and PV. The operation cost of the generating unit *i* (OM_i) is considered be constant and proportional to the produced energy [32], where (K_{OM}) represents the proportional constant.

$$OM_i = K_{OMi} P_i \tag{13}$$

The magnitude of the K_{OM} for various generation units are listed in Table 2. The emission usually includes gases such as SO_2, CO_2 and NO_X. The costs and factors of emision of the DEG, FC, and MTG used here are listed in Table 3 [31].

TABLE 2. PROPORTIONAL CONSTANT

DG	DEG	MTG	FC	WTG	PV
K_{OM}(\$/kWh)	0.0125	0.0060	0.0050	0.0150	0.0010

TABLE 3. EXTERNALITY COSTS AND EMISSION FACTORS FOR NO_X, SO_2, AND CO_2

Emission Type	Externality cost (\$/kg)	Emission factors (Kg/MWh)		
		DEG	MTG	FC
CO_2	0.014	1.432	1.596	1.078
SO_2	0.99	0.454	0.008	0.006
NO_x	4.2	21.8	0.44	0.03

Constraints: To balance the real power, and the load demand the belows equation (1) is used.

The output power of generator unit *i* (P_i) is restricted to its maximum and minimum value.

$$P_i^{Min} \le P_i \le P_i^{Max} \tag{14}$$

Also the SOC of the energy storage system is properly controlled as Eq. (10).

OPTIMAL OPERATING STRATEGY

The genetic algorithm is applied to find the optimal output of dispatchable distributed generator for MMG system with minimum operating cost as described by objective function in the previous section. The implementation strategies are as follows:

1. The central power monitoring system calculates the total load demand (P_L).
2. Output power of WTG is calculated from the performance curve.

3. Output power of solar PV is determined from solar radiation .

4. Reduce the total load from WTG and PV power.

$$\Delta P_L = P_L - (P_{WTG} + P_{PV}) \qquad (15)$$

If $\Delta P_L < 0$, the rest of the power will be given to the battery to charge the ESS. When the ESS is fully charged, the exceed power is unload

If $\Delta P_L > 0$, the remaining power will be given by the ESS or by the distributed generator (DEG, MTG, FC. Meanwhile, the charging and discharging of the ESS is properly monitored. The tuning of output power of DGs by genetic algorithm occurs in the following ways.

1. Initialization: The algorithm begins by creating an initial population. This population is normally randomly reproduced at any desired size.
2. Evaluation: The fitness value of chromosomes is now evaluated by calculating the cost function or objective function. Here, it is tried to find the minimum magnitude of the cost function.
3. Selection: Selection helps to discard the weak individuals and only keeps the best individuals called parents that contribute to the population at the next generation. There are a small number of selection methodologies but the primary concepts is the same, make it more likely the best adjuster individuals will be selected for our upcoming generation.
4. Crossover: In this stage, new individuals are created by combining prospective of chosen individuals. By combining two or more individuals it will create a fitter offspring from each of its parents.
5. Mutation: Mutation typically works by making very small changes at random to an individual's genome.
6. Termination: Now the next generation is started again from step two until it reaches a maximum number of generations.

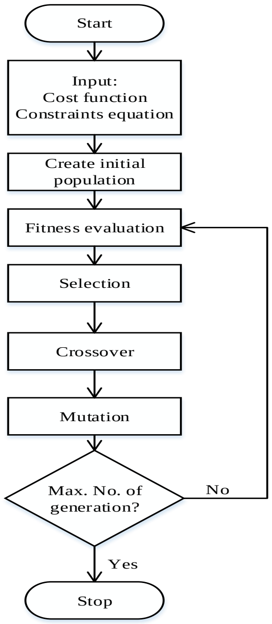

Fig. 9. Flow chart for genetic algorithm

RESULTS AND DISCUSSION

The total load profile for the studied integrated system used for simulation purpose is shown in Fig.10. The scheduling time is 24 hours in a day with the scheduling time interim of 1 hour. The load demand varies between 430kW to 1500kW. The optimization model that is discussed in the past section is implemented to this time-varying load.

The total renewable power i.e. summation of total power from WTG and solar PV is shown in Fig. 11. Also, WTG and solar PV power profile is given to the following figures according to their location in system. After observing the total load and renewable power of the system, the genetic algorithm is used to find out the optimum power generation of microsources subject to minimum operating cost according to control strategy. The various combination of produced power is shown in Figures12-15.

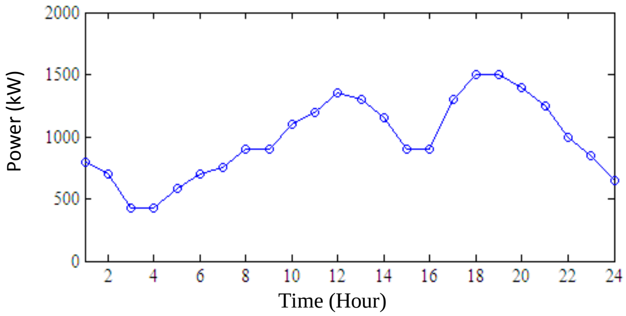

Fig.10 Total load profile of the simulated system

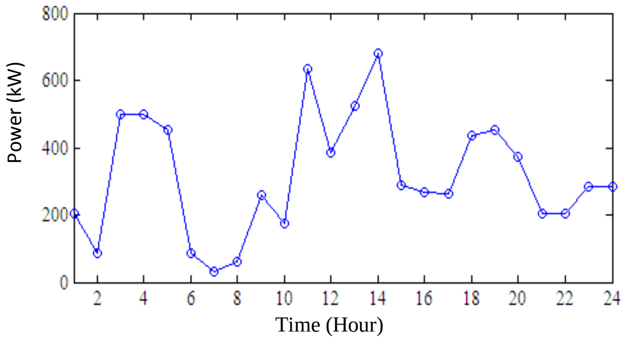

Fig.11 Total renewable power of the simulated system

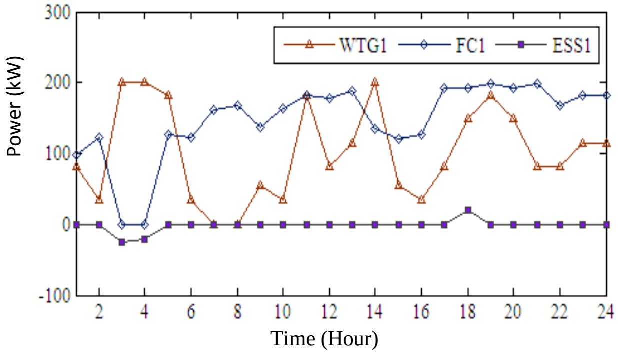

Fig.12 Power profile at MG 1

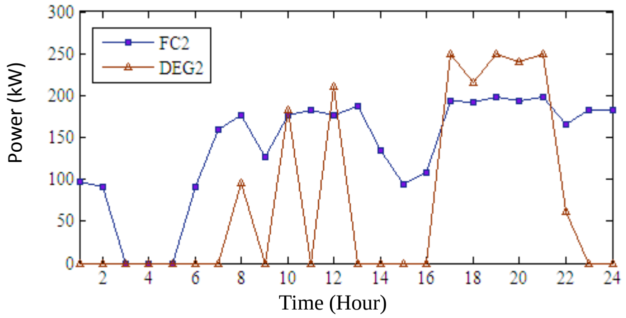

Fig. 13. Power profile at MG 2

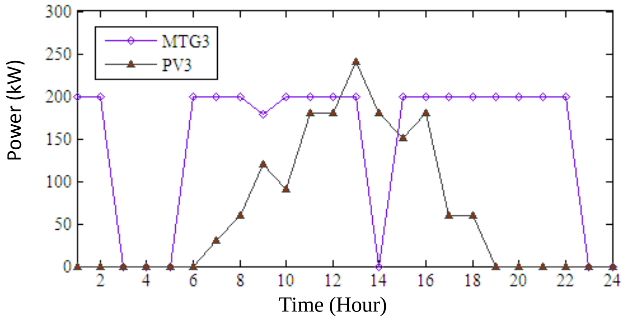

Fig. 14. Power profile at MG 3

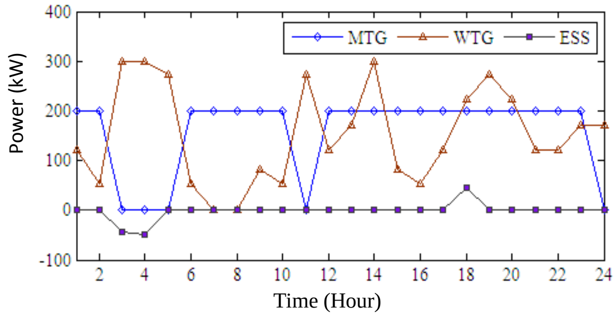

Fig. 15. DGs and ESS at MV level

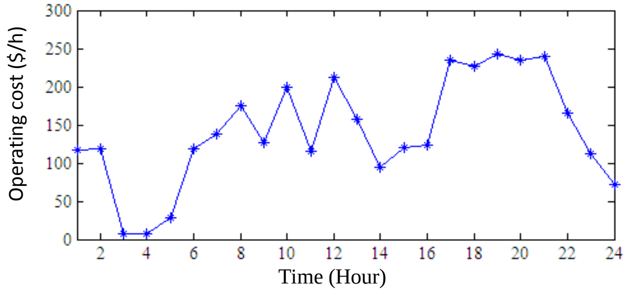

Fig.16. Total operating cost of the system

The Fig.12 to Fig.14, show the output power profile of MG1 to MG3 respectively. The energy supplied or absorbed by the ESS to or from the system is given in the figures. The total operating cost of the system is shown in Fig.16.Only controllable DGs such as DEG, FC and MTG can be tuned. The total renewable power generation of WTG and solar PV are given the first priority to meet the load demand. If the output power taking from PV and WTG is lesser than the load demand the genetic algorithm automatically finds various combination of DGs for producing power to minimize the operating cost and balance the load demand. Also the energy from ESS is properly exchanged. Fig. 12 and Fig. 15 show that the ESS is charged and can save the surplus power at time 3.00 and 4.00 due to available of wind power. During this period all the controllable DGs is shut down that is observed from Fig. 12 to Fig.15. In this case the total operating cost is treated by only operation and maintenance cost of wind turbine generation. As a result the cost of the system is very low as shown in Fig.16. But at 18.00, the ESS is discharged the total load is balanced.

It can be seen from Fig. 13 that the diesel engine generator is the least preferred generator for delivering power because of its higher cost. Due to low cost of MTG and FC, they are firstly selected for power production purpose to meet the load demand. When the DEG delivers power, the operating cost of the system increases. So if the load demand is low, the best selection of distributed generator in terms of operating cost is to switched off the diesel generator. It is used only when there are no other generation options is available. Due to time varying behaviour of load demand the start-stop cycles of DGs increases. Furthermore, the uncertain nature of wind and solar power increases the system complexity.

CONCLUSION

Optimum economic dispatch strategy for the islanded MMGs has been proposed in this paper. Genetic algorithm searches the minimum value of cost function by properly selecting the output power produced from controllable DGs. The objective function consists of operating fuel cost, maintenance cost and cost of emission released from each microsources. Practically, the power required for the connected loads can be effectively supplied with appropriate coordination among distributed generators and energy storage system for such type of system. But in the proposed method start-stop cycles of DGs increases. As a result the forecasted load, wind speed and solar irradiation data should be included to optimum dispatch strategy to reduce the start-stop cycle of DGs. The simulation results justify the correctness of the proposed algorithm. This research can be further modified by proposing new algorithm to optimize production cost that will also satisfy the supply and consumer demand constraints.

DECLARATIONS

Authors' Contribution

All authors contributed equally to this work.

Conflict of interests

The authors have no conflict of publishing this paper.

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