Selecting Energy Storage Systems with Wind Power in Distribution Network

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***Abstract*—In distribution systems, load demand can exceed the feeder thermal limit during peak demand periods and cause system damage. This situation can be prevented by load shedding, which results in financial losses to utilities and customers. The problem can be countered by utilizing energy storage systems (ESS) properly. In this paper, we formulate an optimization problem combining the utilization of ESS and wind power in a typical distribution system, whereby real power is optimally scheduled in an electricity market under the constraint that the load demand cannot exceed feeder thermal limit. This approach ensures the reliable operation of the power distribution system and prevents outages. The developed optimization problem is solved for a typical distribution system. The results clearly demonstrate the economical operation of ESS with wind power in distribution systems to prevent outages and maximize the ESS profit.**

Keywords— Auto Regressive Moving Average; Distribution Network; Electricity Tariff; Energy Storage Systems; Feeder Thermal Limit; Wind Power.

I. Introduction

The electricity market has driven the power industry to exploit all possible economic and operational options that ensure the utilization of renewable resources and other options for providing cheap and reliable energy. One of the limitations of renewable sources is the need for energy storage systems (ESS). ESS enhance the predictability of renewable energy sources by smoothing out fluctuations in the difference between the load and generation. Another application of energy storage is to enhance the capacity of distribution feeders and defer the construction of new lines and substations [1]. Feeder deferral has been addressed in many articles, but this problem has not been considered in economic terms [2]– [4]. A cost analysis was performed in which the present value was calculated to determine the economic feasibility of an ESS/PV/wind system. The discount rate, maintenance fees and lifespan effects of ESS on the cost were considered, and the rate of load growth was neglected [5]. Electrical energy time shifting or the energy arbitrage problem of ESS in the energy market have been discussed in many studies [6]– [7] whereas economic analyses of the energy market distribution systems were conducted [8]- [11]. In addition, a procedure for calculating the power system marginal cost curve and its potential applications has been developed [12]. Actual electricity prices have been used to predict future scenarios [13]. ESS market reports have been used to evaluate the market potential for each ESS application and the ESS costs [14]- [15]. In some studies, dynamic programming has been used to achieve optimal ESS charge control [16]– [17]. Though the demonstrated approach is effective but a long time may be required to find the optimal solution and cannot be used to determine the effect of multiple ESS parameters on the economic performance. Wind power is a fairly mature technology among renewable sources but has seen limited integration into the electrical grid because of the inherent intermittency, and therefore, unreliability, of wind energy. ESS are means of supplying constant power from wind power plants, thereby enabling these plants to participate in the energy and ancillary services markets [18]- [22].

In this paper, an optimization problem is formulated to maximize the energy arbitrage of ESS with wind power on a daily basis. This approach also ensures that the ESS and wind power are optimally scheduled to ensure that the load demand does not exceed the feeder thermal limit. Additionally, the approach guarantees the reliable operation of the power distribution system as well as prevents any unwanted outages.

II. Problem Description

The current economic conditions in the electric power industry have forced utilities to maximize the usage of generation facilities as well as transmission and distribution networks. Utilities can operate a distribution feeder up to its thermal limit to avoid building new feeders, but such practices can endanger the network and result in power outages. However, building new lines is financially prohibitive and can provoke consumer complaints. Recently, researchers have proposed the use of ESS to defer the construction of new feeders. In this study, ESS are operated with wind power for optimal participation in the electricity market within the feeder thermal limit.

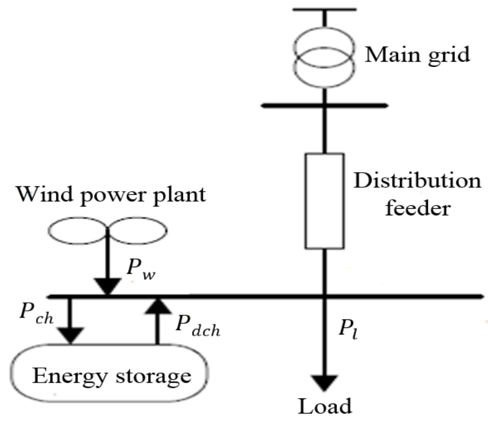


Fig. 1 Energy Storage and wind power plant connected to the distribution feeder and main grid

Fig. 1 shows a typical distribution system that is investigated in this study. The distribution system consists of the ESS, a wind turbine, an electric grid, the user load and a distribution feeder with a limited capacity to transfer power from the grid to the end user. The owners can either use the energy to meet demand or sell the energy to other users at electricity market rates by aggregating their load demand.

A. Wind Power

In this article, the hourly wind speed is forecasted using the seasonal autoregressive integrated moving average (ARIMA) model. The wind speed is forecasted using the seasonal ARIMA $(1,0,1) \times (1,0,1)_{24}$ model, as shown in (1). The estimated parameters of the seasonal ARIMA model are shown in Table I and the details about the building ARIMA model can be found in [23].

$$(1-\varphi_1 B^1)(1-\Phi_{24}B^{24})_t = (1-\theta_1 B^1)(1-\Theta_{24}B^{24})e_t \quad (1)$$

TABLE I: SEASONAL ARIMA MODEL PARAMETERS AND MEAN ABSOLUTE PERCENTAGE ERROR (MAPE) FOR WIND SPEED

φ_1	Φ_{24}	θ_1	Θ_{24}	MAPE
0.9924	-0.1384	-0.1821	-0.9352	4.612%

B. Wind Power Curve

The power generated by wind turbines depends heavily on the wind speed. Wind power can be predicted using wind speed predictions and a wind power curve, which relates the wind power to the wind speed. Wind power characteristics depend on the average wind speed and the turbine manufacturers. In this study, the GE 1.5 MW sle turbine is used. The GE 1.5 MW sle and xle wind turbine power curves are shown in Fig. 2 [24].

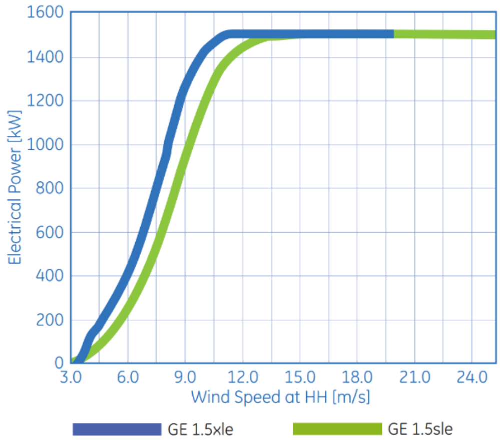


Fig. 2 GE 1.5 MW sle & xle wind power curve [24]

TABLE II: GE 1.5 MW SLE WIND TURBINE TECHNICAL SPECIFICATIONS [24]

Rated power capacity (MW)	**1.5**
Cut-in wind speed (m/s)	3.5
Rated wind speed (m/s)	14
Cut-out wind speed (m/s)	25
Hub height (m)	80

The power characteristics of the wind turbine that are used in this study are chosen to simulate the characteristics of a particular commercial GE 1.5 MW sle wind turbine. Table II lists the characteristics of the GE 1.5 MW sle wind turbine [24].

The wind turbine output can be expressed as follows:

$$P_w(v_i) = \begin{cases} 0 & v_i \le 3.5 \\ \Psi(v_i) & 3.5 < v_i \le 25 \\ 0 & v_i > 25 \end{cases} \quad (2)$$

$$\Psi(v_i) = \begin{cases} \Phi(v_i) & 3.5 < v_i < 14 \\ 1 & 14 \le v_i \le 25 \\ 0 & else \end{cases} \quad (3)$$

where $\Phi(v_i)$ is a fifth-degree polynomial function, which is fitted by the Matlab curve fitting toolbox to the power curve of the GE 1.5 MW sle wind turbine as given below:

$$\Phi(v_i) = 0.1221v_i^5 - 5.334v_i^4 + 85.35v_i^3 - 612.3v_i^2 + 2091v_i - 2740 \quad (4)$$

III. PROBLEM FORMULATION

An optimization algorithm for ESS with wind power is formulated to maximize the profit in the electricity market, while satisfying the distribution system constraints. In this optimization problem, we consider the distribution feeder thermal limit, the hourly load demand, the operation and maintenance (O&M) costs of the ESS, and the level cost of energy of wind turbine. In this approach, ESS operation is optimally scheduled to prevent load shedding and maximize ESS profit. The optimization problem is formulated in the following sections.

A. Objective Function

The objective of this optimization problem is to facilitate the optimal participation of ESS and wind power in the electricity market, while satisfying the system constraints. Equation (5) represents the profit from joint ESS and wind turbine operation. Equation (6) presents the revenue generated by the ESS and wind power. The O&M costs of the ESS and wind turbine operation are given in (7) - (9).

$$Max\ R - C \quad (5)$$

$$R = \sum_{i=1}^{24} (P_{dch_i} - P_{ch_i} + P_{w_i})\lambda_i \quad \forall\, i \quad (6)$$

$$C = Com_{e_i} + C_{w_i} \quad \forall\, i \quad (7)$$

$$Com_{e_i} = C_{omf_i} * P_{max} \quad \forall\, i \quad (8)$$

$$C_{w_i} = LCOE_w * P_{w_i} \quad \forall\, i \quad (9)$$

Where R is Revenue and C is Cost, λ_i represents the electricity price at hour i. P_{wi} is the actual wind power at hour i. P_{ch_i} and P_{dch_i} are the charging and discharging powers of ESS at hour i respectively. Com_{ei} is the operation and maintenance cost of ESS at hour i and C_{w_i} is the production cost of Wind power at hour i. C_{omf_i} is the fixed operation and maintenance cost of ESS at hour i. P_{max} is the maximum power capacity of ESS and $LCOE_w$ is the levelized cost of wind energy.

B. Feeder Thermal Limit Constraint

The load demand and charge/discharge power of the ESS should remain within the feeder thermal limit:

$$P_{ch_i} - P_{dch_i} + Pl_i - P_{w_i} \leq T_l \quad \forall\, i \tag{10}$$

where Pl_i is the load demand at hour i and T_l is the feeder thermal limit.

C. Wind Operating Constraint

The scheduled wind power should remain within the limits of the forecasted wind power:

$$0 \leq P_{w_i} \leq P_{w_i}^f \quad \forall\, i \tag{11}$$

where $P_{w_i}^f$ is the forecasted wind power.

D. ESS Operating Constraints

Equations (12) and (13) ensure that the ESS charge or discharge power remains within the defined limits. The energy balance equations of the ESS are presented in (14) and (15). The energy in the ESS should remain within the limits that are defined in (16). Either equations (17) - (19) ensure that the ESS will charge or discharge at a given time:

$$0 \leq P_{dch_i} \leq P_{max} \quad \forall\, i \tag{12}$$

$$0 \leq P_{ch_i} \leq P_{max} \quad \forall\, i \tag{13}$$

$$E_{i+1} = E_i + P_{ch_i} * \eta_{ch} \quad \forall\, i \tag{14}$$

$$E_{i+1} = E_i - \frac{P_{dch_i}}{\eta_{dch}} \quad \forall\, i \tag{15}$$

$$E_{min} \leq E_i \leq E_{max} \quad \forall\, i \tag{16}$$

$$P_{ch_i} - M\alpha_i \leq 0 \quad \forall\, i \tag{17}$$

$$P_{dch_i} - M(1 - \alpha_i) \leq 0 \quad \forall\, i \tag{18}$$

$$\alpha_i \in \{0,1\} \quad \forall\, i \tag{19}$$

where E_i is the energy of ESS at hour i, η_{ch} and η_{dch} are the charging and discharging Efficiencies of ESS, respectively, E_{max} and E_{min} are the maximum and minimum energy capacities of ESS, respectively, M is a large number and α_i is a binary variable.

The developed optimization problem is solved using Sequential quadratic programming (SQP) which is one of the most successful method for solving nonlinear optimization problems numerically and details of SQP can be found in [25].

IV. RESULTS AND DISCUSSION

The developed optimal algorithm to maximize the ESS and wind power plant profit is simulated for the system that was described in Section II. The levelized cost of wind energy (LCOE) is assumed to be 100 SR/MWh, which includes the investment, O&M, and production costs of wind energy. In this study, the system load, electricity prices, and wind speed are considered to be hourly averages. The system load is the adjusted load of the eastern province of Saudi Arabia. The hourly electricity tariff rates are taken from the Electricity and Cogeneration Regulatory Authority (ECRA) of Saudi Arabia [26].

The hourly measured wind speed data of the Dhahran region at a 15-m height are adjusted for use at a hub height of 80 m. The future wind speed is forecasted using the seasonal ARIMA (1,0,1) $(1,0,1)_{24}$ model. The hourly actual and forecasted wind power are calculated using (1) - (3). The load forecasts are generated by adding an error term to the actual load to match the load forecast errors observed in [27]. The profits are calculated using the actual values of the load, the price, and the wind power. The ESS parameters and the feeder thermal limit are given in Table III.

TABLE III: ESS PARAMETERS AND FEEDER THERMAL LIMIT

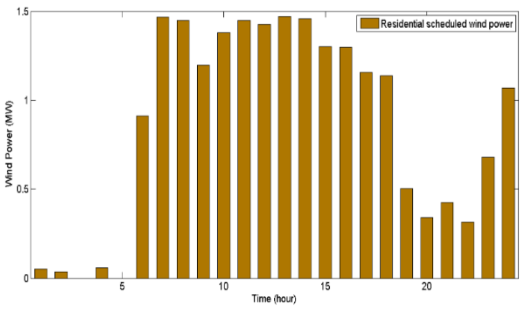
P_{max} (MW)	**1**
E_{max} (MWh)	5
E_{min} (MW)	0
C_{omf} (SR/MWh)	3.75
η_{ch}	0.87
η_{ch}	0.87
η_{dch}	0.75
$\boldsymbol{T_l}$ (MVA)	10

A. ESS and Wind Power Scheduling Profiles

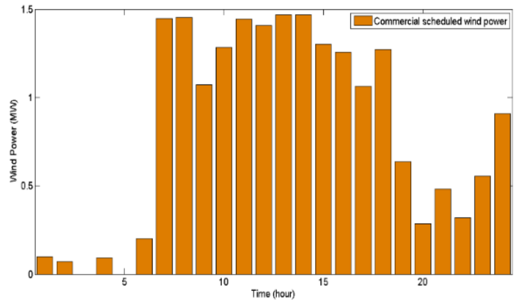
The wind power plant scheduling profiles for residential, commercial, and industrial tariff rates are shown in Fig. 3. The scheduled wind power is zero for the first nine hours for industrial customers because the LCOE of wind energy is assumed to be 100 SR/MWh, and the industrial tariff rates for the first nine hours are also 100 SR/MWh; therefore, the wind power plant does not produce wind energy for industrial customers during these hours.

The charge/discharge power profile and the energy state of the ESS for each hour are shown in Fig. 4. Fig. 4(a) shows the energy and power profile of the ESS for residential electricity tariff rates. The lowest price (i.e., 120 SR/MWh) is obtained for the first six hours; thus, the ESS will charge during these hours and discharge to sell power at the higher price of 220 SR/MWh. Fig. 4(b) shows the energy and power profile of the ESS at commercial electricity tariff rates. The price is lowest at 200 SR/MWh; thus, the ESS will not charge during this period because the maximum tariff is 260 SR/MWh. The ESS will not make a profit if it buys one megawatt for one hour at 200 SR/MWh, and it can only sell 0.75 MW for an hour at 260 SR/MWh, which represents a loss of 5 SR. Thus, the ESS cannot operate at commercial tariff rates. Fig. 4(c) shows the energy and power profile of the ESS for industrial users. The lowest price is 100 SR/MWh; thus, the ESS will charge at this price rate and discharge to sell power at the higher price of 260 SR/MWh. Hence, the ESS can operate to supply industrial loads.

The load demand on the distribution feeder with and without consideration of the ESS and the wind power plant is shown in Fig. 5.



(a)



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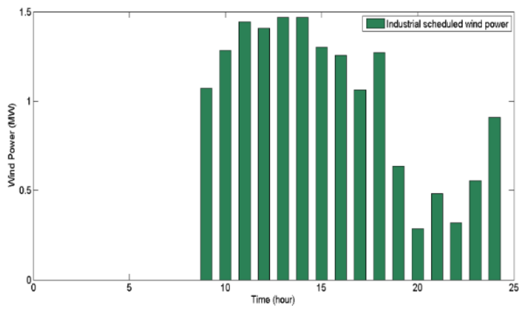
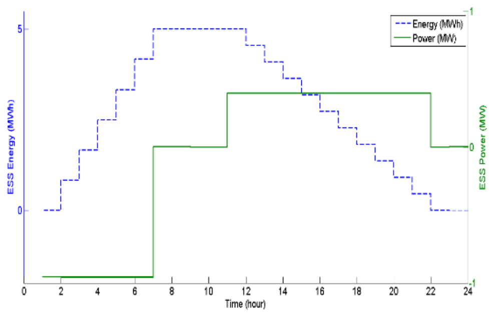
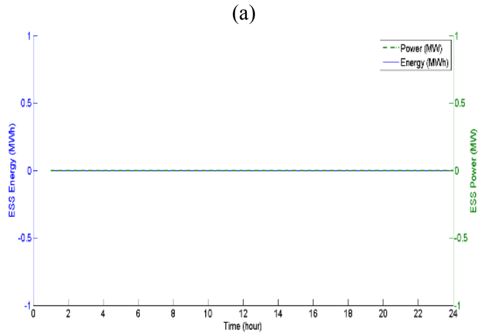


(c)

Fig. 3 Hourly scheduled wind power for (a) residential electricity tariff rates, (b) commercial electricity tariff rates, and (c) industrial electricity tariff rates



(a)



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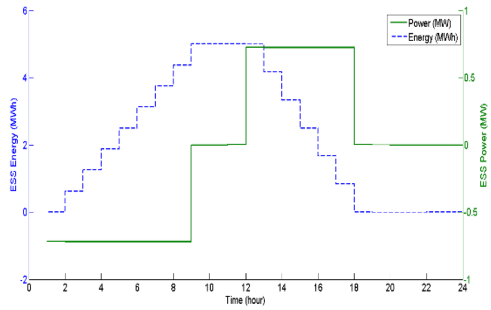
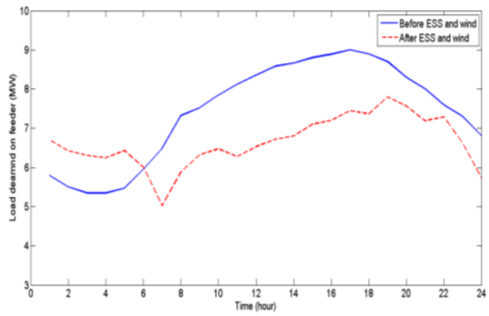
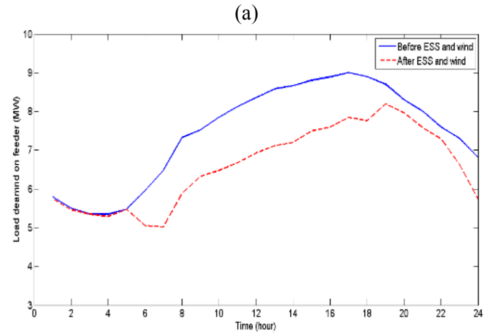


(c)

Fig. 4 Optimal scheduling of power and energy of ESS for (a) residential customers, (b) commercial customers, and (c) industrial customers



(a)



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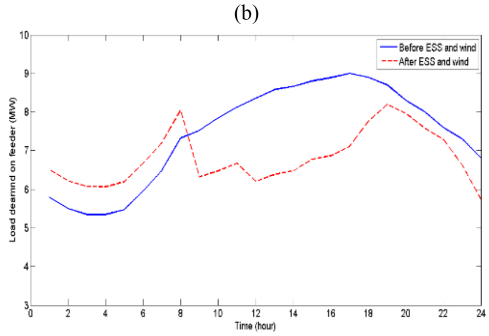

(c)

Fig. 5 Load demand on distribution feeder for (a) residential customers, (b) commercial customers, and (c) industrial customers

The hourly-based daily ESS and wind turbine profits for residential, commercial, and industrial customers are shown in Fig. 6. These profits are calculated based on the actual values of the wind power and the load demand. The optimal profit for commercial customers is higher than that for residential and industrial customers because of the higher commercial electricity tariff rates.

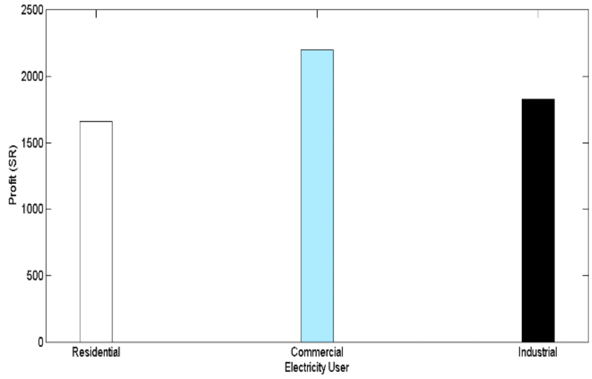

Fig. 6 Profit from ESS and wind turbine combination.

B. Monthly and Annual Profits

The monthly and annual profits from the ESS optimal scheduling are obtained after performing the simulation for the following different types of customer load demands.

- Mixed residential, commercial, and industrial substation
- Residential substation
- Industrial substation

1) Mixed Residential, Commercial and Industrial Substation:

Different annual hourly load demands for the eastern province of Saudi Arabia are used for the mixed residential, commercial, and industrial sector. The annual hourly electricity prices for the industrial, residential, and commercial customers are obtained using the load demand and the electric tariff rates for each customer type.

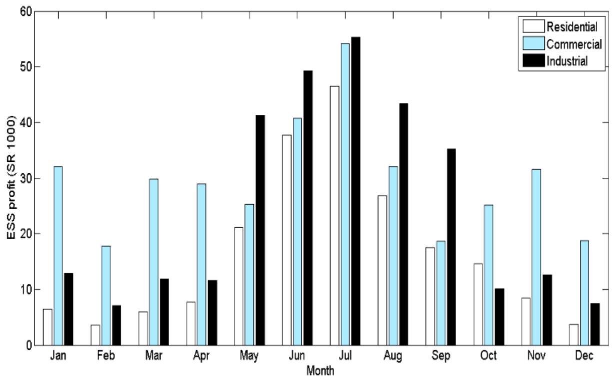

Fig. 7 Monthly profit from ESS and power plant combination for different customer types

The combined profits of the ESS and wind power plant for residential, commercial, and industrial customers are obtained for the annual period using the developed optimization approach for the combined ESS and wind power plant. Fig. 7 shows the monthly profits for the residential, commercial, and industrial customer electricity tariff rates. The profits for the commercial electricity tariff rates are higher than those for the residential and industrial electricity tariff rates because the commercial electricity tariff rates remain greater than or equal to 200 SR/MWh for almost the entire year. The ESS cannot operate at commercial electricity tariff rates. The ESS can only operate at commercial electricity tariff rates if these rates are increased to 285 SR/MWh for a load greater than eight megawatts.

The annual profits at the residential, commercial, and industrial customer electricity tariff rates are shown in Fig. 8. The annual profit reaches a maximum for the commercial customer electricity tariff rates, and the annual profit for the industrial customer electricity tariff rates is higher than that for the residential customer electricity tariff rates.

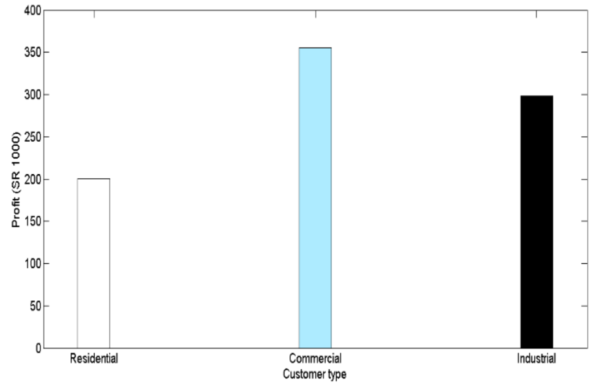

Fig. 8 Annual profit from ESS and wind power plant combination for different customer types.

2) All Residential and All Industrial Substations:

The effects of the load demand and prices for the all-residential and all-industrial sectors are analyzed using the developed optimal ESS scheduling algorithm. The annual load demands are taken from residential and industrial substations in the eastern province of Saudi Arabia. These prices and demands are used to simulate and analyze the performance of the developed optimal ESS scheduling algorithm. The simulation results are shown in Fig. 9 and 10.

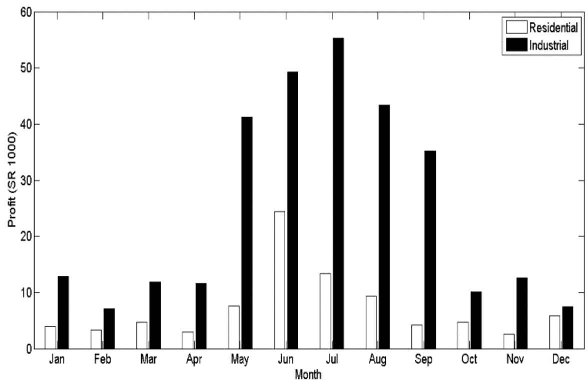

Fig. 9 Monthly profit from ESS and wind power plant combination for all-residential and all-industrial sectors.

Fig. 10 clearly shows that it is more economical to operate both the ESS and wind power plant in the industrial sector for maximum profit. The monthly profit for the industrial electric tariff rates reaches a maximum in July because of the large wind power availability and a high deviation between the maximum and minimum industrial electricity tariff rates. The annual profit from the combined ESS and wind power plant operation in the industrial sector is SR 297,940 and is SR 85,112 in the residential sector.

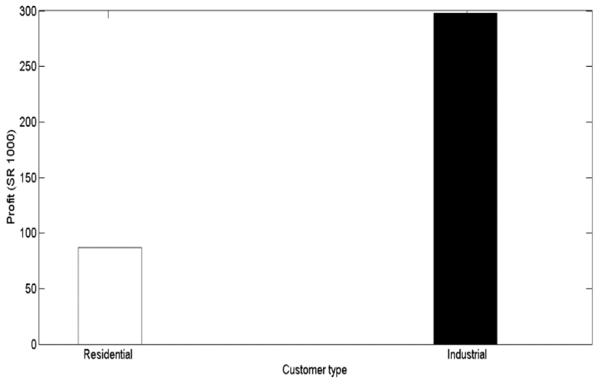

Fig. 10 Annual profit from ESS and wind power plant combination for all-residential and all-industrial sectors.

V. CONCLUSION

The ESS provides a means of deferring feeder upgrades at substantial financial benefits to the grid and system operators. The combined scheduling of the ESS and wind power plant in a constrained distribution feeder is optimized by developing and implementing an algorithm that considers the distribution feeder thermal limit, the electricity price, the load demand, the maximum energy and the power capacity of the ESS, the charging and discharging efficiency of the ESS, and the wind power plant parameters. The developed algorithm is implemented using electricity tariff rates for different customer types and demands from residential, commercial, and industrial customers. The simulation results show that the developed optimal algorithm is economical for combined ESS and wind power scheduling.

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