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A Novel Model to Determine Optimizing Power and Capacity for Energy Storage Systems on Competitive Electricity Markets

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***Abstract* - Distributed generators (DGs) and renewable energy resources (Hydroelectric, photovoltaic, solar thermal technologies, and wind farms…) have been applied widely on planning and operating of distribution systems due to the restructure of electricity market and the development of technology. The energy storage systems (ESSs) can store energy and then retrieve it in the other time, increase flexibility of distribution systems. Hence, many researches and applications have been conducted. Effects of ESSs on planning and operating the wind generators therefore should be carefully investigated. This paper proposes a novel approach to calculate maximum profits of the wind generators and determine optimizing power and capacity of ESSs. This model uses an objective function that includes the total profits for electric energy sales, total costs (investment, operation and maintenance) of ESSs, transmission access fee, and upgrading cost of connected substation transformers. The proposed model is applied to test two 1500kW wind generators. The calculation is programmed by GAMS environment.**

Keyword: Competitive Electricity Markets (CEMs), Distributed Generators (DGs), Energy Storage Systems (ESSs)

I. INTRODUCTION

Recently, the environmental pollutions, technological development and restructure of electricity markets have been enhancing the application of DGs and renewable energy resources in planning, designing and operating distribution systems [1]. The DGs and wind generators have been applied widely on the globe. In 2008, total power of the wind generators have been installed in about 121.19GW and the installing power of wind generators is forecasted by 2020 about 1500GW (increase 29 percent per year) [2]. However, intermittent nature and the uncertainties associated of DGs (wind generators, photovoltaic, hydroelectric…) lead to low stability, power quality and reliability of distribution systems [3, 4]. ESSs can store energy and then use it in the other times so they increase flexibility of distribution systems and DGs. Hence, many researches of ESSs have been implemented in last decade. Total power of the ESSs has been installed about 90GW in 2008, equivalent 2.6% of total electricity power on the world [5, 6]. Peak shaving of distribution systems can be done by ESSs (storing energy during low-demand periods and releasing during high-demand periods) so they can defer to upgrade network (feeders and transformers). Indices for economy, power quality, reliability and stability of distribution systems are improved [7]. Besides, in the restructure of electricity market, ESSs store energy during times of low price (low-demand) and retrieve during times of high price (high-demand) so economic efficiency of distribution companies and profits of DGs are expanded. Therefore, many authors researched and applied the ESSs on planning, operating distribution systems and the DGs for CEMs. The ESSs have been applied to improve stability and power quality of renewable energy resources [8, 9, 10], to enhance power quality and reliability for distribution systems [11, 12, 13, 14], and load demand balance [15]. Optimal size of ESSs with objectives as above has been determined. In the CEMs, volatility energy price depends purchase time from market. ESSs have been used in distribution substations [16] to load shifting, to decrease energy purchase cost on electricity markets. This model's objective is maximum amount of total profits (reducing for energy purchase fees, transmission access fees, and deferring facility investment fees) and costs (increase capital, operating and maintenance fee of ESSs) of distribution substations. The operation and maintenance cost, environmental pollutions of DGs using fuels (Diesel, Microtuabin, Combined Heat and Power, Fuel Cells…) are highly impacted by operation modes. Therefore, application of ESSs in optimization operation for these DGs has proposed in [17] with objective function including total cost of investment and operation of ESSs, production saving and emission cost of DGs, and distribution network saving cost. However, applying of ESSs to improve operation efficiency to wind generators has not been much published. This paper proposes a novel approach to calculate maximum profits of the wind generators and determine optimal power and capacity of ESSs on planning and operating of wind generators.

The next parts of this paper are organized as follows. Section II introduces characteristics, model of wind generators and ESSs. The proposed calculate model is introduced Section III. Section IV represents calculation results and discussions of proposed approach, and conclusion is reported in Section V.

II. THE WIND GENERATORS AND ENERGY STORAGE SYSTEMS

A. *Wind generators*

The wind energy is converted to electric energy by wind turbines and generators. There are two basic configurations of wind turbines, the horizontal axis and the vertical axis. The vertical axis turbines are isotropic, receiving wind from any direction. The gearbox and generator can be mounted at or near ground so they have higher durability and lower investment cost than horizontal axis ones. However, some main disadvantages of this type consisting of more expensive produce cost and smaller power ratio compared to horizontal axis counterparts. Therefore, the only horizontal axis wind turbines has been researched and applied widely on the industry [18]. The change of wind speed depends strongly on climatic conditions. These high variations are dependent geographical location, both spatially and temporally. Hence, wind generators power output are also naturally intermittent and highly variable [19]. Wind generators cannot operate when wind speed is lower than the V^{in} speed or higher than the V^{out} speed. Power output of wind generators is represented as follows [20]:

$$PG_{i,h} = \begin{cases} 0 & ,V_{i,h} < V_i^{in} \\ (a_i.V_{i,h} - b_i).PG_i^{max} & ,V_i^{in} \le V_{i,h} \le V_i^{out} \\ PG_i^{max} & ,V_{i,h} > V_i^{out} \end{cases} \quad (1)$$

B. *Energy storage systems*

ESSs have been used as a new solution to optimize distribution systems expanded plan and operation. The ESSs offer additional benefits to owners because they can improve the economic efficiency, reliability, stability and flexibility of both distribution systems and DGs. In practice, many possible ESS technologies have been researched and developed. The energy is stored by many types (potential energy, kinetic energy, mechanical energy, chemical energy, thermal energy and electrical energy…) depending on technological development. Energy can be stored by potential energy for pumped hydro storage (PHS), kinetic or mechanical energy for flywheel energy storage (FES) and thermal energy for thermal energy storage (TES). The air is compressed within an air reservoir and it is discharged to operate combustion gas turbines for compressed air energy storage (CAES). These technologies mentioned above are successfully applied in France, America, Japan, Scotland and Wales [6]… Nevertheless, when distribution systems need meet the high demand load in short-terms, primary stored energy types as above usually do not satisfy. Storage technologies of electric energy using super capacitors (SC) or superconducting magnetic energy storage (SMES) have been researched and developed as alternatives. These technologies offer large power and high efficiency factor (about 95%) but small storage energy and short operation duration so they are not appropriate to load shifting, peak shaving or generator power's characteristics changing of DGs. Chemical energy based electric storage technologies commonly use battery energy storage systems (BESS) with lead-acid batteries, sodium-sulphur batteries (NaS), lithium-ion batteries (Li-ion) and flow batteries (VRB, ZnBr). Although, the investment cost of BESS is high, they offer low operation and maintenance costs, high power and capacity, long operation duration without harmful emissions or noise [6] As a result, this technology has been used popularly. BESS technology will be chosen to investigate in this research.

III. THE PROPOSED ANALYZING MODEL

In competitive electricity markets, objectives of investors are maximum profits of electrical energy sales benefits and costs of investment and operation. Electric price changes depend different sale times on CEMs and power output of wind generators depends to climatic conditions. Therefore, this research proposes to use BESS technology to increase profits for investors. This means that electric energy of wind generators is stored on low-price periods and sold to CEMs on high-price periods. The proposed model uses an objective function that includes the total profits of electric energy sales, total costs (investment, operation and maintenance) of ESSs, and upgrading cost of connected substation transformers. Constraints of the model consist of power balance of distribution systems, power and capacity balance of ESSs, and power and capacity limits of ESSs.

A. *Increased profits of electric energy sales*

Electricity price and load demand for power systems are mutually dependent as a linear function [2]. When load demand is increased, electricity price is raised and vice-versa. Assumption that, electricity price depends load demand as formula (2).

$$r_h = a_{Pr\,i}.P_h + b_{Pr\,i} \quad \forall h \in H \qquad (2)$$

The BESS charges on periods for low price, negative BESS's power, so that power of wind generators selling to markets is described by formula (3). The storage electric energy is discharged at the high price with positive power and power factor k_F. The formula (4) expresses sale power for wind generators in this case.

$$PS_h = PG_h - PB_h \quad \forall h \in H \qquad (3)$$

$$PS_h = PG_h + k_F.PB_h \quad \forall h \in H \qquad (4)$$

On overall planning period, therefore, total profits for electric energy sales in case of changing generator power's characteristics of wind generators by BESS are presented as (5). These profits are converted to the first time of planning via discount rate r.

$$BP = \sum_{t=1}^{T} \left(\frac{1}{(1+r)^t}.365.\sum_{h=1}^{H} r_h.PS_h \right) \qquad (5)$$
$$\forall t \in T, \forall h \in H$$

B. *Increased cost of wind generators*

All costs on model also are calculated by the first time of planning using discount rate r.

1. *Investment cost of BESS*

Electric energy can be charged, discharged and stored by BESS. Hence, investment cost of BESS is related to maximum power and capacity. This capital cost is presented as follows:

$$CB=\sum_{t=1}^{T}\frac{1}{(1+r)^{t}}.\left(PB^{max}.C_P^C+EB^{max}.C_E^C\right)\quad \forall t\in T \qquad (6)$$

2. Operating and maintenance cost of BESS

This operating and maintenance costs of BESS include fixed cost depending on power, variable cost depending on capacity and operation time.

$$COM=\sum_{t=1}^{T}\frac{1}{(1+r)^{t}}.\left(PB^{max}.C_P^{OM}+EB^{max}.C_E^{OM}\right) \qquad (7)$$
$$\forall t\in T$$

where, C_E^{OM} is increased at operation time and it is assumed to go up by 20% per year [17].

3. Electricity energy loss cost on BESS

The efficiency factor of BESS is about 65% to 85% [5, 6, 7] so electricity energy loss cost on itself is determined as follows:

$$CF=\sum_{t=1}^{T}\left(\frac{1}{(1+r)^{t}}.365.\sum_{h=1}^{H}(1-k_F).PB_h.r_h\right) \qquad (8)$$
$$\forall t\in T,\forall h\in H$$

4. Transmission access fee

The transmission access fees in the competitive electricity markets rely on power value and accessing times. During the periods of high electric price, the accessing fees are raised and vice-versa. Therefore, this cost is increased because BESS delivers power at high electric price times.

$$CT=\sum_{t=1}^{T}\left(\frac{1}{(1+r)^{t}}.365.\sum_{h=1}^{H}PS_h.r_{F,h}\right) \qquad (9)$$
$$\forall t\in T,\forall h\in H$$

5. Upgrading cost of connected substation transformers

The transmission power through substation transformers can be increased when BESS discharges at high electric price times. At the same, generator power of wind generators is also high. Therefore, upgrading cost of connected substation transformers is calculated as follows.

$$CS=\sum_{t=1}^{T}\frac{1}{(1+r)^{t}}.\frac{PS^{max}}{Cos j}.C_S^S\quad \forall t\in T \qquad (10)$$

C. The proposed objective function

The proposed model uses an objective function that includes the total profits for electric energy sales, total costs (investment, operation and maintenance) of BESSs, and upgrading cost of connected transformers. This objective function is combined equations that are defined in previous sections, from (5) to (10).

$$\begin{aligned}J &= BP-CB-COM-CF-CT-CS\\
&=\sum_{t=1}^{T}\frac{1}{(1+r)^{t}}.\Bigg(365.\sum_{h=1}^{H}r_h.PS_h-(PB^{max}.C_P^C+EB^{max}.C_E^C)\\
&\quad-(PB^{max}.C_P^{OM}+EB^{max}.C_E^{OM})-365.\sum_{h=1}^{H}(1-k_F).PB_h.r_h \qquad (11)\\
&\quad-365.\sum_{h=1}^{H}PS_h.r_{F,h}-\frac{PS^{max}}{Cos j}.C_S\Bigg)\rightarrow Max\\
&\forall t\in T,\forall h\in H\end{aligned}$$

D. Constraints of the proposed model

The proposed model has determined optimizing size of BESS by previous economic requirements. Technical requirements must be guaranteed simultaneously by following constraints.

TABLE I. SETS, INDICES, VARIABLES AND PARAMETERS

No	Symbol	Definition
I. Sets and Indices		
1	i	Set of wind generators ($i\in N$)
2	N	Total number of wind generators
3	h	Set of calculation time, hour
4	H	Total of time on a calculation period, hour
5	H_1	Total charge times of BESS, hour
6	H_2	Total discharge times of BESS
7	t	Planning period, year ($t\in T$)
8	T	Overall planning period, year
II. Variables		
9	PS_h	Active power of wind generators sale to CEM at the time h, kW
10	PB_h	Active power of BESS at the time h (kW)
11	EB	Capacity of BESS, kWh
III. Parameters		
12	r	Discount rate, %
13	C_P^C	Capital cost at active power of BESS, $/kW
14	C_E^C	Capital cost at capacity of BESS, $/kW
15	C_P^{OM}	Operating and maintenance cost at active power of BESS, $/kW
16	C_E^{OM}	Operating and maintenance cost at capacity of BESS, $/kW
17	α_{Pri}, β_{Pri}	Estimation parameters for electrical price model
18	α_i, β_i	Estimation parameters for wind generators power output model
19	ρ_h	Electrical energy price for CEMs at time h, $/MWh
20	$\rho_{F.h}$	Transmission access fee at time h, $/kW.month
21	k_F	Power factor of BESS: - BESS charge, $k_F = 1$ - BESS discharge, $0 < k_F < 1$
22	V_i^{in}	Minimum operation wind speed of wind generators, m/s
23	V_i^{out}	Maximum operation wind speed of wind generators, m/s
24	$V_{i,h}$	Wind speed of wind generators at period h, h
25	PG_h	Active power for wind generators at time h, MW
26	$P_{,h}$	Active power of system at time h, MW
27	PG_i^{max}	Maximum wind generators active power limit, kW
28	$PG_{i,h}$	Active power for wind generators at time h, kW
29	PB^{max}	Maximum active power limit of BESS, kW
30	EB^{max}	Maximum capacity limit of BESS, kWh
31	PS^{max}	Maximum transmission power through connected substation transformer, kW
32	C_S^S	Upgrading capital cost of substation transformer, $/kW
33	$Cos\varphi$	Power factor
34	$PD_{,h}$	Load demand at time h, kW
35	$PG_{i,h}$	Active power of wind generators i sale to CEM at the time h, kW

1. *Constraint of distribution systems power balance*

The total power output of wind generators and BESS through substation transformers must satisfy the load demand in every period of operating time. Thus, the below equation is presented as the system power balance.

$$\sum_{i=1}^{N} PG_{i,h} + k_F .PB_h + P_h = PD_h \qquad (12)$$

$$\forall i \in N, \forall h \in H$$

2. *Constraint of BESS capacity balance*

The power output of wind generators depends on climatic conditions so operation cycle is assumed by one day (24h). In operation cycle, total charge and discharge electric energy of BESS must be balanced as follows:

$$\sum_{h=1}^{H_1} PB_h + \sum_{h=1}^{H_2} k_F .PB_h = 0 \qquad (13)$$

$$\forall h \in H, H_1 + H_2 = H$$

3. *Constraint of BESS power and capacity limits*

With the assumption that operation cycle of BESS is one day. The BESS power and capacity limits depend on generator power's characteristics of wind generators.

$$-PG_h \le PB_h \le PG_h$$

$$EB \le EB^{max} = \sum_{h=1}^{H} PB_h \qquad (14)$$

$$\forall h \in H$$

4. *Constraints of BESS power limits and dynamic power updates*

This constraint allows decreasing computing time and it ensures upgrading power corresponding to equipment parameters.

$$PB_h \le PB_{h-1} + DPB$$

$$PB_h \ge PB_{h-1} - DPB \qquad (15)$$

$$\forall h \in H$$

5. *Constraints of BESS power limit on planning period*

During planning duration, generator power's characteristics of wind generators in an operation cycle are assumed constant. This constraint is given as follows:

$$PB_{h,t} = PB_{h,t-1} \quad \forall h \in H, \forall t \in T \qquad (16)$$

The proposed model including equations from (1) to (16) is a nonlinear programming model. In order to investigate this model, Nonlinear Programming with Discontinuous Derivatives (DNLP) solver in GAMS program language [1, 22] is used to find out an optimal solution.

IV. RESULTS AND DISCUSSIONS

The proposed model is applied to test two 1500 kW wind generators in Ninh Thuan, Vietnam that have been connected to distribution systems by substation transformers as figure 1.

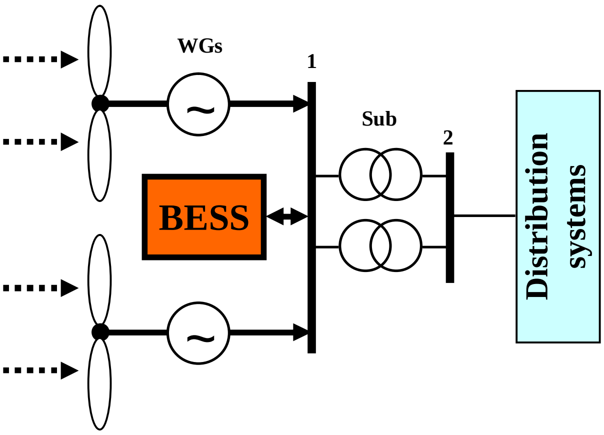

Figure 1. Diagram connected wind generators, BESS and distribution systems

A. *Calculation parameters of proposed model*

1. *The wind generator parameters*

The average wind speed in Ninh Thuan, Vietnam has been investigated in May 2011 and was regulated at operation position of wind generators (height 80m corresponding to correction factor $k_W = 1.4$) on figure 2.

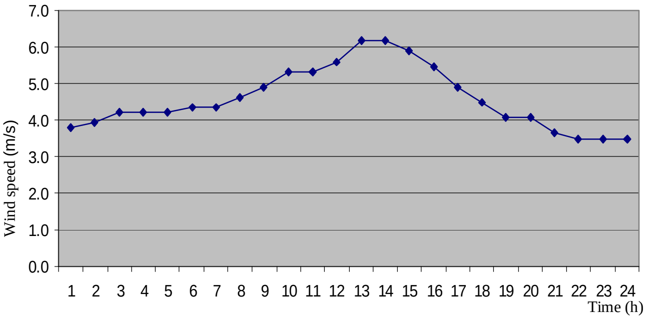

Figure 2. Data of average wind speed on a day

(source: http://www.foreca.com/Vietnam/Phan_Thiet

Wind turbines and generators in Tuy Phong, Ninh Thuan use FL-MD77 turbine type and JFRA 580 generator type (Fuhrlaender-German). The nominal capacity of one wind generator is 1500 kW, nominal voltage is 0.69 kV, maximum and minimum operation wind speed limits are 20m/s and 3m/s, respectively. Generator power on one day of two wind generators has been calculated by (1) with assumption that values for α and β corresponding to 0.2973 and 1.0378 as illustrated in figure 3.

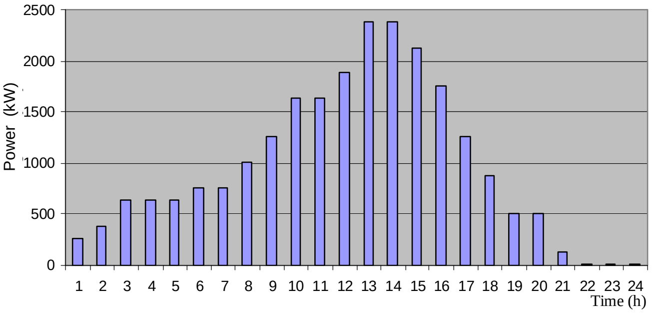

Figure 3. Wind Generators Power

2. *Electrical energy price*

The demand of power system in Vietnam is investigated in December 2008. Electric energy price in electric market is calculated in (2) with two assuming values of α_{Pri} and β_{Pri} corresponding to 0.02 and -115.19. These parameters are expressed in the figure 4.

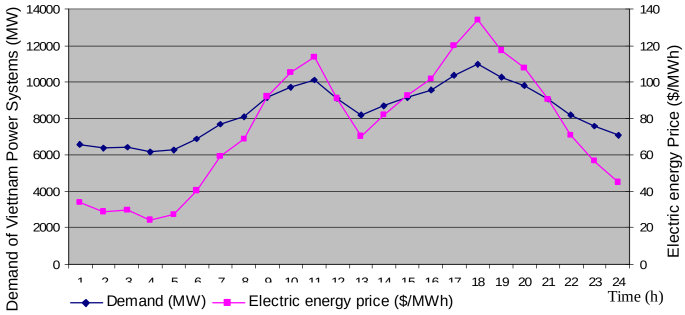

Figure 4. Power system demand and electric energy price in electricity market

3. *The parameters for BESS*

The investment, operation and maintenance costs of BESS are represented on table II.

TABLE II. INVESTMENT, O&M COST OF BESS [6, 16]

No	**Parameters**	**Investment costs** C_P^C, C_E^C	**Operation and Maintenance costs** C_P^{OM}, C_E^{OM}
1	Power ($/kW)	500	10
2	Capacity ($/kWh)	100	0.5

4. *Transmission access fees*

The restructure of electricity market has separated independently transmission companies, distribution companies and generation companies. Consequently, distribution companies that purchase electric energy from market must pay transmission access fees. Accessing fees depend on access time and capacity as on table III.

TABLE III. TRANSMISSION ACCESS FEE [16]

No	**Periods (h)**	**Fees ($/kW.month)**	**Note**
1	1-6	2.0	
2	7-9	2.17	
3	10-22	3.55	
4	23-24	2.0	

5. *The parameters and upgrading cost for connected transformers*

With the assumption, that a 3200kVA capacity of existing substation transformers can guarantee electric transmission of two wind generators. Upgrading fixed and varied costs of connected substation transformers are 200,000$ and 50,000$/MVA, respectively.

B. *The calculation results and discussions*

The feasibility of the proposed model and efficiency of BESS are tested in two cases with parameters on section A. Sale duration of electric energy for wind generators is estimated also in both cases. In case A, BESS is not considered. In case B, BESS is mentioned in the researching model.

1. *Assumptions in analysis*

This research utilizes some economic and technical assumptions for the ease of computation:

- Market demand is much higher than operation power of wind generators. Power and capacity of BESS are not limited in all calculation period. This assumption allows using maximum wind generators capacity and efficiency of BESS. Hence, it is suitable in reality because the penetration of DGs is low in distribution systems.
- Capital, operation and maintenance costs of wind generators in two cases are the same so they can be ignored in analysis.
- Sale electric energy on CEMs via substation transformers is assumed to increase 2% annually.
- Total profits are converted to present time (Net Present Value - NPV) with discount rate is 10%, annually. The calculating service lifetime of BESS is assumed 20 years.
- Upgrading area of substation transformers and building area for BESS are not limited.
- Wind speed in DGs operation location is assumed stability, little change in every calculation cycles.
- Decided variables (power and capacity of BESS) in the proposed model are continuous in order to reduce the complexity of the model (not need to use binary variable). Hence, they should be rounded to match real equipments on markets.

With these above assumptions, calculation and test results of proposed model are shown as follows.

2. *Analyzing results*

a) *Case A*

In this case, power of wind generators is sold out to market as the characteristics in figure 3. Total electric energy value that is provided to market on calculation period is 7,700,059$ and transmission access fees are 265,731$. Therefore, total profits are 7,434,327$ as in table IV.

TABLE IV. TOTAL PROFITS, COSTS FOR CASE A AND CASE B

No	**Profits and Costs**	**Case A ($)**	**Case B ($)**	**Comparison cost between Case B and Case A ($)**
1	Profits for electric energy sale	7,700,059.0	8,508,204.0	808,145.0
2	Transmission access cost	265,731.0	273,879.0	-8,148.0
3	Investment cost of BESS	0.0	634,082.0	-634,082.0
4	Operation and Maintenance costs of BESS	0.0	15,261.0	-15,261.0
5	Upgrading cost of connected transformers	0.0	0.0	0.0
	Total	***7,434,327.0***	***7,584,981.0***	***150,654.0***

b) Case B

The optimal decision of the proposed model shows the optimal selling power of wind generators through substation transformers in a calculation cycle depicted in figure 5. In this case, BESS is considered as an optimal selection to improve efficiency of wind generators. Although, high investment cost, electric energy sale profits are high. Thus, operation power of BESS in a calculation cycle is selected as in figure 6. The optimal power and capacity of BESS are decided to invest by 632.43kW and 3178.66kWh, respectively.

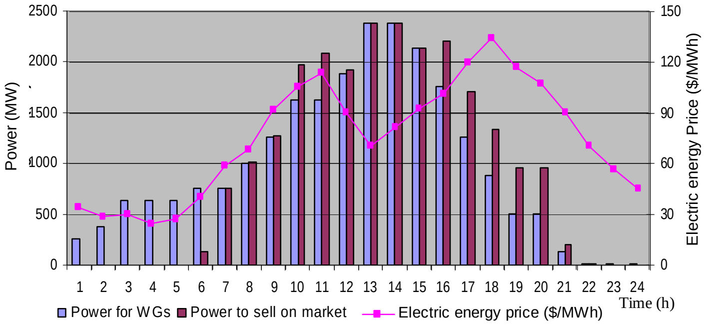

Figure 5. Power for WGs and sale on market

Figure 5 illustrates that market price of electric energy at durations from 0h to 5h is very low with minimum price is 24.41$/MWh at 4th hour. In these durations, BESS stores all energy of wind generators so that electric power sold to market is 0kW. At 6th hour, BESS only stores a part of wind generators power of 630.08kW, corresponding to 83.20% because the electric energy price on market start increasing sharply. The price of electric energy at 10th to 11th hour and 16th to 20th hour is extremely high, maximum price is 133.95$/MWh at 18th hour. This is perfect times for BESS to discharge and sell energy to markets. The maximum power is sold by 451.56kW at 11th hour and 16th to 20th hour. After the 21st hour, electric energy price is lessened. This leads to the reduction of selling power of BESS. At the same time, it resumes storing energy that is estimated by 69.61kW corresponding to 52.35% at 21st hour. In the remaining periods including 7th to 9th and 12th to 15th hours, the electric energy price is fairly high and there are power and energy losses in BESS. Therefore, wind generators sell directly electric energy to market through substation transformers.

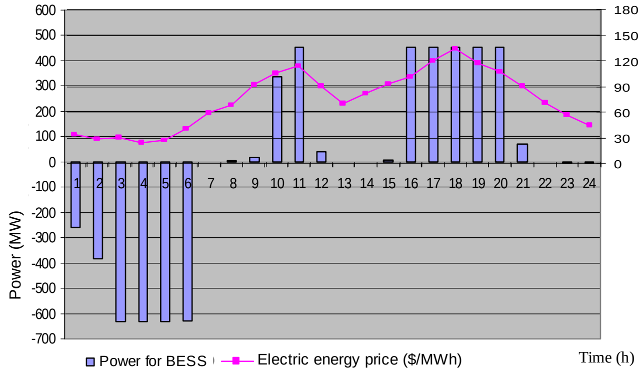

Figure 6. Power to chanrge and rechanrge for BESS

Table IV shows that the investment and production costs of BESS are 634,082.0$ and 15,261.0$, respectively. The electric energy is sold to markets at high load demand durations (high electric energy price) so that transmission access fees are raised corresponding by 8,148.0$. Total costs on this case are 923,222.0$ and are higher than those of case A by 657,491.0$. Nevertheless, profits by electric energy sale on the calculation period have been increased by 808,145.0$ compared to case A, corresponding to 1.96%. Hence, case B offers better economic efficiency.

As can be seen in the figure 5, maximum powers transmitted through substation transformers are equal in the both cases. Therefore, connected substation transformers need not to upgrade.

V. CONCLUSION

Planning of distribution systems have been changed significantly for recent years because of the application of DGs and renewable energy resources. However, power of these sources is highly variable due to weather, so that economic (electric energy sale) and technical (power quality, reliability, and stability) indicators of distribution systems are decreased. These problems can be solved by ESSs because ESSs change the generator power's characteristics of wind generators. This research has proposed a new approach to determine optimizing size of ESSs and calculate maximum profits of the wind generators within economic and technical constraints. The testing results of this research show that BESSs investments in planning and operating wind generators have been improved indicated by economic and technical outcomes (for both wind generators and distribution systems). BESSs charges electric energy during periods of low electric energy price (low demand) and recharges during periods of high electric energy price (high demand). As a result, total profits for electric energy sale are increased. Moreover, BESSs can shift loading characteristics that result to a decrease of peak demand of distribution systems as a solution for Demand Side Management (DSM). Therefore, upgrading cost of distribution systems (feeders, transformers…) is also decreased. At the same time, power quality, reliability and stability of distribution systems are improved and this solution contributes to the decrease of environmental pollution as well.

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