A Novel Model Improved the Efficiency of Distribution Generators in the Competitive Electricity Markets by Energy Storage Systems

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***Abstract* - Recently, the competitive electricity markets and the development of technology have been enhancing the wide application of distributed generators (DGs) and renewable energy resources on planning and operating of distribution systems. 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 DGs therefore should be carefully investigated. This paper proposes a novel approach to calculate maximum profits of the DGs 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, O&M) of ESSs, transmission access fee, and upgrading cost of connected substation transformers. The proposed model is applied to test two 1500kW wind powers. 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. The DGs and wind powers (WPs) have been applied widely on the globe. In 2008, total power of the WPs have been installed in about 121.19GW and the installing power is forecasted by 2020 about 1500GW [1]. However, intermittent nature and the uncertainties associated of DGs lead to low stability, power quality and reliability of distribution systems [2]. 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 [3]. Peak shaving of distribution systems can be done by ESSs so they can defer to upgrade network. Indices for economy, power quality, reliability and stability of distribution systems are improved [4][5]. Besides, in the restructure of electricity market, ESSs store energy during times of low price and retrieve during times of high price 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 [6], to enhance power quality and reliability for distribution systems [7][8], and load demand balance [9]. 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 [10][11] to load shifting, to decrease energy purchase cost on CEMs. This model's objective is maximum amount of total profits and costs of distribution substations. However, applying of ESSs to improve operation efficiency to WPs has not been much published. This paper proposes a novel approach to calculate maximum profits of the WPs and determine optimal power and capacity of ESSs on planning and operating of WPs.

The next parts of this paper are organized as follows. Section II introduces characteristics, model of WPs 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 POWERS AND ENERGY STORAGE SYSTEMS

A. Wind Powers

The wind energy is converted to electric energy by wind turbines and generators. The change of wind speed depends strongly on climatic conditions. These high variations are dependent geographical location, both spatially and temporally. Hence, WPs output are also naturally intermittent and highly variable [12]. WPs cannot operate when wind speed is lower than the V^{in} speed or higher than the V^{out} speed. Power output of WPs is represented as follows [13]:

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

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. Recently, many authors researched and developed electric storage technologies based chemical energy that used battery energy storage systems (BESS) with lead-acid batteries, sodium-sulphur batteries (NaS), lithium-ion batteries and flow batteries. Although, the investment cost of BESS is high, they offer low O&M costs, high power and capacity, long operation duration without harmful emissions or noise [3]. 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 CEMs, 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 WPs' power output depends to climatic conditions. Therefore, this research proposes to use BESS to increase profits for investors. This means that electric energy of WPs is stored on low-price periods and sold to CEMs on high-price periods. The proposed model will be presented as below.

A. *Increased profits of electric energy sales*

Electricity price and load demand for power systems are mutually dependent as a linear function [13]. When load demand is increased, electricity price is raised and vice-versa. Assumption that, electricity price depends load demand as (2).

$$\rho_h = \alpha_{Pr\,i}.P_h + \beta_{Pr\,i} \quad \forall h \in H \qquad (2)$$

The BESS charges on periods for low price so that power of WPs 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 WPs 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, total profits for electric energy sales in case of changing generator power's characteristics of WPs by BESS are presented as (5). These profits are converted to the first time of planning via discount rate r.

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

B. *Increased cost of wind powers*

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

These O&M costs of BESS include fixed cost depending on power, variable cost depending on capacity and operation time.

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

3) Electricity energy loss cost on BESS

The efficiency factor of BESS is about 65% to 85% [4] so electricity energy loss cost on itself is determined as follows:

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

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.

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

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 WPs is also high. Therefore, upgrading cost of connected substation transformers is calculated as follows.

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

C. *The proposed objective function*

This objective function is combined equations that are defined in previous sections, from (5) to (10).

$$J = BP - CB - COM - CF - CT - CS$$
$$= \sum_{t=1}^{T}\frac{1}{(1+r)^t}.\Bigg(365.\sum_{h=1}^{H}\rho_h.PS_h - (PB^{\max}.C_P^C + EB^{\max}.C_E^C) \qquad (11)$$
$$-(PB^{\max}.C_P^{OM} + EB^{\max}.C_E^{OM}) - 365.\sum_{h=1}^{H}(1-k_F).PB_h.\rho_h$$
$$-365.\sum_{h=1}^{H}PS_h.\rho_{F,h} - \frac{PS^{\max}}{Cos\phi}.C_S\Bigg) \rightarrow Max$$

D. *Constraints of the proposed model*

The proposed model has determined optimizing size of BESS with technical requirements must be guaranteed simultaneously by following constraints.

1) Constraint of distribution systems power balance

The total power output of WPs 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.

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

2) Constraint of BESS capacity balance

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

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

3) Constraint of BESS power and capacity limits

The BESS power and capacity limits depend on generator power's characteristics of DGs on operation cycle.

$$-PG_h \le PB_h \le PG_h$$
$$EB \le EB^{max} = \sum_{h=1}^{H} PB_h \quad \forall h \in H \tag{14}$$

4) Constraints of BESS power limits

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

$$PB_h \le PB_{h-1} + \Delta PB$$
$$PB_h \ge PB_{h-1} - \Delta PB \qquad \forall h \in H \tag{15}$$

5) Constraints of BESS power limit on planning period

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

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

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 [15] is used to find out an optimal solution.

TABLE I. SETS, INDICES, VARIABLES AND PARAMETERS

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

IV. RESULTS AND DISCUSSIONS

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

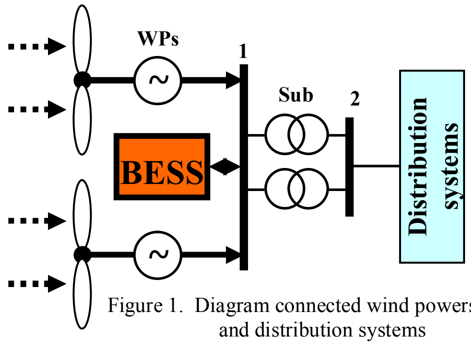

Figure 1. Diagram connected wind powers, BESS and distribution systems

A. Calculation parameters and assumptions

Generator power on one day of two 1500kW WPs has been calculated by (1) as figure 2 and electric energy price in market is calculated in (2).

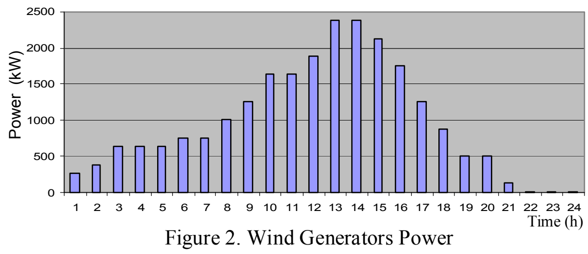

Figure 2. Wind Generators Power

The power and capacity investment costs of BESS are 500$/kW and 100$/kWh, respectively. Similarly, the O&M costs are 10$/kW and 0.5$/kWh.

Market demand is much higher than operation power of WPs. Power and capacity of BESS are not limited in all calculation period. 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. Decided variables in the proposed model are continuous in order to reduce the complexity of the model. Hence, they should be rounded to match real equipments.

B. Analyzing results

The feasibility of proposed model and efficiency of BESS are tested in two cases. In case A, BESS is not considered and BESS is mentioned in the researching model, case B.

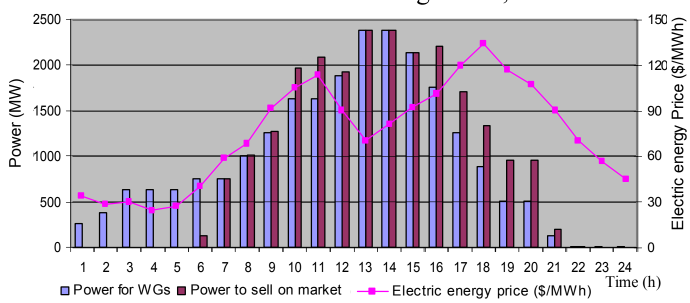

Figure 3. Power for WPs and sale on market

The optimal decision of the proposed model shows the optimal selling power of WPs through substation transformers in a calculation cycle depicted in figure 3. The market price of electric energy at durations from 0h to 5h is very low with minimum price is 24.41$/MWh at 4th hour. In these durations, BESS stores all energy of WPs so that electric power sold to market is 0kW. At 6th hour, BESS only stores a part of WPs power of 630.08kW, corresponding to 83.20% because the electric energy price on market start increasing sharply. The price of electric energy at 10th to 11th hour and 16th to 20th hour is extremely high, maximum price is 133.95$/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, WPs sell directly electric energy to market through transformers.

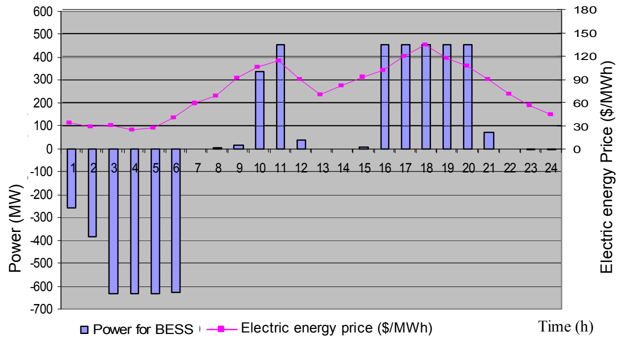

Figure 4. Power to chanrge and rechanrge for BESS

Although, investment cost is high. Thus, operation power of BESS in a calculation cycle is selected as in figure 4. The optimal power and capacity of BESS are decided to invest by 632.43kW and 3178.66kWh, respectively.

Table IV shows that the investment and production costs of BESS are 634,082.0$ and 15,261.0$, respectively. The electric energy is sold to markets at high load demand durations so that transmission access fees are raised corresponding by 8,148.0$. 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.

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

No	Profits and Costs	Case A ($)	Case B ($)	Comparison B and 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	O&M 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***

As can be seen in the figure 3, maximum powers transmitted through transformers are equal in the both cases. Therefore, connected 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 DGs. This research has proposed a new approach to determine optimizing size of ESSs and calculate maximum profits of DGs within economic and technical constraints. The testing results of this research show that BESS investments in planning and operating WPs have been improved indicated by economic and technical outcomes. 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 DSM. 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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