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Day-Ahead Energy Management for Isolated Microgrids Considering Reactive Power Capabilities of Distributed Energy Resources and Reactive Power Costs

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Abstract- In this paper, a day-ahead energy management (EM) for isolated microgrids (MGs) is proposed to obtain the optimal dispatch such that the costs related to the fuel consumption of diesel generators, load shedding, and renewable energy curtailment are minimized. Usually, fuel consumption costs of diesel generators are considered to be dependent on active power generation only. However, neglecting the related reactive power costs might result in increased operation costs and deviations in the dispatches from the optimal solutions. Hence, this paper co-optimizes the costs related to both active and reactive powers of diesel generators. In addition, this study considers the reactive power capability of inverter-interfaced distributed energy resources (DERs). The energy management problem is formulated as a nonlinear programming problem in GAMS environment and is solved using the CONOPT solver. Four different cases are presented to show the effect of considering the reactive power costs of the diesel generators and the reactive power capability from the inverter-interfaced DERs on the operating costs and dispatch results of the isolated MG.

Keywords Microgrids (MGs); Renewable Energy Sources (RESs); Active/Reactive Power Dispatch; Distributed Energy Resources (DERs); Battery Energy Storage Systems (BESSs); Renewable Energy Curtailment; Load Shedding; Reactive Power Capability Curves.

Nomenclature

Indices and Sets:

Ω_g^i	Set of generators connected to bus “i”
Ω_l^i	Set of lines connected to bus “i”
$g \in G$	Diesel Generator
$i,j \in I$	Indices for buses
L	Set of lines
$t \in T$	Time periods “h”
x_i	Type of load at bus “i” that can be shed (residential and commercial)

Constants and Parameters:

α	Load shedding percentage $\in$ {0, 25, 50, 75, 100}
θ_{ij}	Phase angle of line “ij”
η_{ch}, η_{dis}	Charging and discharging efficiency of BESS
Δt	Time slot “h”
$\emptyset$	Rated power factor angle of generator
Φ_l	Power factor angle of different loads
a_g, b_g, c_g	Active power cost coefficients of diesel generators
a'_g, b'_g, c'_g	Reactive power cost coefficients of diesel generators
C_d	Diesel fuel cost \$/L or \$/gal

E_{max}	Max induced EMF of diesel generator "V"
G_{IIR}	Solar incident irradiance
G_{STC}	Irradiance at STC
$I_{c,max}$	Max current of converter
K	Temperature coefficient
$P_{g,max}$	Max active power of generator "g"
$P_{g,min}$	Min active power of generator "g"
$P_{i,max}^{ch}$, $P_{i,min}^{ch}$	Max / min charge power of BESS at bus "i"
$P_{i,max}^{dis}$, $P_{i,min}^{dis}$	Max / min discharge power of BESS at bus "i"
$P_{i,t,Avail}^{PV}$	Available PV power connected to bus "i" at time "t"
$P_{i,t,Avail}^{W}$	Available wind power connected to bus "i" at time "t"
P_{STC}	Power at standard test conditions
$S_{g,rating}$	VA rating of Generator "g"
$S_{ij,max}$, $S_{ij,min}$	Max and min VA rating capacity of line "ij"
$SOC_{i,max}$	Max state of charge of BESS connected to bus "i"
$SOC_{i,min}$	Min state of charge of BESS connected to bus "i"
T_a	Ambient temperature
T_c	PV cell temperature
u_{ci} , u_{co}, u_r	Cut in, cut out, and rated wind speeds "m/s"
$V_{c,max}$	Max converter voltage "V"
V_{DER}	DER voltage "V"
$V_{i,max}$, $V_{i,min}$	Max and min bus voltage "V"
V_t	Synchronous generator terminal voltage "V"
VOC	Cost value of curtailment "$/kWh"
$VOLL_{x_i}$	Value of lost load cost "$/kWh" for load type "x"
X	Reactance of transformers and grid filters "Ω"
X_s	Synchronous reactance of synchronous generator "Ω"
Z_{ij}	Impedance of line "ij","Ω"

Variables:

$\delta_{i,t}$, $\delta_{j,t}$	Voltage angle of bus "i" or "j" at time "t"
P_{DER}	DER active power dispatch For RESs (PV, Wind): $P_{DER} = P_{i,t}^{PV}$ or $P_{i,t}^{W}$ For BESSs: $P_{DER} = P_{i,t}^{dis} - P_{i,t}^{ch}$
$P_{ij,t}$	Active power flow through line "ij" at time "t"
$P_{i,t}^{ch}$	BESS active power charging at bus "i" and time "t"
$P_{i,t}^{dis}$	BESS active power discharging at bus "i" and time "t"
$P_{i,t}^{l}$	Active load at bus "i" at time "t"
$P_{i,t}^{lsh}$	Active load shed at bus "i" & time "t" (=0 for industrial load)
$P_{i,t}^{PV}$	PV dispatched active power at bus "i" and time "t"
$P_{i,t}^{PVC}$	Curtailed PV power at bus "i" and time "t"
$P_{i,t}^{W}$	wind dispatched active power at bus "i" and time "t"
$P_{i,t}^{WC}$	Curtailed wind power at bus "i" and time "t"
Q_{DER}	DER reactive power dispatch For RESs (PV, Wind): $Q_{DER} = Q_{i,t}^{PV}$ or $Q_{i,t}^{W}$ For BESSs: $Q_{DER} = Q_{i,t}^{BESS}$
$Q_{g,t}$	Reactive power dispatch of generator "g" at time "t"
$Q_{ij,t}$	Reactive power flow through line "ij" at time "t"
$Q_{i,t}^{BESS}$	BESSs reactive power dispatch at bus "i" & time "t"
$Q_{i,t}^{l}$	Reactive load at bus "i" at time "t"
$Q_{i,t}^{lsh}$	Reactive shedding at bus "i", time "t" (=0 for industrial load)
$Q_{i,t}^{PV}$	PV dispatched reactive power at bus "i" and time "t"
$Q_{i,t}^{W}$	Wind dispatched reactive power at bus "i" and time "t"
$S_{ij,t}$	Apparent power flow through line "ij" at time "t"
$SOC_{i,t}$	State of charge of BESS at bus "i" and time "t"

Acronyms:

BESSs	Battery Energy Storage Systems
DERs	Distributed Energy Resources
DFIG	Doubly Fed Induction Generator
DG	Distributed Generator
EM	Energy Management
FCWG	Full Converter Wind Generator
GAMS	General Algebraic Modeling System
LV	Low Voltage
MG	Microgrid
OPF	Optimal Power Flow
PV	Photovoltaic
RESs	Renewable Energy Sources
SOC	State of Charge
STC	Standard Test Conditions
VOC	Value of Curtailment
VOLL	Value of Loss of Load
WT	Wind Turbine

1. Introduction

Nowadays, distributed generators (DGs) are widely utilized in modern distribution systems. One of the ways to have effective utilization of DGs is to deal with them as a localized group in the so called microgrids (MGs) [1]. MGs are small power systems consisting of DGs that may be dispatchable like diesel generators or non-dispatchable like wind turbines (WTs) and photovoltaic (PV) systems in addition to energy storage systems like batteries. The total global MG capacity is expected to grow from 3.5 GW in 2019 to nearly 20 GW in 2028 [2]. In general, MGs can operate in either grid connected mode or isolated mode when there is no access to the electric grid. Operation of isolated MGs is more challenging as their sole supply of power is their local sources. Thus, system operators have to efficiently perform EM in isolated MGs to effectively utilize the available power sources in supplying the demand in the most techno-economical way [3].

Recently, the EM in isolated MGs has been the focus of several studies. For example, in [4], an EM model is proposed to study the effect of MG operation on operation costs and emissions for different operating conditions. In [5], a dynamic programming is derived to solve the EM problem in MGs to reduce costs and emissions. In [6], optimal generation and peak load dispatch with smart loads integrated in an EM model is proposed for an isolated MG. In [7], EM is used in an isolated MG to reduce energy cost, power fluctuations, and emissions while maximizing the reliability. In [8], EM of MGs considering multiple energy sources, uncertain loads, forecasting and demand side management is provided. In [9], a centralized EM model is proposed for an isolated MG considering the three-phase distribution system model to study its effect on optimal operation of the MG. A security constrained optimal EM for a residential MG is developed in [10] to consider the transition mode between grid-connected and isolated operation while minimizing the operation costs. In [11], EM in MGs is proposed in the presence of micro compressed air energy storage with RESs uncertainty consideration to minimize the operation costs of energy storage, emissions, and energy not supplied while applying demand side management programs. In [12], an operation model for an isolated MG involving RESs with blue battery concept is proposed. Whereas in [13], consideration of electric and thermal reserve requirements with multicarrier infrastructure along with energy hub functions are derived in a MG. In [14], a multi-objective optimization problem seeking for the optimal operation schedule and emission reduction for a RESs and electric vehicles based smart grid is presented. In [15], optimal scheduling of electrical vehicles in a renewable based MG is proposed. Whereas in [16], five different operational scenarios are developed in an MG incorporating PVs, electric vehicles, and, load shifting control to provide an efficient EM model. While in [17], a multi-objective optimization is formulated to find the optimal sizing for PVs, WTs, and battery energy storage systems (BESSs) for a hybrid MG. In [18], an EM strategy considering BESSs efficiency for a grid tied MG is proposed to minimize the operation costs. While in [19], a hierarchical energy dispatch scheme incorporating BESSs is presented using multi-agent based algorithm in an MG. However, in the aforementioned studies, the contribution of reactive power from DERs was not considered. This leads to loss of the opportunity to gain benefits from the reactive power capability of DERs. Moreover, the cost of reactive power was not taken into account. Therefore, optimal dispatch results may be affected and errors in the calculated total operation costs will occur as the reactive power demands will be supplied mainly from diesel generators.

The optimization of reactive power from DERs to allow for ancillary services such as voltage support and reduction of power losses is considered in [20], [21]. However, these studies did not consider the costs related to the reactive power. In addition, most of these studies solve the OPF problem either for the active power dispatch or the reactive power dispatch, which may result in deviations from the system optimal solutions. Despite some studies has taken the costs of reactive power into account in the problem of reactive power dispatch [22], [23], but the active power dispatch has not been considered. Simultaneous active/reactive power dispatch in the EM problem can lead to accurate operation decisions compared to the separate dispatch for active power or reactive power.

As shown from the above review, reactive power costs from conventional generators are usually neglected for simplifications. Therefore, this work investigates the impact of taking the diesel reactive power costs into account on the overall operation costs. Moreover, the impact of utilizing the reactive power capability of inverter interfaced DERs on the operation costs is studied. Hence, in this paper, a day-ahead energy management in an isolated MG is proposed based on network-constraint multi-period AC OPF. The isolated MG has a variety of power/energy sources; including diesel generators, WTs, PV systems, and BESSs. The optimization problem aim is to decide for the day-ahead optimal dispatch of the MG. The objective is to effectively manage the available sources such that the costs related to diesel generators operation, RESs power curtailment and load shedding are minimized. Hence, the main contributions in this paper compared to the previous literature can be highlighted as follows:

- Reactive power costs of diesel generators are taken into account and are co-optimized with the active power costs. In other studies, reactive power costs are usually neglected or considered separately from active power costs although they are related. Neglecting reactive power costs leads to non-optimal dispatch results and introduces errors in the calculated total operational costs.
- The reactive power capabilities of the inverter-interfaced DERs are utilized with the consideration of the capability curves of the inverters to alleviate the use of diesel generators in supplying reactive power.
- Detailed modeling of the synchronous diesel generators by the consideration of their capability curves is utilized to provide a realistic behavior of these generators.
- Using real values for different costs such as fuel cost, RESs power curtailment, and VOLL for different types of loads to provide realistic results.

The remaining of the paper is organized as follows. Section two gives the modeling of the isolated MG components including diesel generators, WTs, PVs, and BESSs. Section three provides the detailed EM problem formulation. Section four discusses the MG test system description while Section five presents the results and discussions. Conclusions are outlined in Section six.

2. Modeling of the Isolated Microgrid Components

The system considered in this study is a LV isolated MG which contains diesel generators, WTs, PVs, and BESS in addition to three types of loads: residential, commercial, and industrial. The model for each component is given in the following subsections.

2.1. Diesel Generators [24], [25]

Synchronous generators are rated at a certain voltage and power factor which they can carry without temperature rise. The active power output is limited by the prime mover capability while the reactive power output capability is limited by armature current limit and field current limit. At normal operating conditions, the generator operation must be within the capability curve limits to avoid overheating, and hence, the generator is safe from damage.

- *Armature Current Limit:*

The armature current results in copper losses leading to increased temperature in armature windings. This encounters a limitation on generator maximum current flowing in the armature without overheating. The apparent power rating is related to the armature current and the terminal voltage of the generator. This limit is given by:

$$P_g^2 + Q_g^2 \leq S_{g,rating}^2 \quad (1)$$

- *Field Current Limit:*

A maximum bound on the field value current is enforced by the heating in the field winding due to copper losses in the field circuit. This limit can be expressed by:

$$P_g^2 + (Q_g + \frac{V_t^2}{X_s})^2 \leq (\frac{E_{max}*V_t}{X_s})^2 \quad (2)$$

- *Prime-mover Limits:*

Limits on the mechanical power input from the prime-mover impose constraints on the active power generation. These limits can be represented by:

$$P_{g,min} \leq P_g \leq P_{g,max} \quad (3)$$

2.2. Wind Turbines

Although doubly fed induction generators (DFIGs) are commonly used with variable speed WTs, recent advances in power electronics have made full-scale converter wind generation type (FCWG) a strong competetor. One of the main advantages of FCWG over DFIG is the greater reactive power capability range [26], [27]. Therefore, FCWG type is utilized in this paper. The relation between the output power and the wind speed of a WT can be represented by [28]:

$$P^W(u) = \begin{cases} 0, & u \leq u_{ci} \; or \; u \geq u_{co} \\ \frac{P_{rated}(u-u_{ci})}{(u_r-u_{ci})}, & u_{ci} \leq u \leq u_r \\ P_{rated}, & u_r \leq u \leq u_{co} \end{cases} \quad (4)$$

2.3. Photovoltaic Systems

The output power of a PV array can be represented by a function of the solar irradiance, cell temperature, and the physical properties of the PV modules. The output power produced by PV systems is calculated by [29], [30]:

$$P_{PV} = P_{STC}\frac{G_{IIR}}{G_{STC}}[1+K(T_c-T_a)] \quad (5)$$

2.4. Battery Energy Storage Systems (BESSs)

In this paper, BESSs are utilized as they are the most common energy storage type. The charging and discharging of a BESS are restricted by the maximum charging and discharging powers. The BESS state of charge (SOC) must also lie within specific limits. The SOC of the battery is calculated based on its previous value and charging/discharging powers as follows:

$$SOC_t = SOC_{t-1} + (P_t^{ch} * \eta_{ch} - P_t^{dis} / \eta_{dis}) * \Delta t \quad (6)$$

2.5. Reactive Power & Capability Curves of Inverter Interfaced DERs

In this paper; WTs, PVs and BESS are assumed to be inverter interfaced so that reactive power as well as active power could be supplied according to the inverters' capability. It is possible to represent the inverter current and voltage limitations, analogous to the synchronous generators, by the following equations, respectively [31], [32]:

$$P_{DER}^2 + Q_{DER}^2 \leq (V_{DER} * I_{c,max})^2 \quad (7)$$

$$P_{DER}^2 + (Q_{DER} + \frac{V_{DER}^2}{X})^2 \leq (\frac{V_{c,max}*V_{DER}}{X})^2 \quad (8)$$

3. The Energy Management Problem Formulation

In this section, the day-ahead EM problem in isolated MGs is formulated in details as follows.

3.1. Objective Function

The EM objective is to minimize the total MG operation costs involving fuel related costs, cost of load shedding and RES curtailment costs.

$$\text{Minimize OF} = \{C_d * (\sum_{t\epsilon T}\sum_{g\epsilon G}[a_g P_{g,t}^2 + b_g P_{g,t} + c_g] + \sum_{t\epsilon T}\sum_{g\epsilon G}[a'_g Q_{g,t}^2 + b'_g Q_{g,t} + c'_g])\} + \{\sum_{t\epsilon T}\sum_{i\epsilon I}(VOLL_{x_i} * P_{i,t}^{lsh})\} + \{\sum_{t\epsilon T}\sum_{i\epsilon I} VOC * (P_{i,t}^{PVC} + P_{i,t}^{WC})\} \quad (9)$$

The fuel cost is a function of the fuel consumption and it is given by the first term in the objective function. Usually, fuel consumption data in (L/h) or (gal/h) at 25%, 50%, 70%, and 100% of the diesel generator power rating are given by the manufacturer. According to these data, the fuel consumption characteristics can be fitted to a quadratic polynomial function of the active power output and the cost coefficients can be obtained [29]. While the simplest form for the related reactive power costs from diesel generators is the triangle method where the reactive power cost coefficients are related to their corresponding active power cost coefficients where $a'_g = a_g\, sin^2\emptyset$, $b'_g = b_g\, sin\emptyset$, $c'_g = c_g$ [22], [23].

The second term of the objective function is the load shedding related cost. VOLL is a metric which approximates the cost per unit energy not delivered to consumers. Alternatively, this is the price consumers will pay to avoid disconnection of supply [33]. Many studies have used arbitrary value for the VOLL, but this might affect the accuracy of the problem model and the cost results [10], [34], [35]. Therefore, in this paper, inflation adjusted real VOLL values are utilized to obtain more accurate results and practical view of the decision making problem [33].

RESs power curtailment is an involuntary reduction in the generated power from what it could be produced to provide power balance or to support frequency requirements, basically for small and remote areas. Curtailment costs are given in the third term of the objective function.

3.2. Problem Constraints

The day-ahead EM problem constraints are divided into equality and inequality constraints as follows.

3.2.1. Equality Constraints

These constraints describe the active/reactive power balance, active/reactive/apparent power flow through lines, BESSs SOC, prevention of simultaneous BESSs charge/discharge, RESs curtailment, and load shedding at each bus and time slot as follows.

- Active Power Balance for each bus and time slot:

$$\sum_{g\epsilon\,\Omega_g^i} P_{g,t} + P_{i,t}^{W} + P_{i,t}^{PV} + P_{i,t}^{dis} - P_{i,t}^{ch} + P_{i,t}^{lsh} - P_{i,t}^{l} = \sum_{j\epsilon\,\Omega_l^i} P_{ij,t} \quad (10)$$

- Reactive Power Balance for each bus and time slot:

$$\sum_{g\epsilon\,\Omega_g^i} Q_{g,t} + Q_{i,t}^{W} + Q_{i,t}^{PV} + Q_{i,t}^{BESS} + Q_{i,t}^{lsh} - Q_{i,t}^{l} = \sum_{j\epsilon\,\Omega_l^i} Q_{ij,t} \quad (11)$$

- Active Power Flow through Lines for each time slot:

$$P_{ij,t} = \frac{V_{i,t}^2}{z_{ij}} \cos\theta_{ij} - \frac{V_{i,t} * V_{j,t}}{z_{ij}} \cos(\delta_{i,t} - \delta_{j,t} + \theta_{ij}) \quad (12)$$

- Reactive Power Flow through Lines for each time slot:

$$Q_{ij,t} = \frac{V_{i,t}^2}{z_{ij}} \sin\theta_{ij} - \frac{V_{i,t} * V_{j,t}}{z_{ij}} \sin(\delta_{i,t} - \delta_{j,t} + \theta_{ij}) \quad (13)$$

- Apparent Power Flow through Lines for each time slot:

$$S_{ij,t}^2 = P_{ij,t}^2 + Q_{ij,t}^2 \quad (14)$$

- BESSs State of Charge for each bus and time slot:

$$SOC_{i,t} = SOC_{i,t-1} + (P_{i,t}^{ch} * \eta_{ch} - P_{i,t}^{dis} / \eta_{dis}) * \Delta t \quad (15)$$

- Prevent Simultaneous Charge and Discharge of BESSs:

$$P_{i,t}^{ch} * P_{i,t}^{dis} = 0 \quad (16)$$

- RESs Curtailment for each bus and time slot:

$$P_{i,t}^{WC} = P_{i,t,Avail}^{W} - P_{i,t}^{W} \quad (17)$$

$$P_{i,t}^{PVC} = P_{i,t,Avail}^{PV} - P_{i,t}^{PV} \quad (18)$$

- Load Shedding for each bus and time slot:

$$P_{i,t}^{lsh} = \alpha P_{i,t}^{l} \quad (19)$$

$$Q_{i,t}^{lsh} = P_{i,t}^{lsh} \tan \Phi_l \quad (20)$$

3.2.2. Inequality Constraints

Theses constraints describe the diesel generator capability curves, inverter interfaced DERs capability curves, BESS SOC limits and charge/discharge power limits, load shedding limits, line capacity limits and bus voltage limits.

- Diesel Generator Active and Reactive Power Limits (Generator Capability Curves):
  - -Prime-mover Limits for each time slot:

$$P_{g,min} \le P_{g,t} \le P_{g,max} \quad (21)$$

  - -Armature Current Limits for each time slot:

$$P_{g,t}^2 + Q_{g,t}^2 \le S_{g,rating}^2 \quad (22)$$

  - -Field Current Limits for each time slot:

$$P_{g,t}^2 + (Q_{g,t} + \frac{V_{i,t}^2}{X_s})^2 \le (\frac{E_{max} * V_{i,t}}{X_s})^2 \quad (23)$$

- Inverter Interfaced DERs' Capability Curves:
  - -Inverter Current Limits for each bus and time slot:

$$P_{DER,t}^2 + Q_{DER,t}^2 \le (V_{DER,t} * I_{c,max})^2 \quad (24)$$

  - -Inverter Voltage Limits for each bus and time slot:

$$P_{DER,t}^2 + (Q_{DER,t} + \frac{V_{DER,t}^2}{X})^2 \le (\frac{V_{c,max} * V_{DER,t}}{X})^2 \quad (25)$$

- BESSs State of Charge Limits for each time slot:

$$SOC_{i,min} \le SOC_{i,t} \le SOC_{i,max} \quad (26)$$

- BESSs Charge and Discharge Active Power Limits:

$$P_{i,min}^{ch} \le P_{i,t}^{ch} \le P_{i,max}^{ch} \quad (27)$$

$$P_{i,min}^{dis} \le P_{i,t}^{dis} \le P_{i,max}^{dis} \quad (28)$$

- Load Shedding Limits for each bus and time slot:

$$0 \le P_{i,t}^{lsh} \le P_{i,t}^{l} \quad (29)$$

- Lines Capacity Limits for each time slot:

$$S_{ij,min} \le S_{ij,t} \le S_{ij,max} \quad (30)$$

- Bus Voltages Bounds for each bus and time slot:

$$V_{i,min} \le V_{i,t} \le V_{i,max} \quad (31)$$

4. Test System Description

The low voltage MG shown in Figure 1 is used in this paper to implement the proposed EM strategy [31], [36]. An 80-kW diesel generator is connected to Bus 1 to represent the slack bus for this isolated MG. The total active and reactive powers for the loads are presented in Figure 2. The available powers for RESs at the given buses are shown in Figure 3 [31]. The cost parameters for diesel generators are obtained using the curve fitting *MATLAB* tool "*cftool*" to fit the fuel consumption data to a second order polynomial function. The specification data for the diesel generators are shown in Table 1 whereas the inverter interfaced DERs data are listed in Table 2. The charging/discharging efficiencies of the BESS are assumed to be 77% [37]. The maximum and minimum bus voltages are supposed to be 1.05 and 0.95 p.u., respectively.

Three types of loads are considered in this system; residential, commercial and industrial with their profiles taken from [31], [36]. It is assumed that load shedding can be done for 0, 25%, 50%, 75% or 100% of the commercial and residential loads at any bus. The cost of load shedding compensation is included utilizing real cost data from [33] and after inflation adjustment to 2019 $, the VOLL for residential and commercial loads are obtained. The related RES curtailment costs considered in this paper is utilized from [38] after taking average and inflation adjustments to 2019 $. In addition, the price of the diesel fuel is averaged and inflation adjusted to 2019 as obtained from [39], [40]. These data are given in Table 3.

5. Results and Discussions

The day-ahead EM optimization problem is modeled as a nonlinear programing (NLP) problem in the General Algebraic Modeling System (GAMS) environment [41] and is solved using the CONOPT solver. GAMS is a high-level optimization platform for solving different types of optimization problems. It has many powerful solvers such as CONOPT, DICOPT, KNITRO, and CPLEX. The CONOPT solver is a feasible path solver based on the generalized reduced gradient algorithm. To ensure the proper functionality, after running the GAMS model, the solution report shows the model and solver statuses indicating whether there are compilation errors and check whether the solution is global or local optimum [42].

The optimization problem is solved for different cases; with/without the consideration of the reactive power costs and with/without consideration of the reactive power capabilities from RESs and BESS to investigate the impact of considering/neglecting them.

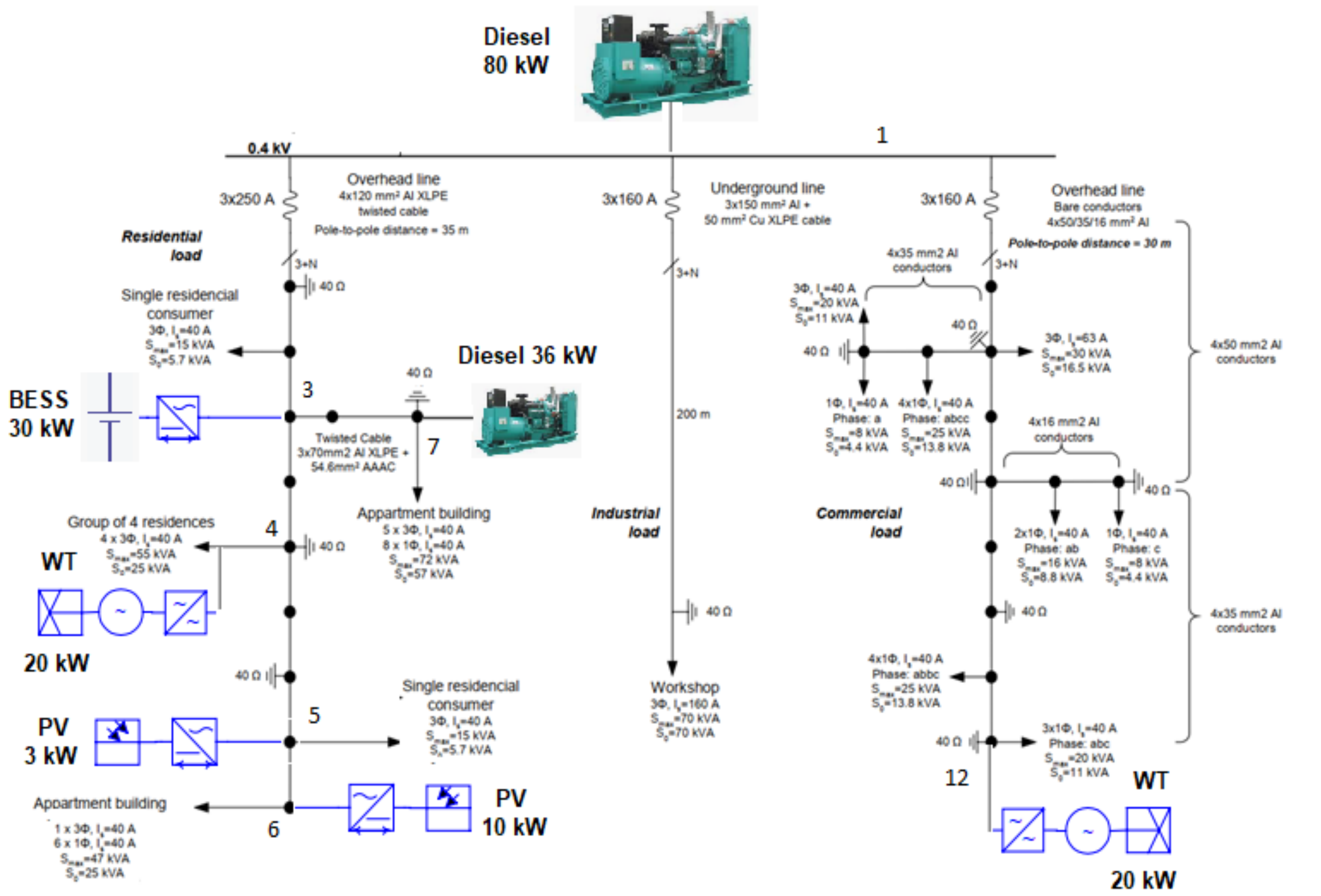

Figure 1. LV benchmark Microgrid [31], [36]

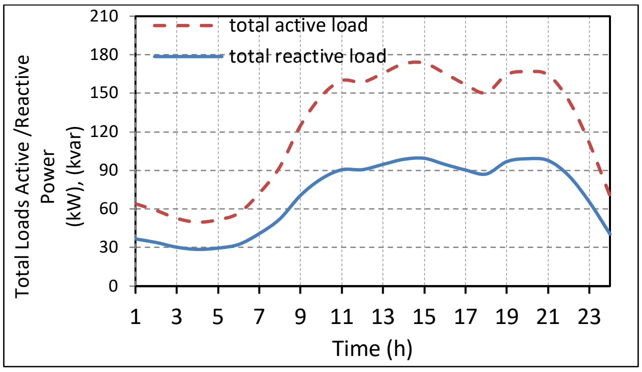

Figure 2. Total active and reactive power loads

Table 1. Specification data for diesel generators

Bus	Diesel Generator Specifications		Fuel Consumption coefficients			Type used
	Rated Power "kW"	Min Power "kW"	a_g	b_g	c_g	
1	80	40	0.5149	4.474	0.7389	Caterpillar DE110E2
7	36	18	0.7485	1.473	0.5761	Caterpillar DE50E0

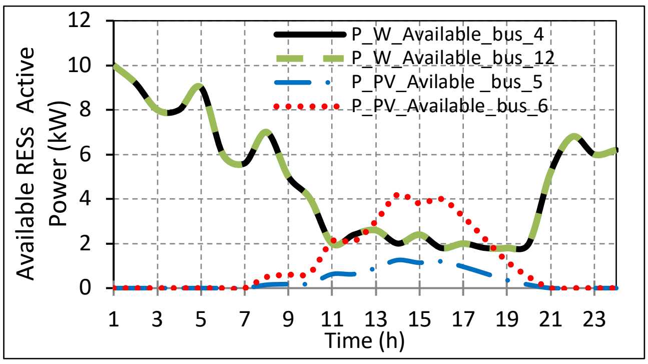

Figure 3. Available active power for RESs

Table 2. Inverter Interfaced Distributed Energy Resources (DERs) data

Bus	Type	Rated Power "kW"	Inverter Type used
3	BESS	30	Delta M30A/M50A
4	WT	20	TRIO-20.0-TL-OUTD-W
5	PV	3	ABB–PVI
6	PV	10	ABB–PVI
12	WT	20	TRIO-20.0-TL-OUTD-W

Table 3. Further system data

VOLL for Commercial Loads	55.88 "$/kWh"
VOLL for Residential Loads	2.39 "$/kWh"
RES Curtailment Cost (VOC)	0.1 "$/kWh"
Diesel Fuel Price in 2019	3 "$/gal"

5.1. Case (1): Neglecting Reactive Power Costs and Reactive Power Support from Inverter Interfaced DERs

In this case, the diesel reactive power costs are not considered and there is no reactive power support from inverter interfaced DERs. In other words, the term related to reactive power costs from diesel generators is omitted from the objective function and both RESs and BESS are able to provide active powers only. The results of this case are displayed in Figure 4 to Figure 7. As shown in Figure 6, the active power dispatches of the diesel generators are at their minimum values (40 kW, 18 kW) all the time in order to maximize the benefit from RESs and BESS discharging as their operation costs are neglected. Active power of the WTs is partially curtailed at t=1 to t=7 as shown in Figure 4. This is because the demand is low and the available power from WTs is high. At this time, the BESS starts to charge as there is excess of generation till its maximum capacity at t=7, as depicted in Figure 6 and Figure 7. No curtailment occurred for PVs, as their available active power is small.

Whereas, at high demand (starting from t=8), no RESs power curtailment occurred, Figure 4. During this period, the BESS discharges power to help supplying the high demand (starting from t=10) and some loads are shed as shown in Figure 6 and Figure 7. The costs of load shedding are 27,548 $/day.

The optimized total operation costs in this case, where the diesel reactive power costs are not accounted, are 119,222 $/day. However, the actual total operation costs should be 141,446 $/day as there are 22,224 $/day (reactive power costs) not added. The neglected reactive power costs are calculated as follows; after the optimization is executed, the un-optimized reactive power costs from the dispatched diesel reactive power, , are calculated using the relevant terms of Equation (9).

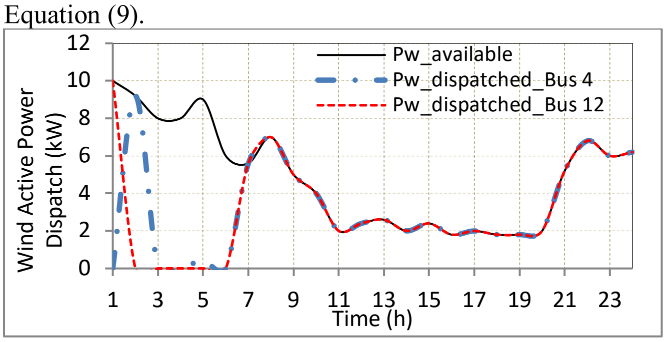

Figure 4. Wind active power dispatch (Case 1)

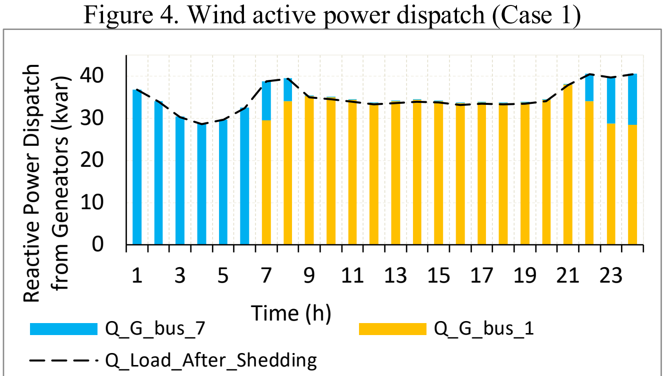

Figure 5. Reactive Power Dispatch of Diesel Generators (Case 1)

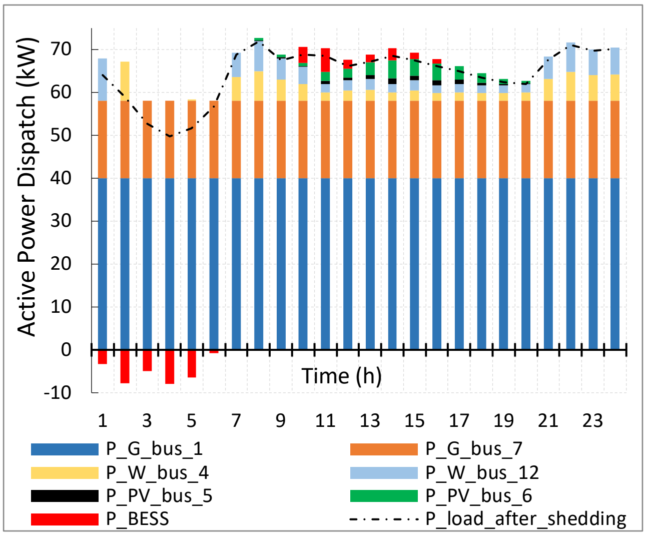

Figure 6. Active Power Dispatched from the Different Sources (Case 1)

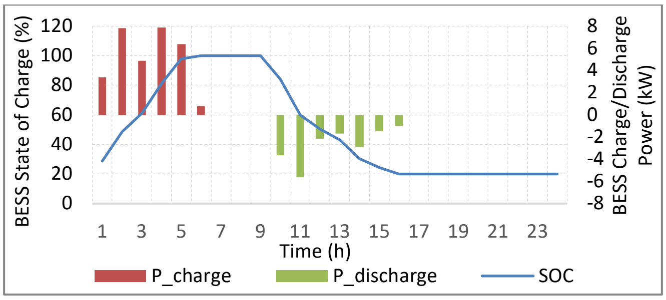

Figure 7. BESS charge/discharge power and SOC (Case 1)

5.2. Case (2): Neglecting Reactive Power Costs while Considering Reactive Power Support from Inverter Interfaced DERs

In this case, the diesel reactive power costs are neglected while inverter interfaced DERs are assumed to supply reactive power. The results of this case are displayed in Figure 8 to Figure 11. Observing Figure 9, the reactive powers produced from diesel generators are slightly decreased compared to Case 1. This is because the reactive power costs were not optimized in both cases while in case 2 some reactive power is supplied from inverter interfaced DERs. Hence, in this case, both diesel generators and inverter based DERs are treated similarly regarding the reactive power injection. The results of active power dispatch for diesel generators, RESs, BESS charging and discharging, and load are close to the previous case and are shown in Figure 8. WT power curtailment is seen from Figure 10.

In this case, diesel generators can supply active power at a given cost and reactive power at no costs while inverter interfaced DERs can supply both active and reactive powers at no cost. Therefore, the reactive power loads are supplied mainly from diesel generators while the active power loads are mainly supplied from DERs. The reactive powers supplied from the WTs and PVs are shown in Figure 9.

The optimized total operation costs per day in this case are 119,229 $ without considering the reactive power costs (18,693 $). This makes the actual total operation costs to be 137,922 $. The diesel reactive power costs in this case are less than the previous case because some of the reactive power is provided from RESs. The cost of load shedding is 27,555 \$/day and the cost of RES curtailment is 8 \$/day.

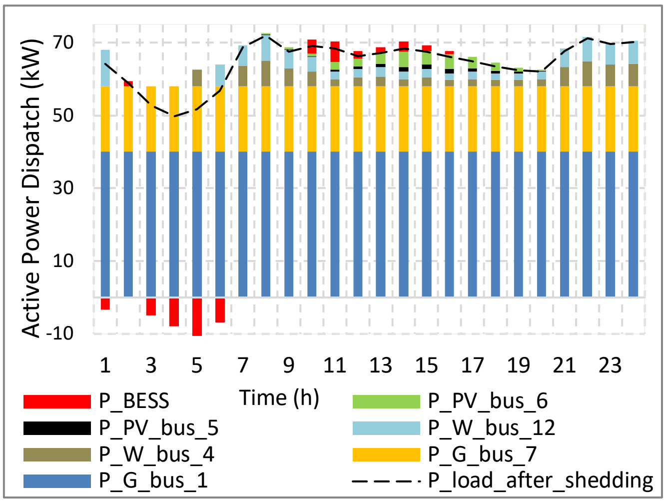

Figure 8. Active Power Dispathced from the Different Sources (Case 2)

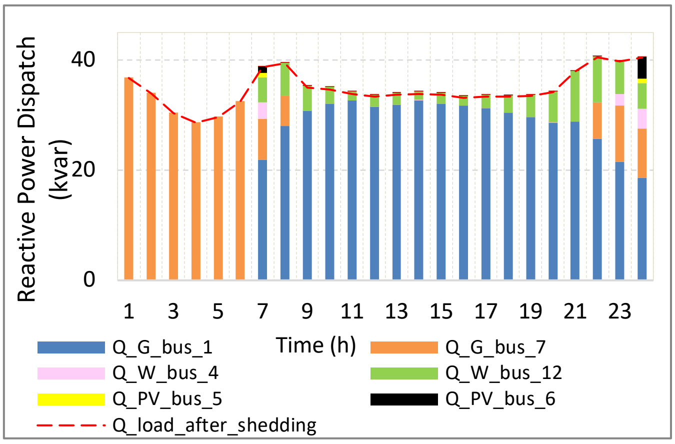

Figure 9. Reactive Power Dispatched from the Different Sources (Case 2)

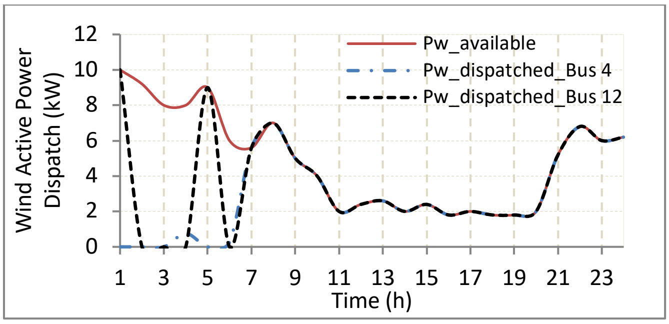

Figure 10. Wind Ative Power Dispatch (Case 2)

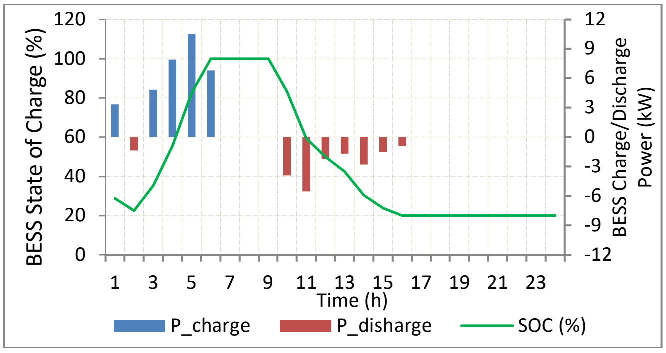

Figure 11. BESS charge/discharge power and SOC (Case 2)

5.3. Case (3): Considering Reactive Power Costs Without Reactive Power Support from Inverter Interfaced DERs

In this case, there is no capability for inverter interfaced DERs to generate reactive power while considering the diesel reactive power costs. The results of this case are displayed in Figure 12 to Figure 16. The diesel generators' active power dispatches are as the previous cases, Figure 13. The diesel reactive power dispatches are presented in Figure 15 which indicates a reduction in the dispatch compared to the previous cases. This is because the reactive power costs are taken into account in the optimization objective. On the other hand, load shedding is slightly increased compared to the previous cases as the diesel reactive power costs are considered which restrict reactive power support. As in case (1) and (2), active power from WTs is curtailed at t=1 to t=7, Figure 12, because of the low demand. The BESS starts to charge during this time till its maximum capacity at t=8, Figure 13 and Figure 16. At high demand (from t=9 to t=21), no RESs active power are curtailed, Figure 12 and the BESS discharges as shown in Figure 13 and Figure 16. Moreover, during this period some loads are shed, as seen from Figure 13, which add some costs to the system (27,794 \$/day).

The optimized (actual) total operation costs are 132,726 \$/day which are less than cases (1) and (2) due to the consideration of the diesel reactive power costs in the optimization. The reactive power cost from diesel generators in this case is 13,250 \$/day, which is less than the previous cases. The curtailment costs are 16 \$/day and are small as expected.

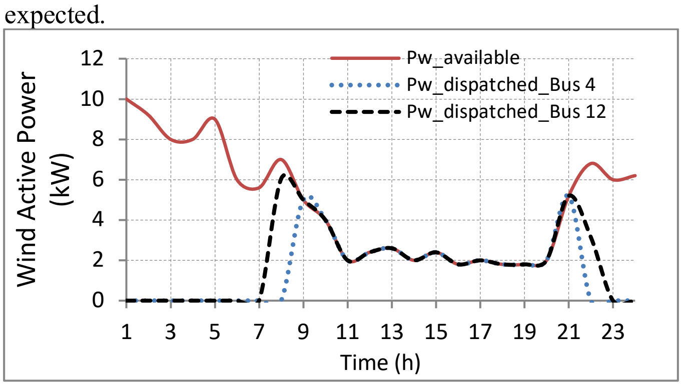

Figure 12. Wind power dispatch and available wind (Case 3)

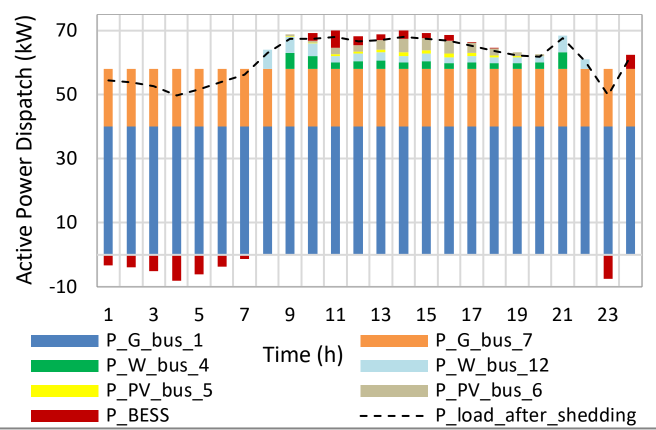

Figure 14. Active Power Dispatch from the Different Sources (Case 3)

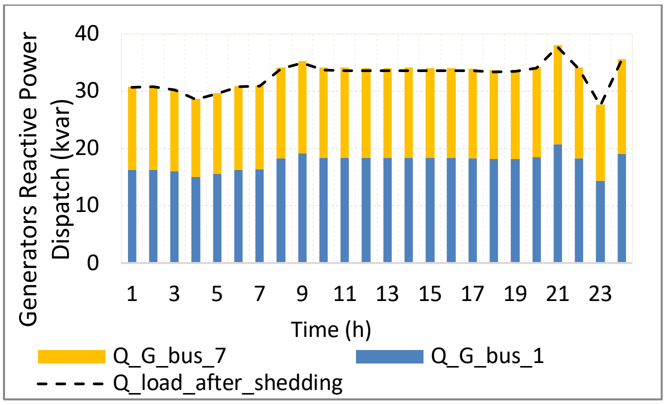

Figure 15. Reactive Power Dispatch of Diesel Generators (Case 3)

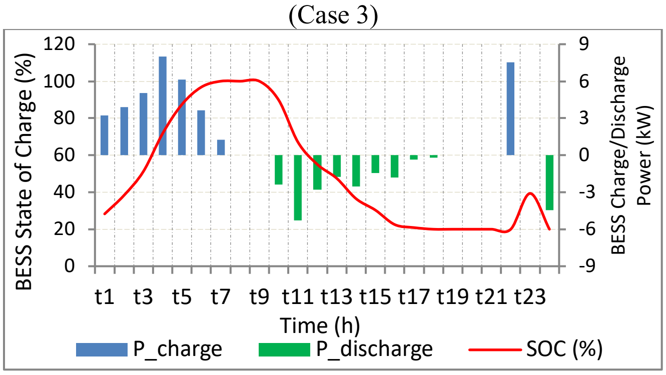

Figure 16. BESS charge/discharge power and SOC (Case 3)

5.4. Case (4): Considering Reactive Power Costs and Reactive Power Support from Inverter Interfaced DERs

This case verifies the impact of utilizing the reactive power capability of inverter interfaced DERs in reducing the operation costs while taking the reactive power costs from diesel generators into account. The results of this case are displayed in Figure 17 to Figure 20. The diesel generators' active power dispatches are as the previous cases, Figure 17. The results of RESs active power dispatch, BESS charging and discharging are close to the previous cases and are shown in Figure 17, respectively. The reactive power dispatch of the WTs, PVs, and BESS are depicted in Figure 18. These reactive powers are sufficient to supply the loads at no costs, and accordingly, no reactive power is supplied from diesel generators. Figure 17 shows that load shedding is slightly reduced compared to Case (3) due to the reactive power support from inverter interfaced DERs. However, the load shedding is still slightly higher than cases (1) and (2) because of restrictions due the reactive power costs in the optimization.

In this case, the optimized (actual) total operation costs per day are 119,395 $, which is the lowest as compared to all the previous cases. The cost of load shedding is 27,626 $/day and the cost of RES curtailment is 8 $/day. There are small fixed reactive power costs of 95 $/day in this case. The different costs for all the four cases are tabulated in Table 4.

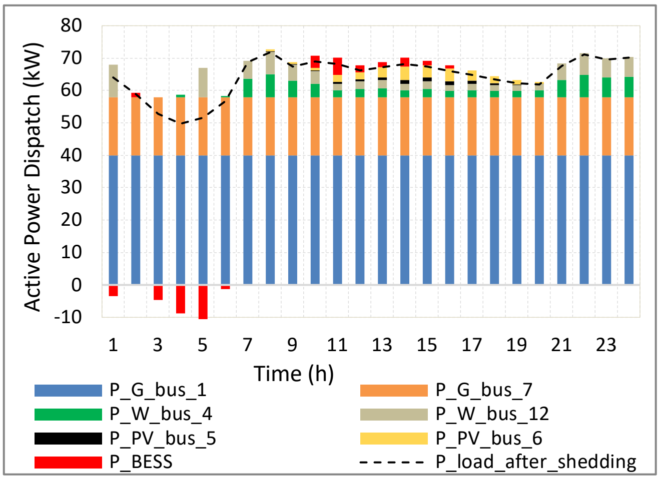

Figure 17. Active Power Dispatch from the Different Sources (Case 4)

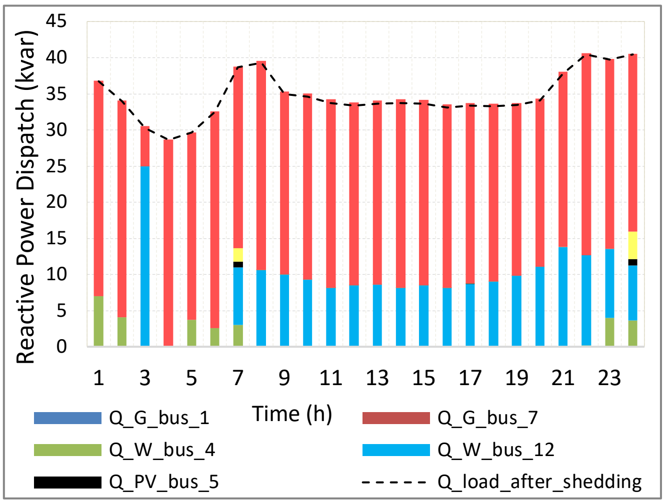

Figure 18. Reactive Power Dispatch from the Different Sources (Case 4)

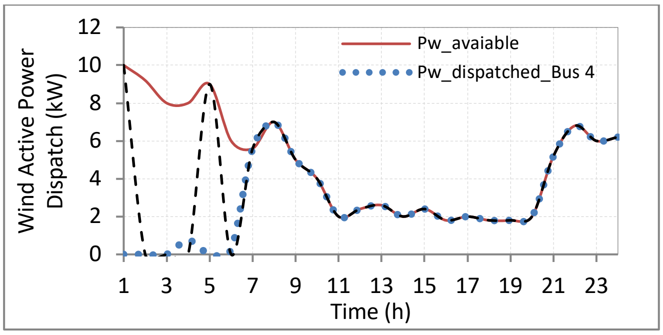

Figure 19. Dispatched wind and its curtailment (Case 4)

Table 4. Breaking down the costs for the different cases

Costs ($/day) / Case Number	Diesel Active Power Cost	Diesel Reactive Power Costs	Load Shedding Costs	RESs Curtailment Costs	Optimized Total Operation Costs (1)	Diesel Reactive Power Costs (Not accounted) (2)	Total Operation Costs (Actual Costs) (1) + (2)
Case (1)	91,666	Not considered	27,548	8	119,222	22,224	141,446
Case (2)	91,666	Not considered	27,555	8	119,229	18,693	137,922
Case (3)	91,666	13,250	27,794	16	132,726	Already accounted	132,726
Case (4)	91,666	95	27,626	8	119,395	Already accounted	119,395

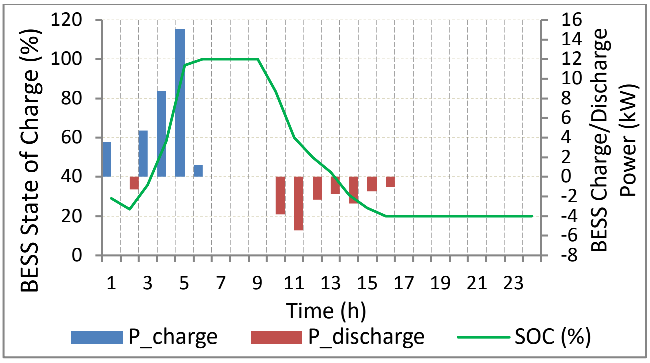

Figure 20. BESS charge/discharge power and SOC (Case 4)

6. Conclusions

The operation costs of diesel generators usually include fuel costs related to active power only without considering those related to reactive power costs. Moreover, the reactive power support from inverter interfaced DERs is not always utilized. This paper investigated the impact of co-optimizing the fuel costs related to active and reactive powers of diesel generators while considering the reactive power support from inverter interfaced DERs to achieve the optimal dispatch for the available resources of the MG. The costs related to load shedding and power curtailment from RESs were also considered. Moreover, the detailed models for different resources were presented, especially for diesel generators where the actual capability curves were used instead of the widely used box constraints. In addition, realistic values of the costs for fuel, load shedding, RESs curtailment compensation and all other parameters of the MG components were used to provide meaningful economic insights.

The EM problem was formulated as a nonlinear optimization problem and was solved in the GAMS environment using the CONOPT solver. The results presented in the paper showed the possible deviations of the optimal dispatch results and erroneous operation costs when neglecting the reactive power fuel costs related to diesel generators. Accordingly, combined active/reactive power dispatch is essential in the EM of isolated MGs to provide correct results. Moreover, utilizing the reactive power capabilities of inverter interfaced DERs can significantly reduce the operating costs of isolated MGs. Hence, it is recommended to allow inverter interfaced DERs inject reactive power in case of isolated operation rather than operating at a unity power factor.

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