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ORIGINAL CONTRIBUTION

Cost-based Unit Commitment in a Stand-Alone Hybrid Microgrid with Demand Response Flexibility

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Abstract Microgrids (MGs) provide an efficient and economic solution to multiple problems in electrical energy systems. MGs supply electricity and heat to customers through wind turbines, gas turbines, fuel cells, photovoltaic systems, and cogeneration. To ensure a balance between demand and supply of electricity and reduced power procurement from the main grid, it becomes essential for the system operators to generate power locally with renewable sources of energy. Storage devices ensure a balance between energy production and utilization, mostly during sudden load variation and power availability. In this way, energy storage devices act as power reserve similar to conventional generators spinning reserve. Microgrids meet both heat and power needs, and also support voltage regulation, reduce brownouts, reduce energy supply costs, improve system reliability and decreased emissions, and improve power quality. In this research work, an optimization framework for cost-based unit commitment (UC) of a specific type of MG is performed and analyzed. Renewable sources of energy including wind power and solar PV, conventional sources of energy such as diesel generators, and energy storage devices like battery are modeled in an islanded mode of operation of microgrid. The proposed model intends to inspect the dispatch of power in a microgrid in a manner to minimize the overall cost of operation of the MG and at the same time reduce the number of diesel generators to be committed for a particular operation considering additional constraints like demand flexibility constraints. The operation is performed based on mixed-integer linear programming (MILP) over a twenty-four hour time duration, and a comparison is made for the simulation results.

Keywords Distributed generation · Microgrid · Unit Commitment · Solar PV · Wind Energy · Energy Storage Systems

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Nomenclature

Indices

t	Time interval index
i	Thermal generating unit index
k	Sections taken to linearize the cost function for fuel

Parameters

L_t	Power demand at time t
a_i, b_i, c_i	Fuel cost coefficients of thermal unit
$U^0{}_i/S^0{}_i$	Time for which i^{th} thermal generator is on/off at the start of the operation (h)
$P^k{}_{i,ini}$	Initial value of power in segment k of linear function for fuel cost for ith thermal generator (MW)
$P^k{}_{i,fin}$	Final value of power in segment k of linear function for fuel cost for ith thermal generator (MW)
$C^k{}_{i,ini}$	Initial value of cost for segment k of linear function for fuel cost for ith thermal generator (\$/h)
$C^k{}_{i,fin}$	Final value of cost for segment k of linear function for fuel cost for ith thermal generator (\$/h)
$\Delta P^k{}_i$	Extent of segment of linear function for fuel cost for ith thermal generator (MW)

$P_i^{max/min}$	Min/max limitation for generated power of ith thermal generator.
DT_i/UT_i	Minimum up/down time of ith thermal generator (h)
T	Number of intervals for minimum up/down time
n	Segments taken to linearize the cost function for fuel
RU_i/RD_i	Up/down ramp limits of ith thermal generator (MW/h)
$SDC_{i,t}/STC_{i,t}$	Realistic time-dependent start-up/ shutdown cost of i^{th} thermal generator ($/h)
Cs_i/Sd_i	Shutdown/ Start-up cost of ith thermal generator ($)
SD_i/SU_i	Ramp limits of start-up/shutdown for ith thermal generator (MW/h)
S^k_i	Slope for cost in segment k of linear function for fuel cost for ith thermal generator ($/MW)
EWC	Estimate for wind curtailment
$P_{i,t}^{tmin}$	Minimum time-dependent operating limit of thermal unit i
$P_{i,t}^{tmax}$	Maximum time-dependent operating limit of thermal unit i
W_t	Availability of wind at time t (MW)
S_t	Availability of irradiance to solar photovoltaic at time t (MW)
SOC^{min}/SOC^{max}	Limits of state of charge of the battery (MW)
$P_t^{ch,min}/P_t^{ch,max}$	Charging power limits of battery at time t (MW)
η_{ch}/η_{dis}	Efficiency of the battery

Variables

P_t^w	Active power generation of wind turbine at tth time
P_t^{wc}	Curtailed wind power at tth time
$u_{i,t}$	Running status of the ith generator at tth time
$z_{i,t}$	Shutdown status if unit i at tth time
$y_{i,t}$	Start-up status if unit i at tth time
$C_{i,t}$	Cost of fuel for ith thermal generator at tth time ($)
$p^k_{i,t}$	Schedule of operation of ith thermal generator at tth time (MW)
$P_{i,t}$	Generated power of ith thermal generator at tth time (MW)
OF	Objective function for total operating cost
D_t	Demand value at time t
$\alpha_{min}/\alpha_{max}$	Minimum/maximum demand response flexibility
SOC_t	State of charge of the battery at the tth time (MW)
P_t^w	Wind power generation at tth time (MW)
P_t^s	Generated active power of solar PV system at the tth time (MW)
P_t^{ch} / P_t^{dis}	Charging/discharging power of battery at the t time, respectively(kW)

Introduction

The transition of the current global power system to the smart grid model has led to various attempts to integrate green renewable energy and energy storage equipment into distribution networks [1, 2]. With the huge integration of decentralized energy resources and changing energy demands, new energy production and consumption models have been introduced into traditional energy system architectures [3, 4]. New technologies for power generation and storage are being developed and sold, including solar power devices, wind turbines, microturbines, fuel cells, thermal unit, gas turbines, superconducting magnetic energy storage (SMES), super-capacitors, and battery storage systems. However, in this article, the most developed and widely used technologies namely wind, solar, battery, and thermal unit are discussed [5].

The microgrid concept assumes that the load and energy clusters operate as a centralized or decentralized hierarchical control system. Furthermore, unlike transmission systems, MG is essentially a distributed network. This creates a variety of issues related to the functioning of grid performance and grid balance. An attractive method is a microgrid. It can adapt to different types of grid and market environments. In addition to the ability to switch between islanded and grid-connected mode of operation to improve power supply demand, it is an attractive option for the associated partners and it enhances system efficiency, including a reduction in congestion, voltage control, and reducing losses [6, 7]. Optimal resource allocation task in the microgrid, such as unit commitment (UC), also requires special attention when adding different resources of energy like battery storage system [8].

Due to the different types of complications in the microgrid, many algorithms have recently been proposed to inspect this area [9]. More or less, all works for conventional UC problems have been enhanced and relatively transformed into settings of the grid applications [10].

Considering the high performance and adaptability of the optimization technique of mixed-integer linear programming (MILP) and the accessibility of solvers, MILP has been used in many recent studies to solve UC problems and it has the capability to find a global optimal solution. In [11], a mixed-integer linear programming method for a centralized energy management system (EMS) has been developed for the unit commitment scheduling and economic dispatch of microgrid units. Generation scheduling to minimize the cost for both operator and consumer with storage technology is investigated in [12]. A network constrained dispatch of renewable energy is discussed in [13]. Integrated energy supply planning to minimize operating costs under uncertainty is proposed in [14]. Based on MILP, high-precision processes have been developed to optimize microgrids such as thermal generators, fuel cells, microturbines, and battery energy storage systems (BESS) [15]. Much effort has been made to develop optimization algorithms to optimize microgrid operations, but few have taken into consideration different aspects of power system operations with the same problem. Till now, from the authors' knowledge, no contribution has been made considering the renewable sources and demand response flexibility as mentioned in Table 1. This paper proposes a cost-based unit commitment model that integrates renewable energy and BESS into MG.

The block diagram of AC microgrid under consideration is shown in Fig. 1 and the simulation approach is given in Fig. 2.

The main contributions of the study are given as follows:

1. Explaining the role of wind, solar, and BESS technologies and demand response flexibility, in improving MG power dispatch, and reducing total operating costs, fuel costs, start-up, and shutdown costs.
2. To investigate different situations to emphasize the accuracy of the given architecture and analyze the simulation results under different scenarios.

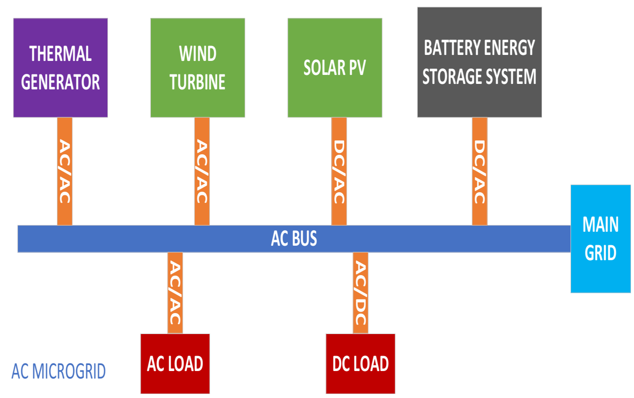


Fig. 1 Block diagram of AC microgrid under test

3. General Algebraic Modeling System (GAMS) optimization software is used to obtain the decision variables in the unit commitment problem.

The remaining paper is organized as follows: Unit commitment problem is expressed by modeling the integrated energy system in section II, and detailed information about datasets is provided. Different simulation results and the case studies are explained in Section III. Lastly, the conclusion is made up based on the simulation result in section IV.

Problem Formulation

There are three major components of the cost function in every problem of unit commitment: thermal unit fuel cost, start-up cost, and shutdown cost. The objective function is

Table 1 Review of unit commitment studies in renewable energy-based electrical system

References	Year	Type of system considered					Optimization technique used	Mode of microgrid operation
		TH	WT	PV	BESS	DRF		
[16]	2019	✓	✓	☒	☒	☒	MATPOWER	Grid-connected
[17]	2016	☒	✓	☒	✓	☒	PSO	Grid-connected
[18]	2017	☒	☒	✓	✓	☒	MILP	Islanded
[19]	2015	☒	✓	☒	☒	✓	Stochastic programming	Grid-connected
[20]	2018	✓	✓	✓	☒	✓	MIP	Islanded
[21]	2018	✓	☒	✓	☒	✓	MILP	Grid-connected
[22]	2019	✓	✓	☒	✓	✓	MIP	Islanded
[23]	2016	✓	✓	☒	☒	✓	Lagrangian relaxation	Grid-connected
[24]	2019	✓	✓	☒	☒	☒	MILP	Islanded
[25]	2017	✓	✓	☒	☒	☒	MILP, stochastic	Islanded
[26]	2020	✓	✓	✓	☒	✓	MIP	Grid-connected
This work	2020	✓	✓	✓	✓	✓	MILP	Islanded

TH, thermal unit; WT, wind turbine; PV, photovoltaic; BESS, battery energy storage system; DRF, demand response flexibility; MIP, mixed-integer programming; PSO, particle swarm optimization; MILP, mixed-integer linear programming

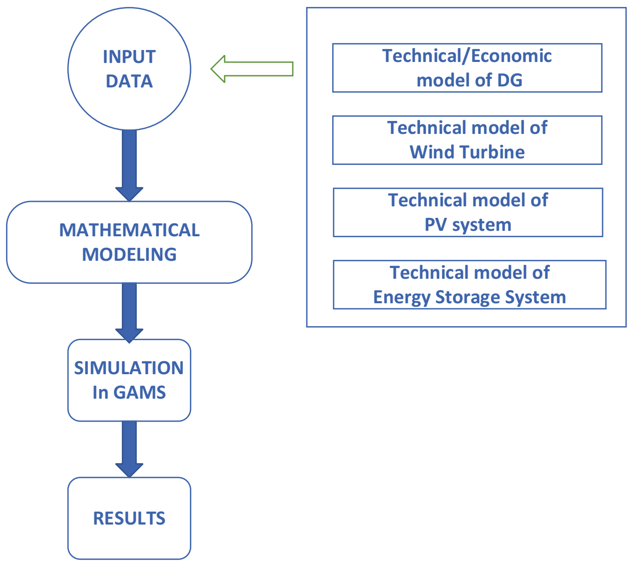


Fig. 2 Simulation approach

to minimize the total operating cost of local generating units. This will also include the wind curtailment cost in case of wind technology is considered. In this paper, optimization modeling for wind generation, solar photovoltaic generation, conventional thermal generator, and battery system is developed. Further, the developed system is solved considering demand flexibility, and the simulation model is discussed. The optimization model with different constraints is expressed in the following section. The optimization model with different constraints is expressed in the following section.

Objective Function

The objective function (OF) for cost minimization is given by

$$OF = \sum_{i,t} \{FC_{i,t} + STC_{i,t} + SDC_{i,t}\} + \sum_{t} F^{wc} \quad (1)$$

where $FC_{i,t}$ is the fuel cost for thermal generators, F^{wc} is the estimation of cost associated with wind curtailment, $STC_{i,t}$ and $SDC_{i,t}$ are the start-up and shutdown cost, respectively. F^{wc} is a function of wind curtailment power P^{wc}_t at the i^{th} bus during t^{th} hour [29].

$$F^{wc} = EWC \times P^{wc}_t \quad (2)$$

EWC is the estimate of wind curtailment. Linearized cost-based UC problem is expressed here and the fuel cost is assumed to be in the form of a quadratic expression of produced real power of the thermal units $P_{g,t}$ considered an acceptable estimation of fuel curve for more accurate results [27]. Parameters, a [\$/(MW^2)], b [\$/(MW)], and c [\$] for the cost function of generators, may be drawn from the measurement statistics of heat run tests.

The linear version of fuel cost calculation as provided in [28] is described in Eq. (3–11).

$$0 \le p^k_{i,t} \le \Delta P^k_i u_{i,t}, \forall k = 1:n \quad (3)$$

$$\Delta P^k_i = \frac{P^{max}_i - P^{min}_i}{n} \quad (4)$$

$$P^k_{i,ini} = (k-1)\Delta P^k_i + P^{min}_i \quad (5)$$

$$P^k_{i,fin} = \Delta P^k_i + P^k_{i,ini} \quad (6)$$

$$P_{i,t} = P^{min}_i u_{i,t} + \sum_k p^k_{i,t} \quad (7)$$

$$C^k_{i,ini} = a_i \left(P^k_{i,ini}\right)^2 + b_i P^k_{i,ini} + c_i \quad (8)$$

$$C^k_{i,fin} = a_i \left(P^k_{i,fin}\right)^2 + b_i P^k_{i,fin} + c_i \quad (9)$$

$$s^k_i = \frac{C^k_{i,fin} - C^k_{i,ini}}{\Delta P^k_i} \quad (10)$$

$$FC_{i,t} = a_i \left(P^{min}_i\right)^2 + b_i P^{min}_i + c_i u_{i,t} + \sum_k s^k_i P^k_{i,t} \quad (11)$$

Wind curtailment considers that the system operators must not be allowed to use the thermal generation when wind energy is available. Wind curtailment occurs under lightly loaded condition when the load on the system is less than the lowest limits that the thermal generators are running and rest of the energy sources are also available including wind energy.

Modeling for Thermal Generators

The capacity constraints of a thermal generator are as follows:

Constraint for Ramp Rate: The generated power of *i*th thermal generator at *t*th time should be within the limits as given by (12–16). The ramp up/down constraints as given in [28] are modeled as follows:

$$P^{tmin}_{i,t} \le P_{i,t} \le P^{tmax}_{i,t} \quad (12)$$

$$P^{tmax}_{i,t} \le P^{max}_i \left[u_{i,t} - z_{i,t+1}\right] + SD_i z_{i,t+1} \quad (13)$$

$$P^{tmax}_{i,t} \le P_{i,t-1} + RU_i u_{i,t-1} + SU_i y_{i,t} \quad (14)$$

$$P^{tmin}_{i,t} \ge P^{min}_{i,t} u_{i,t} \quad (15)$$

$$P^{tmin}_{i,t} \ge P_{i,t-1} - RD_i u_{i,t} - SD_i z_{i,t} \quad (16)$$

Constraints for Minimum Up/Down Time: The operation status of i^{th} thermal generator at t^{th} time is given by $u_{i,t}$. Also, shutdown and start-up statuses are given as $y_{i,t}$, $z_{i,t}$ as in Eq. (17, 18, and 19).

$$y_{i,t} - z_{i,t} = u_{i,t} - u_{i,t-1} \quad (17)$$

$$y_{i,t} + z_{i,t} \leq 1 \quad (18)$$

$$y_{i,t}, z_{i,t}, u_{i,t} \in \{0, 1\} \quad (19)$$

The min uptime (UTi) of i[th] thermal generator is given in (20 to 23) as proposed in [28]

$$\sum_{t=1}^{\mu_i} 1 - u_{i,t} = 0 \quad (20)$$

$$\sum_{t=k}^{k+UT_i-1} u_{i,t} \geq UT_i y_{i,k}, \forall k = \mu_i + 1 \ldots T - UT_i + 1 \quad (21)$$

$$\sum_{t=k}^{T} u_{i,t} - y_{i,t} \geq 0, \forall k = T - UT_i + 2 \ldots T \quad (22)$$

$$\mu_i = \min\{T, \left(UT_i - U_i^0\right) u_{i,t=0}\} \quad (23)$$

The minimum downtime (DT_i) of an i[th] thermal generator is given in (24, 25, and 26) as proposed in [28]

$$\sum_{t=1}^{\mu_i} u_{i,t} = 0 \quad (24)$$

$$\sum_{t=k}^{k+DT_i-1} 1 - u_{i,t} \geq DT_i z_{i,k}, \forall k = T - DT_i + 2 \ldots \quad (25)$$

$$\mu_i = \min\{T, (DT_i - S_i^0)[1 - u_{i,t=0}]\} \quad (26)$$

The viable cost for shutdown and start-up of thermal generator depends on the duration for which the generator has been on or off, respectively. Here, costs for shutdown (Sd_i) and start-up (Cs_i) are taken as constants as given in Eq. (27 and 28)

$$STC_{i,t} = Cs_i y_{i,t} \quad (27)$$

$$SDC_{i,t} = Sd_i z_{i,t} \quad (28)$$

Power Balance Equation

The total power demand should be equal to the total generation for every time slot:

$$P_t^s + P_t^w + P_t^{dis} + \sum_i P_{i,t} \geq L_t + P_t^{ch} \quad (29)$$

Modeling for Wind Energy

The wind turbine power output curve [30] is shown in Fig. 3, and it is modeled as given by Eq. (30).

$$P^w = \begin{cases} P^r \times \left(\dfrac{v - v_{in}}{v_r - v_{in}}\right)^3; v_c \leq v \leq v_r \\ P^r; v_r \leq v \leq v_f \\ 0; v < v_c or v > v_f \end{cases} \quad (30)$$

Here, v,v_f, and v_c are wind speed, cut out, and cut in speed, respectively. v_r is the lowest speed at which rated power P^r is produced.

Wind curtailment is represented as

$$P_t^{wc} = W_t - P_t^w \quad (31)$$

It is beneficial to utilize most of the generated wind energy, because it will lead to a reduction in fuel cost and it is environmentally sustainable due to low emissions, hence, P_t^{wc} should be small. The power generation constraint of the wind turbine is given by

$$0 \leq P_t^w \leq W_t \quad (32)$$

Modeling for Solar PV

Solar PV power generation involves irradiance. The irradiance equation [31, 34] is written as

$$I_t = I_d \times \cos\theta_\beta + I_{dif} \times \frac{(1 + \cos\beta)}{2} + \rho \times I_g \times \frac{(1 - \cos\beta)}{2} \quad (33)$$

where I_d, I_{dif}, and I_g are direct, diffuse, and global irradiance, respectively. ρ is nearby local reflection. β and θ_β are tilt and incidence angle. Solar PV power $P_{i,t}^{PV}$ [32] is stated as:

$$P_t^{PV} = P_{stc}^{PV} \times n_s^{PV} \times n_p^{PV} \times (I_t/1000) \times \left[1 - \in \left(T_t^c - 25\right)\right] \quad (34)$$

where P_{stc}^{PV} is the output of PV module under standard parameters and at the maximum powerpoint. n_p^{PV} and n_s^{PV} represent the required series–parallel combination of solar cells., T_t^c and ∈ are PV module temperature and its numerical multiplier, respectively [32].

Cell temperature is stated as

$$T_t^c = T_t^a + (I_t/800) \times (NOTC - 20) \quad (35)$$

where T_t^a is ambient and NOTC is nominal temperature. The values of s_t for each time are determined with the given model. Limiting power of solar PV is modeled as

$$0 \leq P_t^s \leq S_t \quad (36)$$

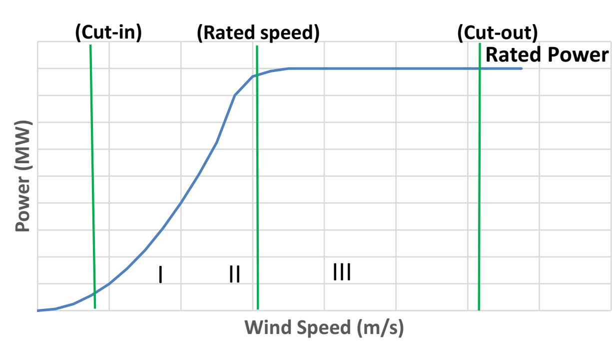


Fig. 3 Wind power output curve

Table 2 Data for BESS

Parameter	Value	Parameter	Value
P_{cmax}	$0.2SOC_{max}$	η_{ch}	0.95
P_{cmin}	0	η_{dis}	0.90
P_{dmax}	$0.2SOC_{max}$	SOC_0	100 MW
P_{dmin}	0	SOC_{max}	300 MW

Battery Modeling

The parameters of the battery are given in Table 2. The relationship between charging power, discharging power, SOC, and depth of discharge (DOD) [13, 34] is given in Eq. (39).

$$SOC^{min} = C^{nb}(1 - DOD^{max}) \tag{37}$$

$$SOC^{max} = C^{nb} \tag{38}$$

where C^{nb} is the nominal capacity of the battery.

$$SOC_t = SOC_{t-\Delta t}.(1 - DOD_t) + \left(P_t^{ch}.\eta_{ch} - P_t^{dis}.\frac{1}{\eta_{dis}}\right).\Delta t \tag{39}$$

The battery storage limits and state of charge are expressed as

$$SOC^{min} \le SOC_t \le SOC^{max} \tag{40}$$

$$P_t^{ch,min} \le P_t^{ch} \le P_t^{ch,max} \tag{41}$$

$$P_t^{dis,min} \le P_t^{dis} \le P_t^{dis,max} \tag{42}$$

Constraints for Demand Response Flexibility

For improving the performance and validity of the MG operation, the unit commitment optimization model should be solved with more constraints like demand flexibility. Conventionally, the generator scheduling was used to make a balance of power between demand and generation which is now changing with time. To increase the performance of the unit commitment problem, the demand is also sometimes changed deliberately and it can be dispatched according to the system requirement. The unit commitment problem considering demand response flexibility is modeled as

$$\sum_i P_{i,t} \ge D_t \tag{43}$$

$$(1 - \alpha_{min})\, L_t \le D_t \le (1 + \alpha_{max})\, L_t \tag{44}$$

$$\sum\nolimits_t D_t = \sum\nolimits_t L_t \tag{45}$$

Equation (44) shows the range for the variation in demand. $\alpha_{max/min}$ gives the minimum or maximum demand response. Equation (43) tells that the overall power requirement cannot change with time. The $\alpha_{max/min}$ is taken to be varying from 0 to 12%.

Data used for the Analysis

Ten thermal generators have been considered for the purpose. The generator characteristics, operating constraints for generator, and data for BESS are inspired from [29]. The simulation parameters for BESS for the unit commitment problem are given in Table 2. Solar and wind power generation and the energy requirements are drawn and displayed in Fig. 4. As can be seen in the figure, solar energy is available for a certain duration of the day, i.e., from 5 to 19th duration and wind energy is accessible twenty-four hours, the highest availability of solar and wind energy is at 13th and 16th hours separately. The maximum demand occurs at 10th and 11th hour.

Results and Discussions

Windows 10 operating system with i7 processor having 8 GB RAM is used for the study. GAMS version 24.4.3 [33] is employed for the coding purpose to obtain the results. The UC problem is solved majorly using stochastic, deterministic, and evolutionary algorithms. But in case of high complexity, evolutionary algorithms may not give a global optimal solution. Considering this, the UC model is solved as MILP using CPLEX optimization solver in

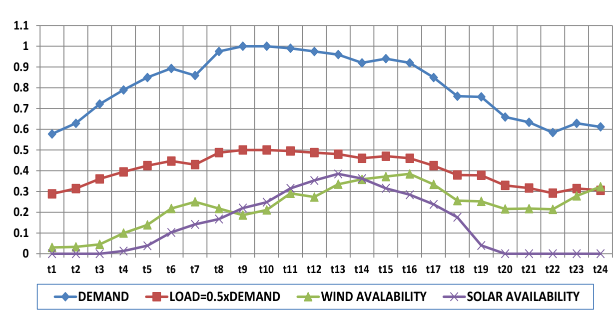


Fig. 4 Variation in fractional load, wind, and solar power availability w.r.t. time

GAMS. GAMS allows high-level mathematical optimization using various deterministic techniques. The problem of UC in microgrid operating in islanded mode is arranged into four separate cases. Case 1, When exclusively conventional thermal generators (DGs) are operating. Case 2, Wind turbine is operational along with DG. Case 3, PV generator along with wind turbine and DG is operational. Case 4, Battery energy storage system (BESS) is operational alongside DG, wind technology, and solar technology.

Case study 1: This is a base case including DG sets only. Figure 5 shows the number of generators to be turned on, the generation schedule, and the level of generation of each unit to provide for the electricity demand by local generation consisting of thermal generators. The total operating cost of the microgrid is \$233,154.2 for a period of 24 h and the cost of fuel, shutdown and start-up costs are \$232,685, \$269.8, and \$199.4, respectively, as shown in Figs. 13 and 10.

Case study 2: Fig. 5 shows that there is a reduction in the commitment status and increment in the de-commitment of DG units when wind technology is integrated into the system. It will further reduce when we consider solar and BESS technology. It is noteworthy that the system operator will have to pay wind curtailment costs for using the generators instead of utilizing the full capacity of wind generation. The total operating cost is \$202,733.7 which is composed of \$129,909 fuel cost for DG, \$72,285 wind curtailment cost of the wind turbine, \$184.9 start-up, and \$355 for shutdown costs. It is seen that the overall operation cost and fuel cost have been reduced by 13% and 44.1%, respectively, as compared to case 1. This is mainly because the wind turbine is supplying an appreciable

CASE 1	g1	g2	g3	g4	g5	g6	g7	g8	g9	g10
t1	0	0	60	250	80	0	30	0	0	0
t2	0	0	90	250	80	0	37.5	0	0	0
t3	98	0	67	250	80	0	30	0	0	0
t4	122	0	92.5	250	80	0	30	0	0	0
t5	128	0	100	250	80	0	30	30	0	0
t6	130	0	105	250	80	0	30	30	0	0
t7	149	0	125	250	80	0	34.5	38	0	22
t8	152	0	130	250	80	0	34.5	41	0	22
t9	158	0	135	250	80	0	38.5	42	0	24
t10	158	0	135	250	80	0	38.5	42	0	24
t11	158	0	132	250	80	0	34.5	42	0	24
t12	152	0	130	250	80	0	34.5	41	0	22
t13	149	0	125	250	80	0	34.5	38	0	22
t14	140	0	115	250	80	0	30	34.5	0	20
t15	146	0	120	250	80	0	30	38	0	20
t16	140	0	115	250	80	0	30	34.5	0	20
t17	148.5	0	125	250	0	0	34.5	38	0	22
t18	138.5	0	110	250	0	0	0	34	0	20
t19	136	0	110	250	0	0	0	34	0	20
t20	128	0	101.5	250	0	0	0	0	0	0
t21	121	0	90	250	0	0	0	0	0	0
t22	104	0	71	250	0	0	0	0	0	0
t23	117.5	0	90	250	0	0	0	0	0	0
t24	110	0	85	250	0	0	0	0	0	0

CASE 2	g1	g2	g3	g4	g5	g6	g7	g8	g9	g10
t1	0	0	0	250	80	0	45.9	0	0	0
t2	0	0	0	250	105	0	54	0	0	0
t3	99.3	0	0	250	80	0	30	0	0	0
t4	104.6	0	75	250	0	0	0	0	0	0
t5	90	0	75.7	250	0	0	0	0	0	0
t6	0	0	57.7	250	0	0	0	0	0	0
t7	0	0	84.1	250	0	0	0	0	0	0
t8	87.2	0	55	250	0	0	0	0	0	0
t9	121.5	0	85	250	0	0	0	0	0	0
t10	85.6	0	55	250	0	0	0	30	0	0
t11	0	0	0	250	0	0	0	46.4	0	0
t12	0	0	0	266.5	0	0	0	45	0	0
t13	0	0	0	250	0	0	0	0	0	0
t14	0	0	0	250	0	0	0	0	0	0
t15	0	0	0	250	0	0	0	0	0	0
t16	0	0	0	250	0	0	0	0	0	0
t17	0	0	0	250	0	0	0	0	0	0
t18	0	0	0	250	0	0	0	0	0	0
t19	0	0	0	250	0	0	0	0	0	0
t20	0	0	0	250	0	0	0	0	0	0
t21	0	0	0	250	0	0	0	0	0	0
t22	0	0	0	250	0	0	0	0	0	0
t23	0	0	0	250	0	0	0	0	0	0
t24	0	0	0	250	0	0	0	0	0	0

CASE 3	g1	g2	g3	g4	g5	g6	g7	g8	g9	g10
t1	0	0	0	250	80	0	45.9	0	0	0
t2	0	0	0	250	105	0	54	0	0	0
t3	99.3	0	0	250	80	0	30	0	0	0
t4	120	0	0	250	0	0	40.592	0	0	0
t5	80	0	0	250	0	0	30	0	0	0
t6	0	0	0	250	0	0	0	0	0	0
t7	0	0	0	250	0	0	0	0	0	0
t8	0	0	0	250	0	0	0	0	0	0
t9	0	0	0	250	0	0	0	0	0	0
t10	0	0	0	250	0	0	0	0	0	0
t11	0	0	0	250	0	0	0	0	0	0
t12	0	0	0	250	0	0	0	0	0	0
t13	0	0	0	250	0	0	0	0	0	0
t14	0	0	0	250	0	0	0	0	0	0
t15	0	0	0	250	0	0	0	0	0	0
t16	0	0	0	250	0	0	0	0	0	0
t17	0	0	0	250	0	0	0	0	0	0
t18	0	0	0	250	0	0	0	0	0	0
t19	0	0	0	250	0	0	0	0	0	0
t20	0	0	0	250	0	0	0	0	0	0
t21	0	0	0	250	0	0	0	0	0	0
t22	0	0	0	250	0	0	0	0	0	0
t23	0	0	0	250	0	0	0	0	0	0
t24	0	0	0	250	0	0	0	0	0	0

CASE 4	g1	g2	g3	g4	g5	g6	g7	g8	g9	g10
t1	0	0	0	250	80	0	33.515	0	0	0
t2	80	0	0	250	80	0	30	0	0	0
t3	99.3	0	0	250	80	0	30	0	0	0
t4	130	0	0	250	0	0	0	0	0	0
t5	90	0	0	250	0	0	0	0	0	0
t6	0	0	0	250	0	0	0	0	0	0
t7	0	0	0	250	0	0	0	0	0	0
t8	0	0	0	250	0	0	0	0	0	0
t9	0	0	0	250	0	0	0	0	0	0
t10	0	0	0	250	0	0	0	0	0	0
t11	0	0	0	250	0	0	0	0	0	0
t12	0	0	0	250	0	0	0	0	0	0
t13	0	0	0	250	0	0	0	0	0	0
t14	0	0	0	250	0	0	0	0	0	0
t15	0	0	0	250	0	0	0	0	0	0
t16	0	0	0	250	0	0	0	0	0	0
t17	0	0	0	250	0	0	0	0	0	0
t18	0	0	0	250	0	0	0	0	0	0
t19	0	0	0	250	0	0	0	0	0	0
t20	0	0	0	250	0	0	0	0	0	0
t21	0	0	0	250	0	0	0	0	0	0
t22	0	0	0	250	0	0	0	0	0	0
t23	0	0	0	250	0	0	0	0	0	0
t24	0	0	0	250	0	0	0	0	0	0

Fig. 5 Hourly power generation schedule for thermal generator (MW) under case 1, 2, 3, and 4

portion of the total energy requirements of the MG which is evident from Fig. 6.

Case study 3: In this case, renewable generation including both solar and wind technology is modeled to see the relation between power generation by renewable and non-renewable sources and its impacts on the scheduling of conventional thermal generator. As it is shown in Fig. 7, to supply the electric power demand, power generation is divided among thermal units, wind turbine, and solar PV. The number of thermal generating units has been further reduced which is seen from Fig. 5. The overall cost of operation has reduced to $189,538.9 and the fuel cost of DG unit to $116,998.5 which is shown in Figs. 12 and 13.

Case study 4: The application of energy storage systems into the microgrid has seen a growing trend in the recent past. It facilitates the incorporation of renewable power sources into the power system by storing a certain amount of energy and then reinjecting it into the system to facilitate power exchange and improve overall system characteristics. Firstly, when peak demand is more than the generation, it helps in reducing increased energy supply and thus reduces generation cost and network installations. Secondly, it helps in reducing uncertainty arising due to power generation from renewable sources and makes the system more robust. Considering these advantages, battery storage technology is integrated into the system. It will charge the battery during off-peak loads and discharge it during peak loads to reduce the overall operating cost which can be seen from Fig. 8. The charging and discharging patterns can be seen from Fig. 9. Variation in start-up and shutdown cost can be seen from Fig. 10. Start-up cost first increases and then decreases due to operating constraints, while shutdown cost will only decrease as we move from case 1 to case 4. Considering this case, wind curtailment cost further gets reduced to a minimum value as given in Fig. 11. Reduction in fuel cost for thermal generators is shown in Fig. 12. Total operating cost as compared to case 1 has been reduced by 22% as shown in Fig. 13.

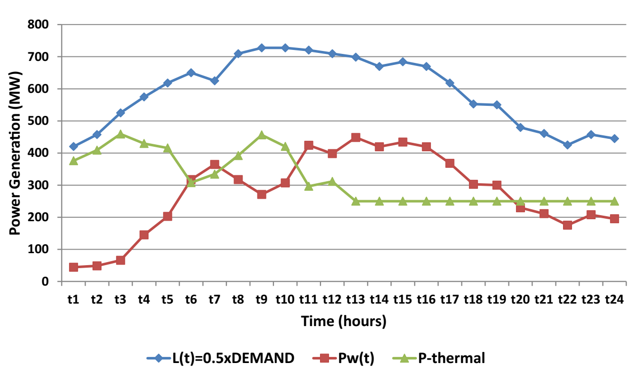


Fig. 6 Total power generation schedule under case 2

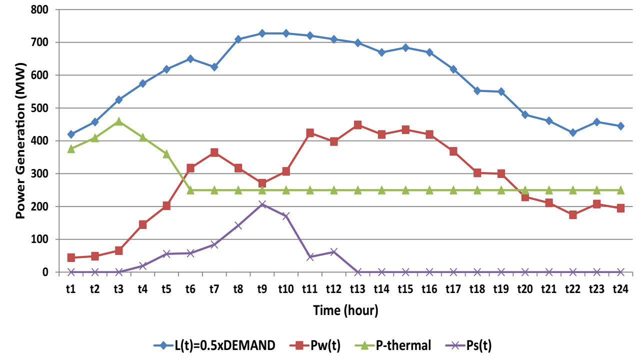


Fig. 7 Total power generation schedule under case 3

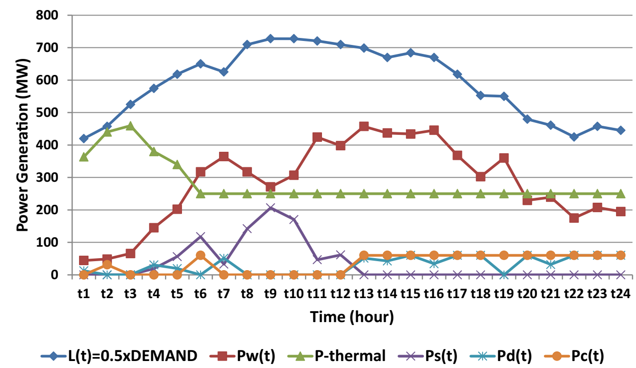


Fig. 8 Total power generation schedule under case 4

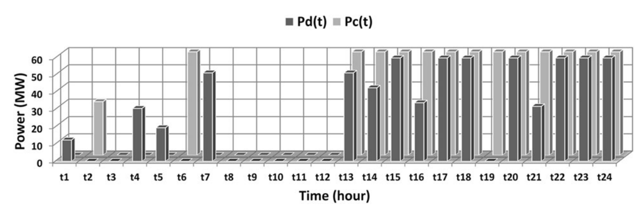


Fig. 9 Power despatch of BESS in case 4

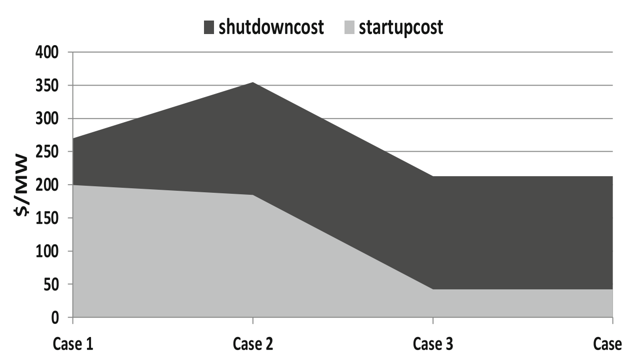
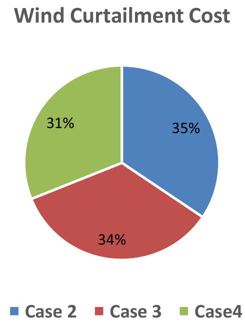


Fig. 10 Variation in start-up and shutdown cost

The minimum/maximum flexibility of demand response is changed from 0 to 12% in steps of 3, and the response to demand flexibility is analyzed. The average demand response is calculated and drawn for each case as shown in

Fig. 11 Variation in wind curtailment cost



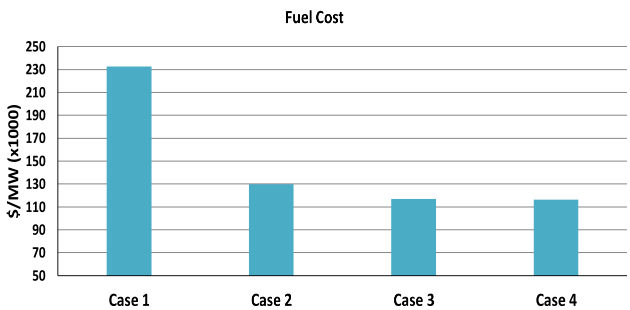


Fig. 12 Variation in fuel cost for DG

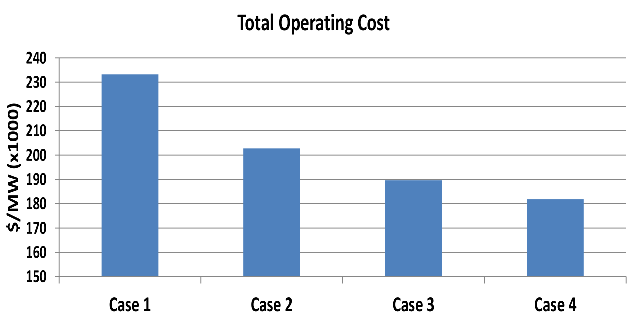


Fig. 13 Variation in total operating cost for the microgrid

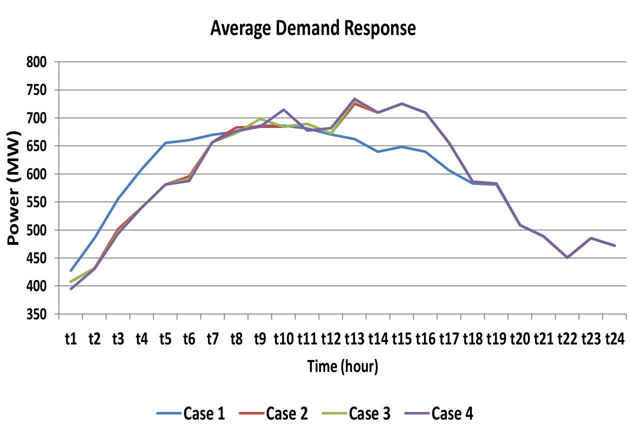


Fig. 14 Average demand response pattern change under each case and sensitivity toward demand flexibility in unit commitment problem

Fig. 14. It can be seen that the demand response is changing from t3 to t7 and from t13 to t18 for individual

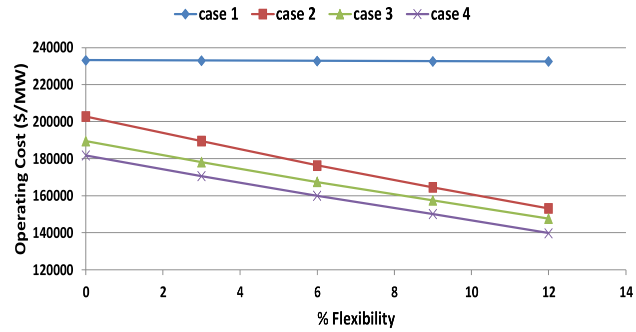


Fig. 15 Variation in total operation cost with demand response flexibility

cases. Figure 15 shows that if the flexibility in demand despatch is given to the system operator, then the total cost of operation would decrease for each case. Table 3 summarizes the outcomes of the simulation performed. A comparison of base case results obtained from the proposed system using MILP under CPLEX optimization solver available in GAMS has been made using different optimization methods such as dynamic programming and Lagrangian relaxation as mentioned in Table 4. Comparison of base case shows better results for MILP technique under CPLEX solver compared to other optimization techniques such as dynamic programming and Lagrangian relaxation.

Conclusions

Optimization framework for the unit commitment of hybrid energy MG is developed in this paper. The model presented is developed based on literature review for unit commitment models. The model is analyzed using the MILP technique considering its high accuracy and flexibility. MG consisting of energy resources such as thermal generator, solar PV, wind energy and battery storage is modeled and investigated with grid islanded scheme of operation. The method is described in a twenty-four hour time duration using GAMS software, and a comparison of simulation results is made for each case. It is observed that increased renewable energy generation leads to reduced non-renewable energy generation and lower operating costs. This involves efficient UC models to overcome irregularity and unreliability. It is observed that renewable power and energy storage systems are crucial parts of MG considering the UC models. Energy storage becomes important both from demand and generation perspective particularly during the incorporation of large renewable power generation into the electrical system. The contribution to battery storage and renewable generation in boosting demand response flexibility of the microgrid has been explained.

Table 3 COMPARISON OF RESULTS FOR THE GIVEN CASES

Case	1	2	3	4
Start-up cost($)	199.4	184.9	42.6	42.6
Shutdown cost($)	269.8	355	212.7	212.7
Wind curtailment cost($)	–	72,285	72,285	65,265
Fuel cost ($)	232,685.1	129,908.8	116,998.5	116,214.6
Total operating cost ($)	233,154.3	202,733.7	189,538.8	181,734.9
Reduction in total cost w.r.t case1(%)	–	13.04	18.7	22.05

Table 4 Comparison of optimization results for base case unit commitment

Programming software	Optimization technique	Operating cost ($)	Time elapsed (sec)	Cost per MW ($/MW)
MATLAB	Dynamic programming	252,203	6.89	17.73
MATLAB	Lagrangian relaxation	244,304	4.32	17.17
GAMS (proposed method)	MILP (CPLEX)	233,154	1.18	16.4

The decrease in cost of fuel for thermal generation is also very large due to high renewable energy penetration. This also helps in mitigating the environmental impacts of using conventional sources of energy and improved energy security. Demand response is studied for all the four cases as mentioned in section III. A comparison of simulation results is provided for four scenarios, and it is observed that case 4 provides promising results than rest of the cases. MILP technique shows better performance compared to other techniques discussed in this paper.

Scope of Improvement

Firstly, the given results are achieved without taking into account energy loss which can be modeled using AC/DC power flow constraints. Secondly, uncertainty modeling of renewable sources using various meta-heuristic techniques can be performed to achieve more accurate results and make the system more robust. Third, to overcome unexpected demand increase or generating unit outage, the UC-reserve constrained modeling of thermal generators connected to the system can be done. Fourth, a problem involving a grid-connected mode of operation considering variable market price may be formulated and compared with an islanded mode of operation of MG.

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