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Modelling the Benefits of Smart Energy Scheduling in Micro-grids

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Abstract-- This paper presents a smart energy management strategy (SMES) to optimise the economic operation in the micro-grid. As a special and important component of smart grids, the micro-grid acts as a bridge to bundle renewable generators, energy storage systems (ESSs) and electric vehicles (EVs) together. It can be operated either by connecting to upstream distribution systems or isolated with the help of ESSs. Economic model of the micro-grid is established considering the influence of energy prices in the day-ahead market. SMES is utilised to schedule the power supply/demand of diversified sources to obtain the optimal economic operation. Smart management of ESSs, EVs and power exchange with the upstream grid if possible are simplified into a single-objective optimisation in the SEMS. Serial quadratic programming (SQP) is employed to achieve a practical method for energy management based on three different operation policies and produces diagrams of the obtained results.

Index Terms--Micro-grid, economic model, day-ahead energy market, smart energy management strategy (SEMS), serial quadratic programming (SQP).

I. INTRODUCTION

With the evolutionary development of power electronic technology, micro-grid is going from the theory research to the example projects. It will be the vital fundamental part in the future macro-system. Micro-grid combines local renewable generators, small or medium traditional power generators, energy storage systems (ESSs), loads and electric vehicles (EVs) together with the control units in the low voltage level [1-3]. From the grid's point of view, a micro-grid can be regarded as a controllable entity within the power system, which mostly operates grid-interconnected but also can turn into the islanded mode during the necessary scenarios [4-5].

Research has been carried out to study how an aggregator schedules the charging or discharging power of energy storage systems to allow the micro-grid operating in a more flexible, economic manner [6-10]. In [6], the costs of micro-grids with regulable loads and battery storage were reduced by selling stored energy at high prices to shave peak loads of the larger system. In [7], the micro-grid operation cost was minimized and battery charge states were optimized by linear programming algorithms. Another linear programming-based unit commitment was developed in [8] with an object to minimisation of the equivalent annual cost for meeting a given energy (electricity and heat) demand profile. In [9], both

power rating and energy rating of ESS was optimal sized based on a comprehensive ESS model under the reliability constraints. A diverse energy generation mix was considered. In [10], a novel method was proposed to transform an existing distribution system into a sustainable autonomous micro-grid. With this methodology, the optimal sizing and siting strategies for distributed generators and structural modifications for micro-grids were suggested to reduce the real power distribution losses of the system.

The widely utilisation of electric vehicles is considered as the best solution to overcome the energy crisis and environmental pollution. The charging demand of numerical EVs leads to the challenge for the operation of micro-grids. Optimal operation of an aggregator for controlled EV charging has been studied in [11-13]. In [11], an aggregator that made efficient use of the distributed power of EVs was proposed to produce the desired grid-scale power. Both the cost arising from the battery charging and revenue obtained by providing the regulation service were considered. In [12], algorithms were presented to find optimal charging rates with the objective of maximising the aggregator's profit. In [13], a problem of scheduling EV charging with ESS from an electricity market perspective with joint consideration for the aggregator energy trading in the day-ahead and real-time market was studied. Vehicle-to-Grid (V2G) provides the opportunity to let the vehicle owners participate in the grid regulation. The benefit model of V2G technology in the power system was built in [14]. A decision-making strategy was established for the deployment of the battery energy stored, taking account of the state of charge, time of day, electricity prices and vehicle charging requirements. In [15], a new approach to analyze the economic impact of V2G regulation was presented.

In this paper, the economic model of the micro-grid combined with ESSs and EVs is proposed. The prices in energy day-ahead market, power ratings and energy ratings of ESSs and charging/discharging behaviours of EVs are considered. This model is utilized into the micro-grid to schedule the power supply/demand of variable sources for the optimal economic-operation under three possible operation policies [16]. Followed the optimal schedules, the revenue gained by the micro-grid operator reaches the maximum point respectively.

The organization of this paper is as follows: in Section III, economic model of the micro-grid is detailed proposed. The assumptions and constraints are described. Afterwards in

Section IV, the objective is set to be the maximum achieved revenue in the micro-grid. The optimal problem will be solved by Serial Quadratic Programming (SQP). According to three possible operation policies, the results calculated from the example system are compared in Section V. In the last section, the conclusion can be obtained that: the model proposed in this paper is effective to describe the economic-operation of the micro-grid. The operator can choose to operate grid-interconnected or isolated day-ahead based on the calculated revenues.

II. ECONOMIC MODEL OF MICRO-GRID

Micro-grid is composed by micro-generators, consumers and storage devices which act as an independent party in the micro-grid and bid in the storage energy market [17].

For simplify analysis, the assumptions are made:

- (1) Electrical power is the only product concerned in the economic model. Heat or other by-products by the micro-generators are neglected.
- (2) Every single micro-grid operator is considered in the economic model. The benefits related to the coordination of several micro-grid operators are ignored.
- (3) The objective is to optimise the economic operation of the micro-grid.
- (4) In order to stimulate the integration of renewable generators, their power supplies are not participated in the economic optimization as well as load demands. The bids for renewable generators are constant in the whole day. In this paper, photovoltaic and wind generators are considered.
- (5) EVs in the micro-grid are scheduled to charge or discharge in the specified hour, thus a corresponding constant price for EV charging or discharging is followed in the whole day.
- (6) Hourly bid and output power for micro-turbines are contracted day-ahead. The step up/down cost for the micro-turbine is constant in the whole day.
- (7) The hourly price for the power exchange in the line connecting the distributed and micro grid is obtained from day-ahead electricity market.
- (8) As the independent party in the micro-grid operation, the prices for power rating and energy rating of ESS are the same and constant in the whole day.
- (9) The mark-up price for the micro-grid operator is constant in the whole day.
- (10) To facilitate numerical analysis, the continuous supply/demand power is segmented into discrete predefined time steps over a period of 24 hours.

The structure of the micro-grid is shown in Figure 1.

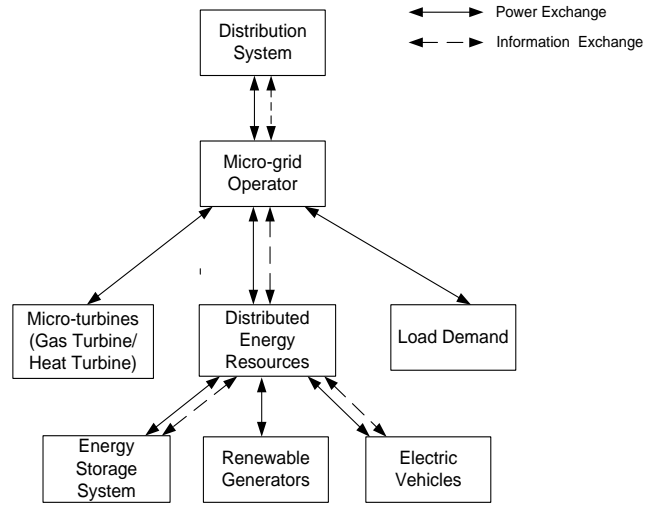


Fig. 1. Micro-grid structure

A. Operation Policies

The revenues of the micro-grid will be maximized in the following operation policies [16] respectively.

- (1) The micro-grid is separated from the upstream distribution grid and the SEMS aims to serve the total demand of the micro-grid, using its local production, storage system and EV discharging.
- (2) The SEMS aims at serving the total demand of the micro-grid using its local production as much as possible, without exporting power to the upstream distribution grid.
- (3) The micro-grid participates in the open market, buying and selling active and reactive power to the grid, similar as an energy service provider or consumer.

B. Economic Model of Micro-Grid

The revenue of the micro-grid can be simply expressed as

$$R_{MG} = \sum_{t=1}^{24} (IC_{MG}(t) - C_{MG}(t)) \quad (1)$$

Micro-grid operator earns the revenue as the electricity carrier from generators to loads. The operator buys electricity with minimal cost from locally distributed generators, micro-turbines, storage systems, EV discharging and a grid under stipulations of the above 2nd and 3rd policies. Thereafter supply subtracting network losses will be sold with maximal income to loads, EV charging demands, and grid under the above 3rd policy.

- (1) The income of the micro-grid operator at time t

The income gained by the micro-grid operator is

$$IC_{MG}(t) = (C_{Grid}(t) + C_M) P_{Load}(t) + C_{EVC} |P_{EV}(t)| u_{EVC}(t) + C_{Grid}(t) |P_{Grid}(t)| u_{Grid-ex}(t) \quad (2)$$

where

$$u_{EVC}(t) = \begin{cases} 1 & \text{when } P_{EV}(t) > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$u_{Grid-ex}(t) = \begin{cases} 1 & \text{when } P_{Grid}(t) < 0 \\ 0 & \text{otherwise} \end{cases}$$

(2) The cost of the micro-grid operator at time t

$$C_{MG}(t) = C_{Grid}(t) |P_{Grid}(t)| u_{Grid-in}(t) + C_{MT}(t) P_{MT}(t) + C_{MTR} |P_{MT}(t) - P_{MT}(t-1)| \\ + C_{PV} P_{PV}(t) + C_{WT} P_{WT}(t) + C_{ESP} |P_{ES}(t)| + C_{ESE} (W_{ES}(t) - W_{ES}(t-1)) u_{ESE}(t) \\ + C_{EVD} |P_{EV}(t)| u_{EVD}(t) + C_{Grid}(t) P_{Loss}(t) \quad (3)$$

where

$$u_{Grid-in}(t) = \begin{cases} 1 & \text{when } P_{Grid}(t) > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$u_{ESE}(t) = \begin{cases} 1 & \text{when } (W_{ES}(t) - W_{ES}(t-1)) > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$u_{EVD}(t) = \begin{cases} 1 & \text{when } P_{EV}(t) < 0 \\ 0 & \text{otherwise} \end{cases}$$

The model to describe the charging/discharging behaviours of multiple EVs at instant time t $P_{EV}(t)$ is given in [18], by considering of the EV random initial state of charge (SOC).

The network loss at time t is calculated:

$$P_{Loss}(t) = \frac{1}{2} \sum_{j=1}^n \left(\sum_{i=1}^n \left(G_{i,j} \cdot (|V_{i,t}|^2 + |V_{j,t}|^2 - 2 \cdot |V_{i,t}| \cdot |V_{j,t}| \cdot \cos(\delta_{j,t} - \delta_{i,t})) \right) \right) \quad (4)$$

(3) Standard Power Flow Constraints

The power flow in the micro-grid need to under these constraints [19]:

$$P_{i,t} = \sum_{j=1}^n (|Y_{i,j}| \cdot |V_{i,t}| \cdot |V_{j,t}| \cdot \cos(\theta_{i,j} + \delta_{j,t} - \delta_{i,t}))$$

$$Q_{i,t} = -\sum_{j=1}^n (|Y_{i,j}| \cdot |V_{i,t}| \cdot |V_{j,t}| \cdot \sin(\theta_{i,j} + \delta_{j,t} - \delta_{i,t}))$$

$$0.9 \leq |V_{i,t}| \leq 1.1 \text{ p.u.}$$

$$I_{i,j,t} \leq I_{i,j,\max}$$

$$\sqrt{P_{Di,t}^2 + Q_{Di,t}^2} \leq S_{i,\max}$$

$$P_{PV}(t) + P_{WT}(t) + P_{ES}(t) + P_{MT}(t) = P_{Load}(t) + P_{EV}(t) + P_{Loss}(t)$$

in 1st policy

$$P_{PV}(t) + P_{WT}(t) + P_{ES}(t) + P_{MT}(t) + P_{Grid}(t) = P_{Load}(t) + P_{EV}(t) + P_{Loss}(t)$$

in 2nd & 3rd policies

$$P_{MT}^{\min} \leq P_{MT}(t) \leq P_{MT}^{\max} \quad (5)$$

C. Micro-Grid Operation Optimization

The optimal function is established mainly to maximise the revenue of the micro-grid operator under the power flow constraints in three operation policies above.

$$\max R_{MG} \text{ s.t. Equation(5)} \quad (6)$$

Under the previous assumptions, it takes $P_{ES}(t), P_{Grid}(t), f(t), g(t) \quad t = 1, \dots, 24$ (decision variables) as inputs. The optimal function can be solved by sequential quadratic programming (SQP). The corresponding optimal values are output to find the local maximum of R_{MG} satisfying the constraints.

III. SYSTEM INFORMATION

To investigate the operation revenue of a micro-grid, an example system is given as shown in Figure 2. The information about buses and feeder impedances in the example system is shown in Appendix. The load and renewable generation curves can be obtained one-day-ahead estimation as shown in Figure 3&4.

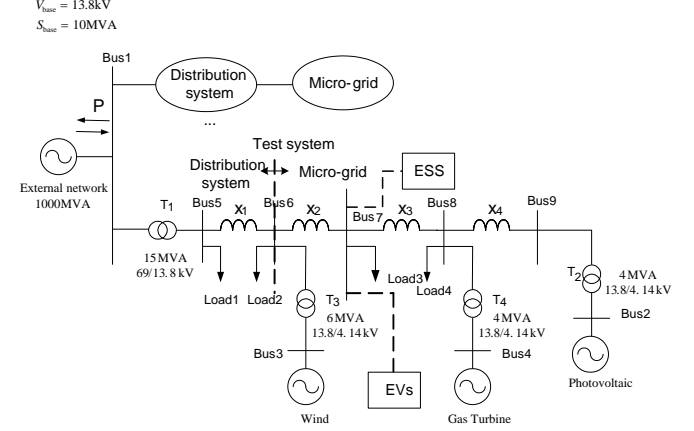


Fig. 2. Micro-grid example system

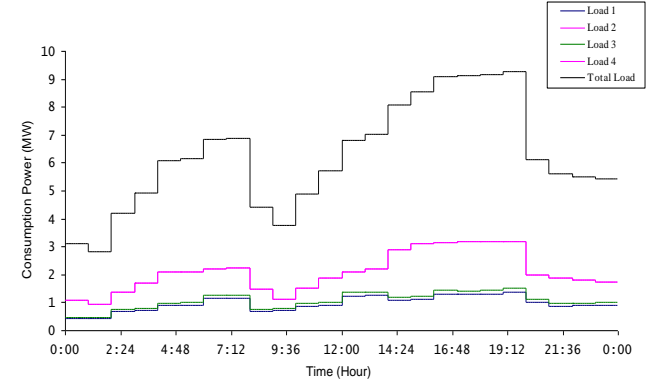


Fig. 3. Daily load curves of the micro-grid example system

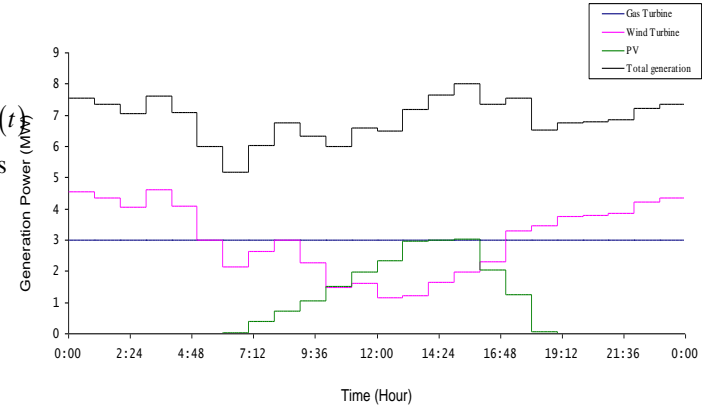


Fig. 4. Daily renewable generation curves of micro-grid example system

Assumptions in the example Micro-grid are made that:

- (1) There are 200 EVs in the micro-grid. While aggregation units (AU) of electric vehicle charging points could efficiently manage electric vehicle charging processes jointly with discharging processes to the grid, the AU in this paper is connected at Bus 7.
- (2) The different connection buses of ESS will more or less affect the actually required ESS capacity. These effects are not concerned in this paper. ESS is also connected at Bus 7.

- (3) 30% EVs are volunteered to participate in discharging procedure.
- (4) Followed policy can not be altered in the day.

The prices for the various sources in the micro-grid are listed in Appendix.

IV. CASE STUDY

According to Equation (6), the hourly $P_{ES}(t), P_{Grid}(t), f(t), g(t) t = 1, \dots, 24$ are scheduled. The maximum revenues obtained by the AU under 3 different policies are listed in Table I.

Table I: Comparisons of revenues for AU (Unit: \$)

		Policy 1	Policy 2	Policy 3
Cost	Generation	1629.9	1629.9	1629.9
	Grid-Import	0	38.4674	187.23
	Storage Service	402.5893	315.2029	629.84
	EV Discharging	28.3680	4.0253	35.1205
Income	Mark-up	2592.56	2592.56	2592.56
	EV charging	28.7216	25.9125	30.0215
	Grid-Export	0	0	577.979
Revenue		560.07	630.8769	721.470
Rate of Rise		0%	12.64%	28.81%

(Generation: Power from MT, PV and WT; Grid-Import/Export: Power exchanged between upstream distribution system and micro-grid.)

From Table I, it is observed that,

- (1) Under Policy 1, the micro-grid is separated from the upstream distribution system. The AU must buy the service from ESS to store/supply power for the balance between the generation and consumption. Only the EV charging/discharging scheduling can be regulated for the economic maximization.
- (2) Under Policy 2, the competition exists among the absorbed power from upstream grid, service of ESSs and EV discharging. AU could benefit from the choices depending on the hourly prices. The EV Charging/discharging scheduling also can be regulated for the economic maximization.
- (3) Under Policy 3, the AU benefits not only from selling energy to the consumers, but it could also buy the services from ESS to store the energy bought from distribution system when the market price is low, and sell the in-stored energy back to the upstream system when the price rises. Benefits are therefore rendered from buying and selling price margins in the market. The EV charging/discharging scheduling is less significant that obtained under Policy 1&2.

V. CONCLUSIONS

In this paper, the economic model describing the operation of the micro-grid is established. In this model, the storage system acts as an independent party to supply services. The EV charging/discharging power, absorb/inject power of energy storage system and power exchange with the upstream grid in grid-interconnected mode are each scheduled to maximum the revenue for the aggregator unit. Sequential quadratic programming is employed to solve the optimal function and

the operator can choose to operate grid-interconnected or isolated day-ahead configuration based on calculated revenues. Normally aggregator unit of the micro-grid will operate in the open market and enjoy the benefits from buying and selling price with associated margins.

VI. APPENDIX

NOMENCLATURE

- $C_{MG}(t)$ - Cost of micro-grid at time t
- C_{EVC} - Price of EV charging cost
- C_{EVD} - Price of EV discharging benefit
- $C_{Grid}(t)$ - Price of open electricity market at time t
- $C_{MT}(t)$ - Price of micro-turbine bid at time t
- C_{MTR} - Price of micro-turbine step-up/down cost
- C_{ESP} - Price of ESS power rating cost
- C_{ESE} - Price of ESS energy rating cost
- C_M - Price of the mark-up
- C_{PV} - Price of photovoltaic bid
- C_{WT} - Price of wind turbine bid
- $IC_{MG}(t)$ - Income of micro-grid at time t
- N - The number of connected EVs
- $P_{EV}(t)$ - EV charging/discharging power at time t. Positive value denotes for charging while negative expresses discharging.
- $P_{Grid}(t)$ - Exchanged power from upstream grid at time t. Positive value denotes for importing while negative expresses exporting.
- $P_{Load}(t)$ - Load demand at time t
- $P_{Loss}(t)$ - Power loss at time t
- $P_{MT}(t)$ - Micro-turbine power at time t
- $P_{MT}^{max}, P_{MT}^{min}$ - Maximum/minimum power of micro-turbine
- $P_{ES}(t)$ - ESS power rating at time t. Positive value denotes for absorbing while negative expresses injecting.
- $P_{PV}(t)$ - Photovoltaic power at time t
- $P_{WT}(t)$ - Wind turbine power at time t
- R_{MG} - Revenue of micro-grid
- T - The total number of timeslots
- $W_{ES}(t)$ - ESS energy rating at time t
- $f(t)$ - Probability of a charging process starting at time t
- $g(t)$ - Probability of a discharging process starting at time t
- $u_{EVC}(t)$ - State of EV charging at time t, 1 if charging, and 0 otherwise.
- $u_{EVD}(t)$ - State of EV discharging at time t, 1 if discharging, and 0 otherwise.

- $u_{Grid-in}(t)$ - State of power importing from grid at time t, 1 if importing, and 0 otherwise.
- $u_{Grid-ex}(t)$ - State of power exporting to grid at time t, 1 if exporting, and 0 otherwise.
- $u_{ESE}(t)$ - State of additional ESS energy capacity required at time t, 1 if requiring, and 0 otherwise.
- $P_{i,t}$ - Active power at Bus i at time t
- $Q_{i,t}$ - Reactive power at Bus i at time t
- $V_{i,t}$ - Voltage magnitude of Bus i at time t
- $\delta_{i,t}$ - Voltage angle of Bus i at time t
- $Y_{i,j}$ - Admittance of line (i, j)
- $\theta_{i,j}$ - Angle associated with $Y_{i,j}$
- n - Number of buses
- $I_{i,j,t}$ - Current in line (i, j) at time t
- $I_{i,j,max}$ - Maximum current capacity in line (i, j)
- $P_{Di,t}$ - Load active power demand at bus i at time t
- $Q_{i,t}$ - Load reactive power demand at bus i at time t
- $S_{i,max}$ - Maximum apparent power capacity in transformer at bus i
- $G_{i,j}$ - Conductance of line (i, j)

Table A.1: Bus Information of the example System [20][21]

Bus No.	Voltage		Load		Bus Type
	V (p.u.)	δ (deg)	V (p.u.)	δ (deg)	
1	1.03	0	0	0	Slack Bus
2	1.01	0	0	0	PV Bus
3	1.03	0	0	0	PV Bus
4	1.01	0	0	0	PV Bus
5	1	0	Fig. 4	-	PQ Bus
6	1	0	Fig. 4	-	PQ Bus
7	1	0	Fig. 4	-	PQ Bus
8	1	0	Fig. 4	-	PQ Bus
9	1	0	0	0	PQ Bus

Table A.2: Line Information of the example System [20][21]

Line No.	Bus No.		Impedance (p.u.)		Tap Ratio
	From	To	R	X	
1	1	5	0	0.01667	1
2	2	9	0	0.01667	1
3	3	6	0	0.01667	1
4	4	8	0	0.01667	1
5	5	6	0.003	0.025	-
6	6	7	0.006	0.055	-
7	7	8	0.006	0.055	-
8	8	9	0.003	0.025	1

Table A.3: Constant Prices [15]

Type	Price
MT	$P_{MT}^{max}=6\text{MW}$, $P_{MT}^{min}=0\text{MW}$, $C_{MTR}=14\$/\text{MWh}$
WT	$C_{WT}=8.8\$/\text{MWh}$
PV	$C_{PV}=8.8\$/\text{MWh}$
EV	$C_{EVC}=2.0\$/\text{MWh}$, $C_{EVD}=9.0\$/\text{MWh}$
ESS	$C_{ESP}=12\$/\text{MWh}$, $C_{ESE}=12\$/\text{MWh}$
Mark-up	$C_M=4\$/\text{MWh}$

Table A.4: 24-hour Prices [16]

Hour	MT (\$/MWh)	Grid (\$/MWh)
1	10.7	3.3
2	10.7	2.7
3	10.8	2.0
4	10.8	1.7
5	10.9	1.7
6	10.9	2.9
7	11.0	3.3
8	11.1	5.4
9	11.2	21.5
10	11.2	57.2
11	11.6	57.2
12	11.7	57.2
13	11.5	21.5
14	11.5	57.2
15	11.5	28.6
16	11.7	27.9
17	11.8	8.6
18	11.9	5.9
19	11.8	5.0
20	11.5	6.1
21	11.2	18.1
22	11.0	7.7
23	10.9	4.3
24	10.8	3.7

VII. ACKNOWLEDGMENT

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IX. BIOGRAPHIES

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