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# An Energy Management System based on Economic and Environmental aspects for Microgrids Incorporating Active and Reactive Power Sources and Demand Response Programs

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## ABSTRACT

*In this paper, a comprehensive centralized structure is proposed for Microgrids (MGs) operation incorporating active and reactive power resources. In this approach, the Distributed Generation (DGs), Energy Storage Systems (ESSs), Demand Response (DR) program, load shifting scheme, switchable capacitor banks and Plug-in Hybrid Electric Vehicles (PHEV) are considered simultaneously. The operation modes of PHEVs is modeled to schedule their charging/discharging and calculate the pollution produced in fossil fuel mode. Fifteen types of costs are integrated into the objective function, and several operational constraints are considered. They include power generation costs from the main grid and DG units, cost of pollution emitted by DG units and PHEVs, and the degradation of plug-in hybrid electric vehicles batteries. The proposed method is programmed using GAMS software as a Mixed-Integer Second-Order Cone Programming (MISOCP) problem, and it is implemented on a test MG. simultaneous management of active and reactive power sources can result in less cost compared to the separated scheduling.*

## Article Info

***Keywords:***
Microgrids (MGs), Load Shifting, Energy Management, Plug-in Hybrid Electric Vehicles (PHEV), Energy Storage Systems (ESSs).

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***List of abbreviations***

| | | |
|---|---|---|
| MGs | : | Micrograms |
| PHEV | : | Plug-in Hybrid Electric Vehicles |
| ESSs | : | Energy Storage Systems |
| DGs | : | Distributed Generation |
| DR | : | Demand Response |
| MINLP | : | Mixed Integer Nonlinear Program |
| VPP | : | Virtual Power Plants |
| RESs | : | Renewable Energy Sources |
| NLP | : | Non-Linear Programming |
| MINLP | : | Mixed Integer Nonlinear Program |
| EVs | : | Electric Vehicles |
| DoD | : | Depth of Discharge |

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| | | |
|---|---|---|
| PCC | : | Point of Common Connection |

### *Nomenclature*

| | | |
|---|---|---|
| $TC$ | : | Total cost ($) |
| $C_{APDG}$ | : | Cost of purchased active power from DGs ($) |
| $C_{EMDG}$ | : | Cost of emission produced by DGs($) |
| $C_{RPDG}$ | : | Cost of purchased reactive power from DGs ($) |
| $C_{SUDG}$ | : | The startup cost of DGs ($) |
| $C_{SDDG}$ | : | Shutdown cost of DGs ($) |
| $C_{APG}$ | : | Cost of purchased active power from the main grid ($) |
| $C_{RPG}$ | : | Cost of purchased reactive power from the main grid ($) |
| $C_{EMG}$ | : | Cost of emission produced by the main grid ($) |
| $C_{DR}$ | : | Cost of DR program ($) |
| $C_{BC}$ | : | Cost of reactive power produced by capacitor banks ($) |
| $C_{CBS}$ | : | Cost of capacitor bank switching ($) |
| $C_{GPHEV}$ | : | Cost of fuel consumed by PHEVs ($) |
| $C_{EMPHEV}$ | : | Cost of emission produced by PHEVs ($) |
| $C_{DoD}$ | : | Cost of battery degradation of PHEVs battery ($) |
| $C_{ST}$ | : | Cost of power exchange by ESSs ($) |
| $R(n,m)$ | : | The resistance of line between bus n and m (Ω) |
| $\lvert I(n,m)\rvert^2$ | : | Squared current magnitude of the line between bus n and m (A2) |
| $PDG(i,t)$ | : | Active power of ith DG at time t (kW) |
| $CPDG(i,t)$ | : | Cost of the active power of ith DG at time t ($/kW) |
| $DGCO2(i,t)$ | : | CO2 emitted by ith DG at time t (kg) |
| $CCO2$ | : | Penalty cost of CO2 ($/kg) |
| $DGNOx(i,t)$ | : | NOx emitted by ith DG at time t (kg) |
| $CNOx$ | : | Penalty cost of NOx ($/kg) |
| $QPDG(i,t)$ | : | Reactive power of ith DG at time t (kVar) |
| $CQDG(i,t)$ | : | Cost of reactive power of ith DG at time t ($/kVAr) |
| $S(i,t)$ | : | Binary variable, if ith DG at time t start 1 otherwise 0 |
| $SUC(i)$ | : | The startup cost of ith DG ($) |
| $Z(i,t)$ | : | Binary variable, if ith DG at time t is turn off 1 otherwise 0 |
| $SHDC(i)$ | : | Shutdown cost of ith DG ($) |
| $PG(t)$ | : | Active power purchased from the main grid at time t (kW) |
| $CPG(t)$ | : | Cost of active power purchased from the main grid at time t ($/kW) |
| $QPG(t)$ | : | Reactive power purchased from the main grid at time t (kVAr) |
| $CQG(t)$ | : | Cost of reactive power purchased from the main grid at time t ($/kVAr) |
| $GCO2(t)$ | : | CO2 emitted by the main grid at time t (kg) |
| $GNOx(t)$ | : | NOx emitted by the main grid at time t (kg) |
| $PDR(cs,t)$ | : | Active power reduced by csth customer at time t (kW) |
| $CDR(cs,t)$ | : | Cost of active power reduced by csth customer At time t ($/kW) |
| $NSBC(bc,t)$ | : | Number of steps of bcth capacitor Bank committed at time t |
| $CSBC(bc)$ | : | Cost of each capacitor step of bcth capacitor bank ($/step) |
| $CSWBC(bc)$ | : | Switching cost of bcth capacitor bank ($) |
| $DCS(ev,t)$ | : | The travel distance of evth PHEV in charge-depleting CD mode (mile) |
| $CS(ev)$ | : | Average gasoline usage of evth PHEV (gallon/mile) |
| $CGAS(t)$ | : | Price of gasoline during period t ($/gallon) |
| $EVCO2(ev)$ | : | CO2 emitted by evth PHEV (kg/mile) |
| $EVNOx(ev)$ | : | NOx emitted by evth PHEV (kg/mile) |
| $FDelta(ev,t)$ | : | The expected battery replacement cost of evth PHEV at time t ($) |
| $PSG(st,t)$ | : | Active power generated by stth ESS at time t (kW) |
| $CSG(st,t)$ | : | Cost of active power generated by stth ESS at time t ($/kW) |
| $PSC(st,t)$ | : | Active power stored by stth ESS at time t (kW) |
| $CSC(st,t)$ | : | Cost of active power stored by stth ESS at time t ($/kW) |
| $\eta_{dch}(ev)$ | : | Discharge efficiency of evth PHEV |
| $\eta_{ch}(ev)$ | : | Charge efficiency of evth PHEV |
| $V(n,t)$ | : | Bus voltage of nth bus at time t (pu) |
| $G(n,m)$ | : | The conductance of line between bus n and m (S) |
| $\theta(n,m,t)$ | : | Angle difference of bus n and m at time t (degree) |
| $B(n,m)$ | : | Susceptance of the line between bus n and m (S) |
| $SOC(ev,t)$ | : | State of charge of evth PHEV at time t (kWh) |
| $PDCH(ev,t)$ | : | Active power discharged by evth PHEV at time t (kW) |
| $PCH(ev,t)$ | : | Active power charged by evth PHEV at time t (kW) |
| $EREQ(ev,t)$ | : | Required energy for evth PHEV during time t (kWh) |
| $SOC0(ev)$ | : | Initial SOC of evth PHEV (kWh) |

$IEV(ev,t)$ : 1 if evth PHEV at time t is available for charging at time t, and 0 otherwise

$\overline{PCH}(ev)$ : Maximum capacity of charging power by evth PHEV (kW)

$X(ev,t)$ : 1 if evth PHEV at time t is charged at time t, 0 otherwise

$\overline{PDCH}(ev)$ : Maximum capacity of discharging power by evth PHEV (kW)

$DCD(ev,t)$ : Travel distance of evth PHEV in charge-sustaining (CS) mode (mile)

$\underline{SOC}(ev)$ : Minimum SOC of evth PHEV (kWh)

$\overline{SOC}(ev)$ : Maximum SOC of evth PHEV (kWh)

$DTotal(ev,t)$ : Total travel distance by for evth PHEV during time t (mile)

$E(ev)$ : The energy required to run evth PHEV on electricity for one mile (kWh)

$\alpha(ev)$ : The coefficient of DoD penalty cost function of evth PHEV

$O(i,t)$ : 1 if ith DG is online, otherwise 0

$\underline{PG}(i)$ : The minimum capacity of generating active power by ith DG (kW)

$\overline{PG}(i)$ : Maximum capacity of generating active power by ith DG (kW)

$\underline{QG}(i)$ : The minimum capacity of generating reactive power by ith DG (kVAr)

$\overline{QG}(i)$ : Maximum capacity of generating reactive power by ith DG (kVAr)

$\overline{PSG}(st)$ : Maximum capacity of generating active power by stth ESS (kW)

$\underline{PSG}(st)$ : The minimum capacity of generating active power by stth ESS (kW)

$\overline{PSC}(st)$ : Maximum capacity of storing active power by stth ESS (kW)

$\underline{PSC}(st)$ : The minimum capacity of storing active power by stth ESS (kW)

$VSG(st,t)$ : 1 if stth ESS is generating active power, otherwise 0

$VSC(st,t)$ : 1 if stth ESS is storing active power, otherwise 0

$SOCS(st,t)$ : SOC of stth ESS at time t (kWh)

$\gamma_{dch}(st)$ : Discharge efficiency of stth ESS

$PDCHS(st,t)$ : Active power discharged by stth ESS at time t (kW)

$\gamma_{ch}(st)$ : Charge efficiency of stth ESS

$PCHS(st,t)$ : Active power charged by stth ESS at time t (kW)

$SOCS0(st)$ : Initial SOC of stth ESS (kWh)

$RUS(st)$ : Ramp up the limit of stth ESS in generation mode (kW)

$RUC(st)$ : Ramp up the limit of stth ESS in store mode (kW)

$RDS(st)$ : Ramp down limit of stth ESS in generation mode (kW)

$RDC(st)$ : Ramp down limit of stth ESS in store mode (kW)

$\underline{SOCS}(st)$ : Minimum SOC of stth ESS (kWh)

$\overline{SOCS}(st)$ : Maximum SOC of stth ESS (kWh)

$\underline{V}(n)$ : Minimum voltage amplitude nth bus (pu)

$\overline{V}(n)$ : Maximum voltage amplitude nth bus (pu)

$SP(n,m,t)$ : Apparent power flowing in line between nth and mth bus at time t (VA)

$\overline{SP}(n,m)$ : Maximum apparent power flowing in line between nth and mth bus (VA)

$\overline{NSBC}(bc)$ : Maximum number steps of bcth capacitor bank

$PD0(i,t)$ : Total demand prior to load shifting for bus i in time period t (kW)

$PDF(i,t)$ : Fixed demand for bus i in time period t (kW)

$PDS(i,t)$ : Maximum shiftable demand for bus i in time period t (kW)

$PD(i,t)$ : Optimal demand that is really consumed for bus i in time period t

$PDSH(i,t)$ : Optimal shiftable demand for bus i in time period t

$LS(i,t',t)$ : Amount of demand that goes from time period t’ to time period t for bus i

MT : Maximum number of periods that demand can be shifted (hours)

***Sets***

i : Set of units

t,t’ : Set of time

cs : Set of costumers participated in DR program

bc : Set of capacitor banks

ev : Set of electric vehicles

st : Set of storage units

n,m : Set of bus number

## I. INTRODUCTION

Although electricity is generated by a variety of resources, users need highly qualified energy with the lowermost price and maximum level of reliability. Microgrids (MGs) and Virtual Power Plants (VPP) are both key replacements for feeding power grids. As VPPs comprise Distributed Energy Resources (DER), it is of particular importance to be scheduled [1,2]. Microgrids and VPPs apply some capacities including integration of Demand Response (DR), Renewable Energy Sources (RESs), and Energy Storage Systems (ESSs) on distribution levels. Estimates indicate that the major part of some market partakers' activities is based on the above two resources.

A number of specifications for MGs have been presented previously [3] reviewing widely practical optimization software and models of MGs. Another review [4] describes the design instructions of MGs, and also functioning considerations and necessities for contributors to the supervision of active grids. It addresses the use of IEC/ISO62264 criteria on MGs and VPPs. Besides, is discusses MGs in terms of various standpoints, including progressive control procedures, ESSs, and economic subjects. The fundamental working notions in MGs affecting the control of the active grids are argued elsewhere [5]. It characterizes the necessities for discriminating the islanding mode in MGs, black-start operation, fault management, and the protecting systems, together with an all-inclusive investigation on the power quality.

In general, two types of formulation or modeling, *viz.* probabilistic and deterministic (or robust) modeling exist for optimum scheduling. The probabilistic modeling of optimal scheduling problem is presented in [6,7]. The non-probabilistic modeling for generation scheduling is highlighted in [8,9]. Furthermore, some probabilistic models to obtain optimum scheduling in VPPs are accessible in [10], and the deterministic method has been applied in [11].

A key objective in MGs is to meet feeding the load at a minimal expense. Therefore, an optimization problem can be proposed on the basis of various noncompulsory and obligatory limitations. This yields an optimal power generation through different sources accessible at the MG. The schedule of DER problem in MGs for minimizing overall cost is denoted by [12].

In [13], the microgrid operation considering DG units and ESSs are investigated. The main advantage of this method is the investigation of MG foe two operation mode, including islanded and connected to the main grid. The PHEVs scheduling and their modeling for different operation modes, DR programs, and emission objective are not studied in this paper. In [14], an innovative sliding mode-based power control strategy is presented for microgrids. In the investigated MG, different types of DG are considered. The main focus of this paper is on controlling of the MG in real-time operation, and day-ahead operation of MG is ignored. A new control strategy for MG control for operation in the islanded condition is proposed in [15]. The employed approach is based on particle swarm optimization as a metaheuristic algorithm. The decision-making variables are the MG controller parameters based on minimization of the error in the current and voltage controllers. The frequency control of MG is studied in [16]. This paper suggests the rotating-mass-based virtual inertia in wind turbines to supply the primary frequency control associated an adaptive Neuro-Fuzzy Inference System (ANFIS) controller, as the secondary frequency control.

The mathematical approaches for optimizing MGs can be grouped into linear [17], Non-Linear Programming (NLP) [18], Mixed Integer Linear Programming (MILP) [19], Mixed Integer Nonlinear Program (MINLP) [20], time series and probabilistic [21], heuristic [22], non-linear regression technique [23], quadratic method [24], mesh adaptive direct search [24], Benders decomposition [25], connection matrix [26], branch-and-bound algorithm [18], lagrangian relaxation decomposition methods [27], hybrid optimization [28], Newton-Raphson method [29], and, eventually, constrained linear least-squares programming [30].

It is primarily necessary to determine the related parameters to examine uncertainties in MGs. A variety of parameters exist in the uncertainty problem with regard to generation, load, and pricing, *viz*. PHEVs [31,32], wind power [33,34], solar energy [33,35], load [33,36], market value [33], outage of generation units [37], weather forecast [38], and storage systems [38].

The voltage stability problem in a microgrid was examined by [23], and a smart energy scheduling was developed to regulate the batteries in such a way to discharge the batteries merely once no high load is expected in the succeeding times. As a result, they can operate as a means of boosting system stability and lowering voltage fall, in spite of high expected loads. In [39], considers voltage and frequency control where a model is suggested on the basis of voltage, frequency, and power regulation for inverters that are the interface of resources and the MG. The former research applies a charge/discharge algorithm to manage Electric Vehicles (EVs). According to the model, the influence of EVs on MG is examined on various penetration levels and for different control parameters.

In [40], the cost modeling of DG has been investigated based on DGs' capability curves. In this paper, first, an active power market has been cleared, and then the volt/Var control is studied according to the results of the first stage. A Benders decomposition method is used as a solution approach to solve the studied reactive power dispatch problem. In [41] a new structure is presented to develop an integrated active and reactive market in distribution networks. Different DG units such as synchronous machine–based DG and WTs offer their active and reactive powers to the proposed market. In [42], a new economical-environmental operational approach based on active and reactive power markets is presented. In the proposed framework, first, the active power market is cleared, then the reactive power market will be activated. In this method, different DG units can participate in the reactive power market. In [43], a stochastic structure is investigated to present an active and reactive market in distribution networks. In this paper, the DGs are able to send their offer to operator for active power production. The reactive power capability of DGs is considered in this paper. To model the stochastic variables, the scenario tree is created using the Weibull and the Gaussian probability density functions (PDFs).

In [44], a power source allocation method considering different features of DG units, energy storage systems (ESSs) and loads is proposed. DG units consist of the wind turbine, PV units, combined heat and power generation (CHP) as well as electric vehicles. In [45] classification and a survey of energy management systems are employed. Four categories of EMS are investigated based on the kind of the reserve system being used, including non-renewable, ESS, demand-side management (DSM) and hybrid systems. In [46], a distributed ESS, called Alternating Direction Method of the multiplier (ADMM) is presented to schedule the central controller and local controllers. The optimal power flow equations are considered in this structure. In [47], a two-stage stochastic optimization problem is formulated for the short-term operation planning of microgrids with multiple-energy carrier networks to determine the scheduled energy and reserve capacity. The uncertainties in the renewable units such as wind and solar photovoltaic generation, and electrical and thermal demands are modeled by scenarios with respective probabilities. A new energy management structure considering proactive and reactive approaches to efficiently address the uncertainties associated with generation and demand in islanded and interconnected operation of a MG is presented in [48]. The MG RESs, DGs, and ESSs with the possibility of power exchanges with the grid.

The current investigation introduces a wide-ranging construct for the concurrent scheduling of active and reactive powers in MGs. It includes diverse consumption expenses, namely 1) the cost of procuring active power from DG units, 2) the cost of $CO_2$ gas emitted by DG unit, 3) the cost of $NO_x$ emission by DG units, 4) the cost of purchasing reactive power from DG units, 5) startup and shut down costs of DGs, 6) the cost of purchasing active power from the main grid, 7) the cost of $CO_2$ gas emitted from the main grid, 8) the cost of $NO_x$ emission from the main grid, 9) the cost of capacitor banks switching, 10) the cost of $CO_2$ and $NO_x$ emitted from PHEVs, 11) the degradation of Plug-in Hybrid Electric Vehicles (PHEV) batteries, and 12) the cost of charging/discharging ESSs.

The main contributions provided by this paper include:

- Proposing a new operation scheme for MG considering active and reactive power management simultaneously.
- Presenting an economic-emission model for MG operation considering the emission of different units, main grid, and PHEVs
- Considering the the degradation of PHEV batteries in the energy managament model
- Proposing a new model for managament of PHEVs in different operation modes according to the electricy and gasoline costs

## II. METHODOLOGY

The approach offered in this proposal is on the basis of a centralized energy management structure in which a central unit is responsible for the management of resources and apparatus in the MG. Central control of the active and reactive powers, and also the apparatus is achieved by a central unit in the presented construct. As active power can be influenced by reactive one in this design, both are incorporated in a single control unit. Section 1 reviews several articles in which the control of reactive power and its optimum dispatch are considered as a discrete problem. It is worthy of note that if this control unit is incorporated into the active power one, an enhancement will be achieved in the number of active power procured, its control, and eventually the overall expense of the microgrid.

The control of active power and its ESSs in this configuration are dependent upon power procured from DGs. various types of generation units, for example, wind, solar, micro-turbines, fuel cell, and geothermal energy are integrated into this study, each of which can individually present its cost to the collector of the MG. The above units present expenses for both reactive and active power. The manipulator of the MG schedules the day prior to activities depending on the costs presented by DGs and the price of power purchased by the major grid. The procurement of renewable power from wind and solar generation units is assured on the basis of supporting policies in numerous countries. In the present study, the whole power generated by these units will be procured based on the prices determined beforehand. Hence, it is not necessary to present expenses.

According to what mentioned above, both active and reactive powers undergo simultaneous control in the suggested scheme. Reactive power generated by DGs, reactive power generated by capacitors, reactive power of loads, and status of tap-changer of transformers connecting the MG to the main grid are elements influencing the flow of reactive power in the grid. Therefore, the overall price can be minimized by the MG manipulator (while meeting the grid restrictions) via the suitable and optimal regulation of the aforementioned factors.

It is worth mentioning that MG manipulator is not capable of direct management of consumed reactive power of the loads unless the consumers partake in the Demand Response (DR) program allowing the manipulator to lower their active and reactive loads concurrently. The presented model assumes that the power ratio of the consumer is constant. As a result, a decrease in whichever of the above will diminish the other.

Capacitors included in the present model are capacitor banks that can connect a certain number of capacitors to the circuit instantaneously. Accordingly, the variables allocated to capacitors are integers. Besides, the variable of tap-changer transformer is an integer changing in a certain range, according to the transformer configuration.

The suggested procedure assumes that there are PHEVs in the MG that are able to participate in managing the energy. These vehicles are capable of charging/discharging the batteries and can inject or store active power at definite hours to and from the MG. The presumed vehicles are PHEV type and are able to operate on two fuel types (gasoline and electricity). According to previous data, the distance moved around every day by each vehicle will be measured, or it can be enquired from the holder of the vehicle via a DR program. The vehicle possessor can notify the distance that the manipulator will move through the following day by exchanging the fees. The two parties can make use of such a mechanism. The manipulator can accurately control the day prior to accomplishments, and the owner will earn some income.

By scheduling PHEVs, the manipulator considers the distance, the cost of fuel, and the cost of electricity. The price of fuel is taken into consideration in this pattern, so considering both activity modes and determining the way the vehicle needs to use fuel or electricity for minimizing the expenses. It is worth mentioning that the proposed model takes the expense of pollution into consideration as well.

The functional life of the batteries is considerably diminished by charging/discharging the PHEVs. Consequently, the degeneration of batteries is also included in the cost function, according to the Depth of Discharge (DoD) as determined by the battery-making companies. This will avoid extra charge/discharge of batteries. Integrating the degeneration cost renders the offered model a more realistic feature.

MGs are connected to the main grid through their Point of Common Connection (PCC). Therefore, the MG is able to generate a portion of its power through the main grid. Thus, the main grid is regarded as one of the generation units as well.

## A. Objective Function

The cost function considered in the proposed model includes several parts defined as follows:

$$\begin{aligned} TC = {} & C_{APDG} + C_{EMDG} + C_{RPDG} + C_{SUDG} \\ & + C_{SDDG} + C_{APG} + C_{RPG} + C_{EMG} + C_{DR} \\ & + C_{BC} + C_{CBS} + C_{GPHEV} + C_{EMPHEV} \\ & + C_{DoD} + C_{ST} \end{aligned} \tag{1}$$

Where

$$C_{PDG} = \sum_{t \in T} \sum_{i \in DG} PDG(i,t) \times CPDG(i,t) \tag{2}$$

$$C_{EMDG} = \sum_{t \in T} \sum_{i \in DG} DGCO2\,(i,t) \times CCO2 + DGNOx\,(i,t) \times CNOx \tag{3}$$

$$C_{QDG} = \sum_{t \in T} \sum_{i \in DG} QPDG(i,t) \times CQDG(i,t) \tag{4}$$

$$C_{SUDG} = \sum_{t \in T} \sum_{i \in DG} S(i,t) \times SUC(i) \tag{5}$$

$$C_{SDDG} = \sum_{t \in T} \sum_{i \in DG} Z(i,t) \times SHDC(i) \tag{6}$$

$$C_{PG} = \sum_{t \in T} PG(t) \times CPG(t) \tag{7}$$

$$C_{QG} = \sum_{t \in T} QPG(t) \times CQG(t) \tag{8}$$

$$C_{EMG} = \sum_{t \in T} GCO2(t) \times CCO2 + GNOx(t) \times CNOx \tag{9}$$

$$C_{DR} = \sum_{t \in T} \sum_{cs \in CS} PDR(cs,t) \times CDR(cs,t) \tag{10}$$

$$C_{BC} = \sum_{t \in T} \sum_{bc \in BC} NSBC(bc,t) \times CSBC(bc) \tag{11}$$

$$C_{CBS} = \sum_{t \in T} \sum_{bc \in BC} \left| NSBC(bc,t) - NSBC(bc,t-1) \right| \times CSWBC(bc) \tag{12}$$

$$C_{GPHEV} = \sum_{t \in T} \sum_{ev \in EV} DCS(ev,t) \times CS(ev) \times CGAS(t) \tag{13}$$

$$C_{EMPHEV} = \sum_{t \in T} \sum_{ev \in EV} \begin{bmatrix} DCS(ev,t) \times EVCO2(ev) \times CCO2 + \\ DCS(ev,t) \times EVNOx(ev) \times CNOx \end{bmatrix} \tag{14}$$

$$C_{DoD} = \sum_{t \in T} \sum_{ev \in EV} FDelta(ev,t) - FDelta(ev,t-1) \tag{15}$$

$$C_{ST} = \sum_{t \in T} \sum_{st \in ST} PSG(st,t) \times CSG(st,t) - PSC(st,t) \times CSC(st,t) \tag{16}$$

## B. Constraints

There are various constraints in the proposed model, some of which are equality, and the rest are inequality constraints.

*1) Load flow equations:* The basic power flow equations are the non-linear and non-convex formulation that complicates solving approach. The power flow formulations of distribution networks are usually modeled using the bus injection model. This model deals with nodal variables such as bus voltages and power injections. The related form of branch flow model can be presented as (17)-(22) [49]. This type of modeling leads to a convex formulation. These type of formulation is a Mixed-Integer Second-Order Cone Programming (MISOCP) problem that can be solved by GAMS solver. The conic formulation of distribution power flow is derived. The major merit of the conic formulations is their convexity, which ensures the optimal global solution.

$$\begin{aligned} & PG(t) + PDG(i,t) - PD(cs,t) + PDR(cs,t) + \frac{1}{\eta_{dch}(ev)} PDCEV(ev,t) \\ & - \frac{1}{\eta_{ch}(ev)} PCHEV(ev,t) + PSG(st,t) - PSC(st,t) = \\ & \sum_{(n,m) \in N_l} \left( P(n,m,t) - R(n,m) \times I^2(n,m,t) \right) + g_n V^2(n,t) \text{ if } n = SB \end{aligned} \tag{17}$$

$$\begin{aligned}&PDG(i,t)-PD(cs,t)+PDR(cs,t)+\frac{1}{\eta_{dch}(ev)}PDCEV(ev,t)\\&-\frac{1}{\eta_{ch}(ev)}PCHEV(ev,t)+PSG(st,t)-PSC(st,t)=\\&\sum_{(n,m)\in N_l}\left(P(n,m,t)-R(n,m)\times I^2(n,m,t)\right)+g_nV^2(n,t)\ \text{if}\ \ n\neq SB\end{aligned} \tag{18}$$

$$\begin{aligned}&QG(t)+QDG(i,t)-QD(i,t)+QDR(cs,t)+NSBC(bc,t)\times QSBC(bc)=\\&\sum_{(n,m)\in N_l}\left(Q(n,m,t)-X(n,m)\times I^2(n,m,t)\right)+b_nV^2(n,t)\ \text{if}\ \ n=SB\end{aligned} \tag{19}$$

$$\begin{aligned}&QDG(i,t)-QD(i,t)+QDR(cs,t)+NSBC(bc,t)\times QSBC(bc)=\\&\sum_{(n,m)\in N_l}\left(Q(n,m,t)-X(n,m)\times I^2(n,m,t)\right)+b_nV^2(n,t)\ \text{if}\ \ n\neq SB\end{aligned} \tag{20}$$

$$\begin{aligned}&V^2(m,t)=V^2(n,t)-2\left(R(n,m)\times P(n,m,t)+X(n,m)\times Q(n,m,t)\right)\\&+\left(R^2(n,m)+X^2(n,m)\right)\times l(n,m)\end{aligned} \tag{21}$$

$$l(n,m)\geq\frac{P^2(n,m,t)+Q^2(n,m,t)}{V^2(n,t)} \tag{22}$$

*2) Constraints of PHEVs:*

$$\begin{aligned}&SOC(ev,t)=SOC(ev,t-1)-\frac{1}{\eta_{dch}(ev)}PDCH(ev,t)+\\&\eta_{ch}(ev)\times PCH(ev,t)-EREQ(ev,t)\qquad if\ t\neq 1\end{aligned} \tag{23}$$

$$\begin{aligned}&SOC(ev,t)=SOC0(ev)-\frac{1}{\eta_{dch}(ev)}PDCH(ev,t)+\\&\eta_{ch}(ev)\times PCH(ev,t)-EREQ(ev,t)\qquad if\ t=1\end{aligned} \tag{24}$$

$$PCH(ev,t)\leq\overline{PCH(ev)}\times X(ev,t)\times IEV(ev,t) \tag{25}$$

$$PDCH(ev,t)\leq\overline{PDCH(ev)}\times\left(1-X(ev,t)\right)\times IEV(ev,t) \tag{26}$$

$$DCD(ev,t)\leq\frac{SOC(ev,t)-\underline{SOC(ev)}}{E(ev)} \tag{27}$$

$$DCS(ev,t)=DTotal(ev,t)-DCD(ev,t) \tag{28}$$

$$DCD(ev,t)\leq DTotal(ev,t) \tag{29}$$

$$EREQ(ev,t)=DCD(ev,t)\times E(ev) \tag{30}$$

$$Delta(ev,t)=1-\frac{SOC(ev,t)}{\overline{SOC(ev)}} \tag{31}$$

$$FDelta(ev,t)=\alpha(ev)\times Delta(ev,t) \tag{33}$$

$$\underline{SOC(ev)}\leq SOC(ev,t)\leq\overline{SOC(ev)} \tag{33}$$

*3) Constraints of DGs:*

$$O(i,t)\times\underline{PG(i)}\leq PDG(i,t)\leq O(i,t)\times\overline{PG(i)} \tag{34}$$

$$QDG(i,t)\leq\sqrt{SDG^2(i,t)-PDG^2(i,t)} \tag{35}$$

$$S(i,t)+Z(i,t)=1 \tag{36}$$

$$O(i,t)-O(i,t-1)=S(i,t)-Z(i,t) \tag{37}$$

*4) Constraints of storage units:*

$$PSG\ (st,t)\leq\overline{PSG\ (st)}\times VSG\ (st,t) \tag{38}$$

$$PSG(st,t)\geq\underline{PSG(st)}\times VSG(st,t) \tag{39}$$

$$PSC(st,t)\leq\overline{PSC(st)}\times VSC(st,t) \tag{40}$$

$$PSC(st,t)\geq\underline{PSC(st)}\times VSC(st,t) \tag{41}$$

$$\begin{aligned}&SOCS(st,t)=SOCS(st,t-1)-\frac{1}{\gamma_{dch}(st)}PDCHS(st,t)+\\&\gamma_{ch}(st)\times PCHS(st,t)\qquad if\ t\neq 1\end{aligned} \tag{42}$$

$$\begin{aligned}&SOCS(st,t)=SOCS0(st)-\frac{1}{\gamma_{dch}(st)}PDCHS(st,t)+\\&\gamma_{ch}(st)\times PCHS(st,t)\qquad if\ t=1\end{aligned} \tag{43}$$

$$VSG(i,t)+VSC(i,t)=1 \tag{44}$$

$$PSG(st,t)-PSG(st,t-1)\leq RUS(st) \tag{45}$$

$$PSC(st,t)-PSC(st,t-1)\leq RUC(st) \tag{46}$$

$$PSG(st,t-1)-PSG(st,t)\leq RDS(st) \tag{47}$$

$$PSC(st,t-1)-PSC(st,t)\leq RDC(st) \tag{48}$$

$$\underline{SOCS\ (st)}\leq SOCS\ (st,t)\leq\overline{SOCS\ (st)} \tag{49}$$

*5) Operational constraints:*

$$\underline{V(n)}\leq V(n,t)\leq\overline{V(n)} \tag{50}$$

$$SP(n,m,t)\leq\overline{SP(n,m)} \tag{51}$$

*6) Capacitor bank constraints:*

$$0\leq NSBC(bc,t)\leq\overline{NSBC(bc)} \tag{52}$$

*7) Tap changer constraints*

$$\underline{TCH}\leq TCH(t)\leq\overline{TCH} \tag{53}$$

*8) Load shifting constraints:*

In the proposed method, a portion of the load can be shifted to other hours. The concept illustration of the load shifting has been shown in Fig. 1. This scheme can be expressed as below:

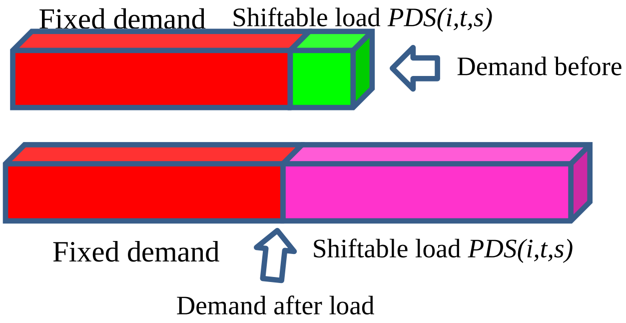


Fig. 1. Parameters and variables related to the load shifting program.

$$PD0(i,t)=PDF(i,t)+PDS(i,t) \tag{54}$$

$$PD(i,t)=PDF(i,t)+PDSH(i,t) \tag{55}$$

$$PD(i,t)=PD0(i,t)+\sum_{t'}LS(i,t',t)-\sum_{t'}LS(i,t,t') \tag{56}$$

$$PDSH(i,t)=PDS(i,t)+\sum_{t'}LS(i,t',t)-\sum_{t'}LS(i,t,t') \tag{57}$$

$$\sum_{t'} LS(i,t,t') \le PDS(i,t) \tag{58}$$

$$LS(i,t,t') = 0 \quad if \quad \begin{cases} t = t' & (a) \\ t + MT < t' \quad or \quad t' + MT < t & (b) \end{cases} \tag{59}$$

Before load shifting, the total load is equal to the fixed load and shiftable load. This can be seen in Equ. (54). The status of the fixed load and shifted load after the load shifting program execution has been shown in Equ. (55) Total demand is written in (56) in terms of the quantity of power which is shifted from other times t' to the current time t; $LS(i,t',t)$, minus the quantity of power that gives up time t to other times t'; $LS(i,t,t')$, for each bus and scenario. Equ. (57) illustrate a similar relation compared to (56) but based on the optimal shiftable load. The maximum load that can be shifted from time t to other periods has been defined by Equ. (58). The constraints (59a) states the load cannot be shifted to the same time while (59b) limited the maximum forward or backward shift time according to the parameter MT.

## III. RESULTS

In this section, simulation results have been presented. The proposed method is implemented on a standard IEEE 33 bus distribution grid as an MG to simulate two different scenarios. The suggested method is modeled using GAMS software, solved by SCIP solver. The required data of loads and lines in the grid are obtained from [50]. The single-line diagram of the intended MG is represented in Fig. 2. The MG is scheduled for a period of 24 hours. For each hour of the day ahead, a load ratio is contemplated according to Fig. 3. Thus, the hourly load at each bus results from multiplying the basic load of each bus by hourly factors. As a whole, 4 types of PHEVs are taken into account, as specified in Table I. The sum of 160 vehicles are incorporated into the MG, and 5 PHEVs are connected to each bus except bus 1. The $\overline{PCH(ev,t)}$, $\overline{PDCH(ev,t)}$, $\eta_{dch}(ev)$ and $\eta_{ch}(ev)$ are considered as 2.4 kW, 2.4 kW, 90% and 90% respectively. The shut down costs of DGs are very small, and they are not comparable with the power system generators.

Seven DG units, as a whole, are included in the MG, as specified in Table II. The specifications of the 4 storage units installed on the MG can be found in Table III. There are 10 capacitor banks in this microgrid, as specified in Table IV. The percentage of reducible demand-response load in different hours of the day is set at 10%. The proposed prices for load reduction and participation in the DR program are presented in Table V. Fig. 4 demonstrates the cost of purchasing active power in different hours of the day from the main grid. Table VI shows the cost of purchasing active power from DG units during different hours of the day. The cost of purchasing reactive power from the upstream grid and the DG units are also equal to 10% of the cost needed to buy the active power. The gasoline prices for the next day are assumed to be $3.049. Some of the other parameters employed in the proposed model can be seen in Table VII.

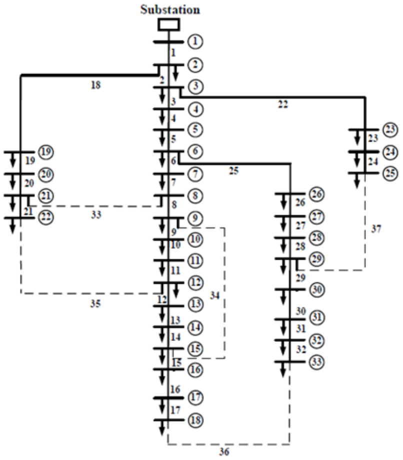


**Fig. 2**. Single diagram of the IEEE 33-bus network.

**TABLE I**
PHEV TYPE SPECIFICATION

| PHEV class | $\overline{SOC(ev)}$ | $E(ev)$ | $CS(ev)$ | $\underline{SOC(ev)}$ |
|---|---|---|---|---|
| Compact | 8.6 | 0.26 | 30.2 | 0.86 |
| Mid-size | 9.9 | 0.3 | 26.4 | 0.99 |
| Large (1) | 12.5 | 0.38 | 20.6 | 1.25 |
| Large (2) | 14.1 | 0.46 | 18 | 1.41 |

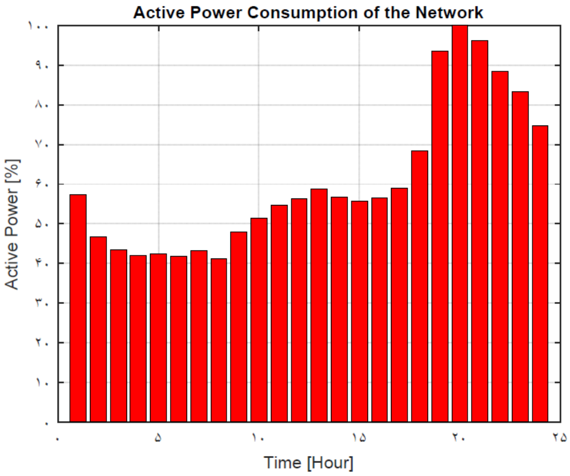


**Fig. 3**. Load profile of the test network for 24 hours of next day.

### TABLE II

DATA OF DG UNITS

| unit | type | bus | $\overline{QDG}(MW)$ | $\underline{QDG}(MVAr)$ | $\overline{PDG}(MW)$ |
|---|---|---|---|---|---|
| i1 | Microturbine | 18 | 0.050 | -0.050 | 0.50 |
| i2 | Microturbine | 29 | 0.025 | -0.025 | 0.25 |
| i3 | Microturbine | 30 | 0.050 | -0.050 | 0.50 |
| i4 | Biomass | 22 | 0.028 | -0.028 | 0.28 |
| i5 | Fuel cell | 33 | 0.050 | -0.050 | 0.50 |
| i6 | Small hydro | 15 | 0.015 | -0.015 | 0.15 |
| i7 | Geothermal | 25 | 0.015 | -0.015 | 0.15 |

### TABLE III

DATA OF ENERGY STORAGE UNITS

| unit | bus | $\overline{PSG(st)}$ | $\underline{PSG}(st)$ | $\overline{PSC(st)}$ | $\underline{PSC}(st)$ | $RUS(st)$ |
|---|---|---|---|---|---|---|
| st1 | 10 | 20 | 2 | 10 | 1 | 10 |
| st2 | 18 | 25 | 2 | 13 | 1 | 12 |
| st3 | 30 | 27 | 2 | 16 | 1 | 13 |
| st4 | 33 | 30 | 2 | 18 | 1 | 15 |
| unit | bus | $RUC(st)$ | $RDS(st)$ | $RDC(st)$ | $CSG(st)$ | $CSC(st)$ |
| st1 | 10 | 5 | 10 | 5 | 70 | 60 |
| st2 | 18 | 6 | 12 | 6 | 80 | 50 |
| st3 | 30 | 8 | 13 | 8 | 150 | 130 |
| st4 | 33 | 9 | 15 | 9 | 250 | 200 |

### TABLE IV

DATA OF CAPACITOR BANKS

| Capacitor | bus | $\overline{NSBC(bc)}$ | $QSBC(bc)[MVAr]$ | $CSBC(bc)$ |
|---|---|---|---|---|
| 1 | 1 | 50 | 0.001 | 10 |
| 2 | 2 | 60 | 0.001 | 15 |
| 3 | 3 | 80 | 0.001 | 20 |
| 4 | 4 | 50 | 0.001 | 25 |
| 5 | 22 | 50 | 0.001 | 10 |
| 6 | 25 | 50 | 0.001 | 12 |
| 7 | 28 | 80 | 0.001 | 10 |
| 8 | 31 | 80 | 0.001 | 15 |
| 9 | 33 | 80 | 0.001 | 20 |
| 10 | 29 | 80 | 0.001 | 25 |

Simulations comprised two different scenarios:

- S1: Separate scheduling of active and reactive powers
- S2: Simultaneous scheduling of active and reactive powers (the proposed model)

S1 assumes a separate schedule of active and reactive powers. For this purpose, the active power is initially scheduled, and the attained values (active power obtained from generation units, storage units, PHEVs, and power exchanged with upstream grid) are employed as input for reactive power scheduling. In S2 (the presented model), on the other hand, the active and reactive powers have synchronized scheduling in a single model. Resultant expenses in S1 and S2 are equal to \$ 7123 and \$ 6114, respectively, suggesting that the overall cost may be reduced when both active and reactive powers are scheduled concurrently. Such an outcome results from integrating the interaction of active and reactive powers, and also the grid parameters into S2 (the recommended scheme). The condition of capacitor banks in S1 is represented in Table VIII. Whereas no capacitor bank has been chosen in S2, capacitors 1, 2, 6, 7, 8 are connected, and capacitors 3, 4, 5, 9, and 10 are disconnected in S1. Capacitor 10 is down because it requires a higher cost for its generated reactive power. Besides, it is situated on a branch with three capacitors of low cost, rendering it cost-effective to be offline because of its cost. Capacitor 4 has a similar cost to capacitor 10. Hence, it is not scheduled to be online.

The SOC condition of energy storage units in S1 and S2, respectively, Fig. 5 reveals that the demand and power cost is lesser at the onset of daily times, during which the storage units are thus charged in S2.

According to the voltage profiles in both scenarios depicted in Figures 6, the voltages are always in the range of allowable limits in all buses, with a better status of the voltage being closer to 1 per unit in S2. To compare more quantitatively, the total voltage deviations from 1 per unit was estimated in buses at a range of daily times, and the observations are shown in Fig. 7. It is evident that S2 outstrips S1 throughout the whole daily times. Maximum variations were recorded from 14 to 18 rising at 14:00 when total voltage deviations in buses equal to 0.3059 and 0.1521 in S1 and S2, respectively.

The effect of different equipment and programs employed in this paper are investigated, and its results are shown in Table IX. For this aim, the influence of demand response program, load shifting program, and energy storage units are survived. In each case, the proposed energy management scheme is simulated without one of them. The obtained results show that demand response and load shifting programs reduce the total cost of about 9% and 14%, respectively. It can be seen that the effect of load shifting program is higher than the DR program and ESSs.

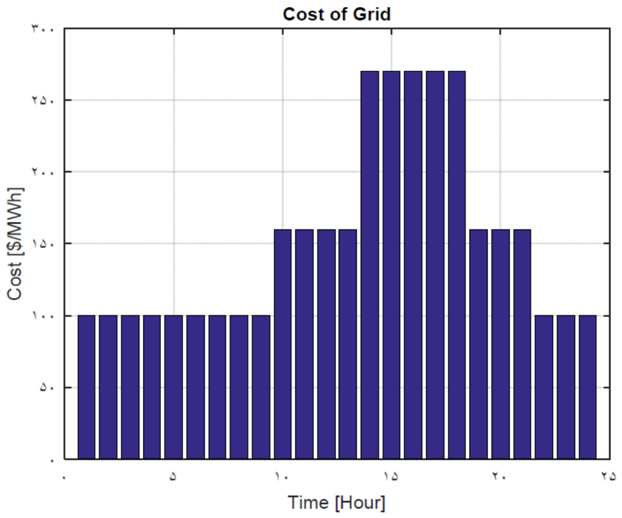


**Fig. 4**. cost of the upstream network for generation of active power Consistency.

### TABLE V

CUSTOMERS LOAD REDUCTION OFFER

| BUS | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | T9 | T10 | T11 | T12 | TYPE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N2 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | COMMERCIAL |
| N3 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N4 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | INDUSTRIAL |
| N5 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | COMMERCIAL |
| N6 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | RESIDENTIAL |
| N7 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | RESIDENTIAL |
| N8 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N9 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | COMMERCIAL |
| N10 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | RESIDENTIAL |
| N11 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N12 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | COMMERCIAL |
| N13 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | COMMERCIAL |
| N14 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N15 | 510 | 510 | 510 | 510 | 510 | 510 | 510 | 510 | 510 | 510 | 510 | 510 | INDUSTRIAL |
| N16 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | RESIDENTIAL |
| N17 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | COMMERCIAL |
| N18 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N19 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N20 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | COMMERCIAL |
| N21 | 530 | 530 | 530 | 530 | 530 | 530 | 530 | 530 | 530 | 530 | 530 | 530 | INDUSTRIAL |
| N22 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | RESIDENTIAL |
| N23 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N24 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | 320 | COMMERCIAL |
| N25 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 | INDUSTRIAL |
| N26 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N27 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | RESIDENTIAL |
| N28 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | RESIDENTIAL |
| N29 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 | COMMERCIAL |
| N30 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | INDUSTRIAL |
| N31 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | RESIDENTIAL |
| N32 | 105 | 105 | 105 | 105 | 105 | 105 | 105 | 105 | 105 | 105 | 105 | 105 | RESIDENTIAL |
| N33 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | COMMERCIAL |
| BUS | T13 | T14 | T15 | T16 | T17 | T18 | T19 | T20 | T21 | T22 | T23 | T24 | TYPE |
| N2 | 300 | 300 | 300 | 300 | 303 | 306 | 321 | 337 | 300 | 300 | 300 | 300 | COMMERCIAL |
| N3 | 110 | 110 | 110 | 110 | 111 | 112 | 118 | 124 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N4 | 520 | 520 | 520 | 520 | 525 | 530 | 557 | 585 | 520 | 520 | 520 | 520 | INDUSTRIAL |
| N5 | 320 | 320 | 320 | 320 | 323 | 326 | 343 | 360 | 320 | 320 | 320 | 320 | COMMERCIAL |
| N6 | 100 | 100 | 100 | 100 | 101 | 102 | 107 | 112 | 100 | 100 | 100 | 100 | RESIDENTIAL |
| N7 | 120 | 120 | 120 | 120 | 121 | 122 | 129 | 135 | 120 | 120 | 120 | 120 | RESIDENTIAL |
| N8 | 110 | 110 | 110 | 110 | 111 | 112 | 118 | 124 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N9 | 310 | 310 | 310 | 310 | 313 | 316 | 332 | 349 | 310 | 310 | 310 | 310 | COMMERCIAL |
| N10 | 120 | 120 | 120 | 120 | 121 | 122 | 129 | 135 | 120 | 120 | 120 | 120 | RESIDENTIAL |
| N11 | 110 | 110 | 110 | 110 | 111 | 112 | 118 | 124 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N12 | 330 | 330 | 330 | 330 | 333 | 337 | 353 | 371 | 330 | 330 | 330 | 330 | COMMERCIAL |
| N13 | 320 | 320 | 320 | 320 | 323 | 326 | 343 | 360 | 320 | 320 | 320 | 320 | COMMERCIAL |
| N14 | 110 | 110 | 110 | 110 | 111 | 112 | 118 | 124 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N15 | 510 | 510 | 510 | 510 | 515 | 520 | 546 | 574 | 510 | 510 | 510 | 510 | INDUSTRIAL |
| N16 | 130 | 130 | 130 | 130 | 131 | 133 | 139 | 146 | 130 | 130 | 130 | 130 | RESIDENTIAL |
| N17 | 330 | 330 | 330 | 330 | 333 | 337 | 353 | 371 | 330 | 330 | 330 | 330 | COMMERCIAL |
| N18 | 110 | 110 | 110 | 110 | 111 | 112 | 118 | 124 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N19 | 110 | 110 | 110 | 110 | 111 | 112 | 118 | 124 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N20 | 320 | 320 | 320 | 320 | 323 | 326 | 343 | 360 | 320 | 320 | 320 | 320 | COMMERCIAL |
| N21 | 530 | 530 | 530 | 530 | 535 | 541 | 568 | 596 | 530 | 530 | 530 | 530 | INDUSTRIAL |
| N22 | 120 | 120 | 120 | 120 | 121 | 122 | 129 | 135 | 120 | 120 | 120 | 120 | RESIDENTIAL |
| N23 | 110 | 110 | 110 | 110 | 111 | 112 | 118 | 124 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N24 | 320 | 320 | 320 | 320 | 323 | 326 | 343 | 360 | 320 | 320 | 320 | 320 | COMMERCIAL |
| N25 | 520 | 520 | 520 | 520 | 525 | 530 | 557 | 585 | 520 | 520 | 520 | 520 | INDUSTRIAL |
| N26 | 110 | 110 | 110 | 110 | 111 | 112 | 118 | 124 | 110 | 110 | 110 | 110 | RESIDENTIAL |
| N27 | 120 | 120 | 120 | 120 | 121 | 122 | 129 | 135 | 120 | 120 | 120 | 120 | RESIDENTIAL |
| N28 | 130 | 130 | 130 | 130 | 131 | 133 | 139 | 146 | 130 | 130 | 130 | 130 | RESIDENTIAL |
| N29 | 310 | 310 | 310 | 310 | 313 | 316 | 332 | 349 | 310 | 310 | 310 | 310 | COMMERCIAL |
| N30 | 500 | 500 | 500 | 500 | 505 | 510 | 536 | 562 | 500 | 500 | 500 | 500 | INDUSTRIAL |
| N31 | 140 | 140 | 140 | 140 | 141 | 143 | 150 | 157 | 140 | 140 | 140 | 140 | RESIDENTIAL |
| N32 | 105 | 105 | 105 | 105 | 106 | 107 | 112 | 118 | 105 | 105 | 105 | 105 | RESIDENTIAL |
| N33 | 330 | 330 | 330 | 330 | 333 | 337 | 353 | 371 | 330 | 330 | 330 | 330 | COMMERCIAL |

TABLE VI

COST OF DGS FOR GENERATION OF ACTIVE POWER

| Unit/hour | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| i1 | 240 | 240 | 240 | 240 | 240 | 250 | 250 | 250 | 250 | 250 | 260 | 260 |
| i2 | 260 | 260 | 260 | 260 | 260 | 260 | 260 | 260 | 260 | 260 | 260 | 260 |
| i3 | 70 | 70 | 70 | 70 | 70 | 75 | 75 | 75 | 75 | 75 | 75 | 75 |
| i4 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| i5 | 260 | 260 | 260 | 260 | 260 | 260 | 260 | 260 | 260 | 260 | 270 | 270 |
| i6 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 | 86 |
| i7 | 83 | 83 | 83 | 83 | 83 | 83 | 83 | 83 | 83 | 83 | 83 | 83 |
| Unit/hour | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| i1 | 260 | 260 | 270 | 270 | 300 | 300 | 300 | 300 | 300 | 300 | 260 | 240 |
| i2 | 260 | 260 | 270 | 270 | 270 | 270 | 270 | 270 | 270 | 270 | 260 | 260 |
| i3 | 75 | 75 | 75 | 75 | 75 | 90 | 90 | 90 | 90 | 90 | 90 | 90 |
| i4 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| i5 | 270 | 290 | 290 | 290 | 290 | 300 | 300 | 300 | 300 | 300 | 300 | 300 |
| i6 | 86 | 86 | 90 | 90 | 90 | 90 | 95 | 95 | 95 | 95 | 85 | 85 |
| i7 | 83 | 83 | 83 | 83 | 83 | 83 | 95 | 95 | 95 | 95 | 83 | 83 |

TABLE VII

DIFFERENT PARAMETERS CONSIDERED IN SIMULATIONS

| value | parameter | value | parameter |
|---|---|---|---|
| 0.95 | $\underline{V}(n)$ | 40 | $CSWBC(bc)(\$/action)$ |
| 1.05 | $\overline{V}(n)$ | 80 | $Closs(\$/MWh)$ |
| 4e-5 | $CCO2[\$/g]$ | 8e-5 | $CNOx[\$/g]$ |

TABLE VIII

STATUS OF CAPACITOR BANKS IN SCENARIO 1

| S1 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cap | t1 | t2 | t3 | t4 | t5 | t6 | t7 | t8 | t9 | t10 | t11 |
| bk1 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| bk2 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| bk6 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| bk7 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| bk8 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| Cap | t13 | t14 | t15 | t16 | t17 | t18 | t19 | t20 | t21 | t22 | t23 |
| bk1 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| bk2 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| bk6 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| bk7 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| bk8 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |

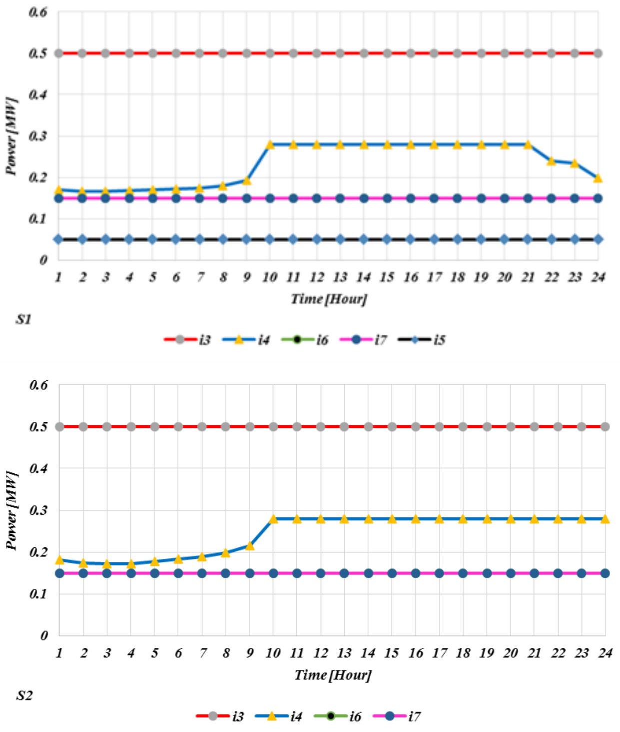


**Fig. 5**. Active power produced by DGs for two scenarios.

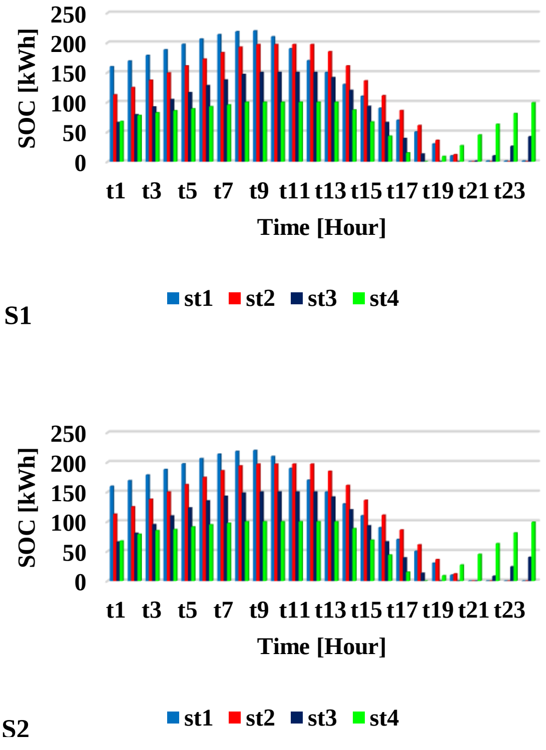


**Fig. 6**. SOC status of energy storage systems for two scenarios

TABLE IX
TOTAL COST OF MG OPERATION IN DIFFERENT CASES ($)

| Scenario/case | Complete scheme | Without DR program | Without load shifting program | Without energy storage systems |
|---|---|---|---|---|
| S1 | 7123 | 6582 | 6222 | 6510 |
| S2 | 6114 | 5595 | 5222 | 5470 |

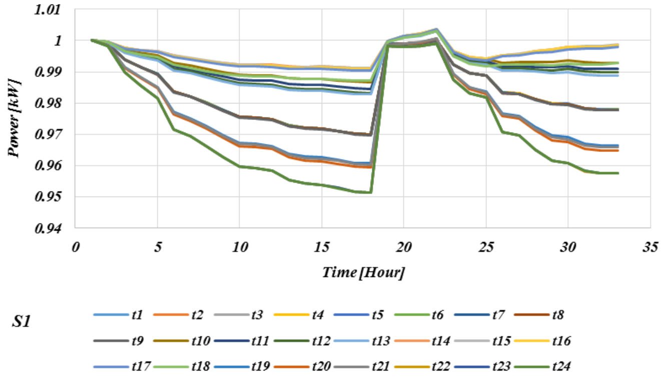
## IV. DISCUSSION

The power produced by various units is shown in Figure 4, indicating that units 3, 4, 6, and 7 are all online in the two modes due to their relatively lower cost. Unit 5 is involved in S1 as well, while it is absent in S2. The reason is that S2 has an integrated schedule resulting in the choice of variables in such a way to increase the demand for the above units. The graphs denote that units 3, 6, and 7 with less price are online throughout the 24 h using their uppermost capability to provide the grid with energy, which is true in the two setups. Unit 4 ranked a less priced unit following units 3, 6, and 7 yielded low power generation throughout the onset and termination times; in mid-hours, however, its generation rose with a rise in power requirement. Power generation in the S1 unit is greater than that of S2 with demands low involvement of high-cost units. It is noteworthy that Unit 5 is online in S1 in spite of expensiveness, whereas it is not in use by no means in S2.

From 12 p.m. ahead, on the contrary, the storage units are gradually discharged and provide a portion of the needed power to increase the demand for buying costly power from the units or the main grid. A similar scenario occurs in S1, but it has a lesser magnitude. Storage unit S1 undergoes discharge solely in the little final daily times. The rest of three storage units exhibit a behavior the same as S2 yet, the discharge rate is greater, and they inject lower power during the final daily times. There are storage units with more desired discharge in S2, with the successful injection of a greater amount of power into the grid from 19 to 21 hrs.

## V. CONCLUSIONS

This paper addressed a novel scheduling framework for the operation of MG, considering different smart devices and programs. The active and reactive power management is conducted simultaneously in the proposed framework. PHEVs, DG units, energy storage units, capacitor banks, and tap changer of the MG transformer are controllable equipment that is employed in the presented approach. Demand response program and load shifting scheme are other tools for MG operator for optimal operation. The suggested strategy is applied to a test MG for different cases. The obtained results show that the integration of active and reactive power can reduce the total cost of system operation. In this paper, the coupled scheme declined the total cost by 15%. Also, the results indicated that DR and load shifting programs could help to minimize the operational cost by 9% and 14% respectively. Also, it can be seen that the operation cost is 11% less when ESSs have participated in the MG operation. Considering the uncertainty of different parameters, the reliability constraints, and MG reconfiguration are some subjects that can be studied in future work.



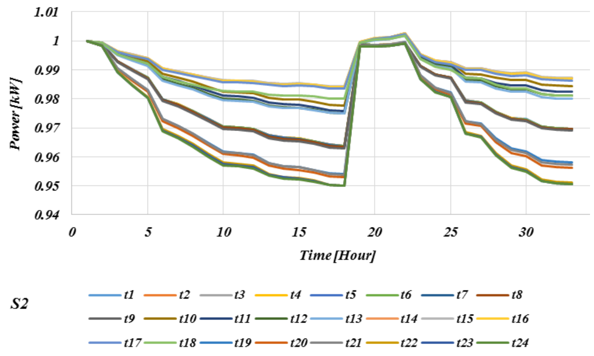


**Fig. 7.** The voltage profiles of the distribution network for two scenarios.

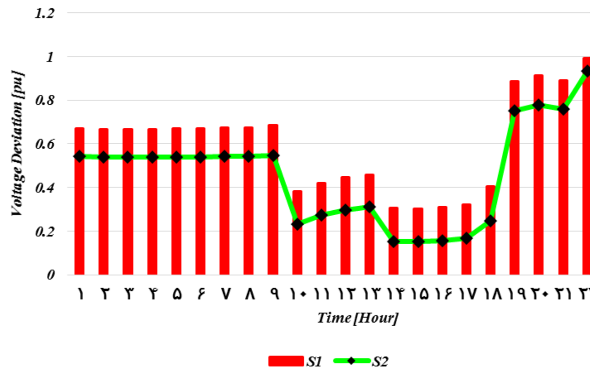


**Fig. 8.** The voltage deviation of the distribution network for two scenarios.

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