International Journal of Engineering Applied Sciences and Technology, 2017
Vol. 2, Issue 6, ISSN No. 2455-2143, Pages 9-14
Published Online in IJEAST (http://www.ijeast.com)

EFFECT OF SMART GRID OPERATION WITH HYBRID ELECTRIC VEHICLES IN PEAK LOADS

Ch. Srinivas Reddy
Department of EEE, Assistant Professor
Guru Nanak Institutions Technical Campus,
Ibrahimpatnam, Telangana, India

Dr. S. Tara Kalyani
Department of EEE, Professor
JNTUH College of Engineering,
Hyderabad, Telangana, India

Abstract— **This paper investigates hybrid electric vehicle (HEV) role in the peak market. We take into account HEV mobility, model for calculating the optimal size of an energy storage system (ESS) in a HEV considering reliability criterion and evaluate impact on smart grid reliability and flexibility. A program model which deals with uncertainties and variations of load variations, as well as HEV charging requirements. Moreover, proposed new practices to evaluate grid flexibility. The optimal ESS sizing problem is proposed which minimizes the investment cost of the ESS, as well as expected smart grid operating cost. A practical model for ESS is utilized. . Illustrative examples show the efficiency of the proposed model.**

Keywords—**Hybrid Electric Vehicles (HEV), Energy Storage System (ESS)**

I. INTRODUCTION

The Energy storage system introduces extensive applications in power system operation, such as enhancing the control, mitigating exceptions and reliability problems of renewable energy resources, load following, voltage and frequency stability, peak load management, power quality improvement, and deferment of system upgrades. Thus involves high investment costs necessitate accurate modeling and optimal sizing of energy storage systems to justify its economic viability and further prevent over or underutilization. Optimistic size of Energy Storage System in a Microgrid [1] and an accurate and practical energy storage system model would enhance modeling of system operation from both economic and security perspectives [3]–[5].

Storage is an indispensable component of a smartgrid. A smartgrid is defined as a small-scale intelligent power network which includes at least one load and one distributed energy resource. The smartgrid is regarded as a controllable load from the system operator's point of view as it would supply its own load and respond to real-time electricity price fluctuations.

By smartgrid implementation, the cost of supplying energy is lowered, power reliability and quality is improved, and system emission is reduced [6] locally. The optimal storage system size has been performed in a microgrid as small energy storage system may not provide economical benefits, desired flexibility or predefined reliability objectives in the microgrid and the large energy storage system involves higher investment and maintenance costs to the grid. Therefore, energy storage system needs to be optimally sized hence the reduction in operating costs justifies the investment on energy storage system.

In [6] a practical model for energy storage system with predefined charge and discharge profile is proposed. Interfacing of energy storage systems with intermittent renewable energy resource is explored in [7]–[9], where the aim is to smooth out the intermittent generation of wind and solar generators and obtain a dispatchable output. An mathematical approach to identify the size of a backup storage unit in a power system, considering reliability requirements is proposed in [10]. The backup could be in the form of battery electrical energy storage.

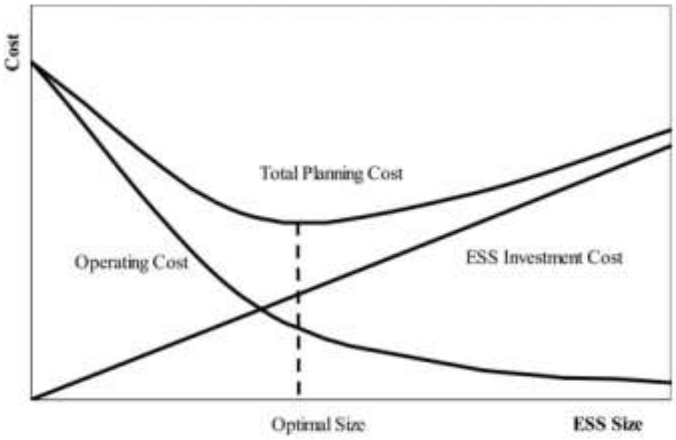

Fig. 1. ESS Sizing

The energy storage system sizing problem for time-of-use rates industrial customers is investigated in [11]. In [12] an analytical approach to find the most-profitable rating of energy storage system that is installed with wind farms to increase their power dispatch ability is proposed. Equally a problem solved in [13] considering the application of energy storage system in a photovoltaic-energy storage for autonomous small islands. An analytical analysis [14] of a variety of energy storage systems sizes and technologies in an standalone wind-diesel microgrid is performed, in which energy storage system is used to improve the penetration of renewable energy sources to smartgrids.

II. Estimation of Aggregated Power Capacity

Impact on power System flexibility by EV participation in market [2] and flexibility issue has thrown light ever since the growing penetration of renewable energy sources aiming at reducing power systems' carbon emission. Being clean and relatively inexpensive, renewable energy sources are making it quite challenging to predict or control their outputs. Integration of renewable energy demands improving power system flexibility, since its variability can lead to complexities in energy balancing, thus compromising the power system operation efficiency and reliability [15], [16].

New market product, the flexible ramping product, has been recently proposed by new approach of independent system operators (ISOs) to facilitate total load variations and uncertainties [17]–[19]. The aim of this product is to build dispatch flexibility in terms of ramp capability in real-time dispatch (RTD) to fulfill energy imbalances that may arise in the near future.

Hybrid Electric Vehicles have become more and more popular, not only because of their capability to decrease carbon emission in movement, but also of their potentials to improve power system reliability and flexibility. Hybrid Electri Vehicles can be quite adjustable in different operation modes: 1) grid to vehicle (G2V); 2) vehicle to grid (V2G); and 3) vehicle to building (V2B) [14], and they have been identified to participate in the electricity market by providing ancillary services such as reserve and regulation in a lot of studies.

However, the constraints on electric vehicle battery capacity and battery cost related to frequent charging/discharging are the core problems restricting electric vehicle flexible performance in the electricity market. Different from the operating reserve, the ramp product can be integrated in real-time dispatch, which is applied on a 5–10 min time scale, and therefore the limitation caused by electric vehicle battery capacity can be relieved. Moreover, the peak capacity is usually dispatched in just several short intervals due to the frequent appearance of more fluctuations.

HEVs, if participating, will not have to charge or discharge frequently, compared with the frequency regulation, while their fast ramping capability can still be considered. What is more important is that by bidding into the ramp market, HEVs can more effectively improve the ISOs dispatch flexibility in real-time dispatch compared with their involvement in reserve or regulation. This is due to the fact that the ramp product can be dispatched in real-time dispatch on a regular basis, whereas regulations are dispatched by automatic generation controls and operating reserves only after major contingency happens.

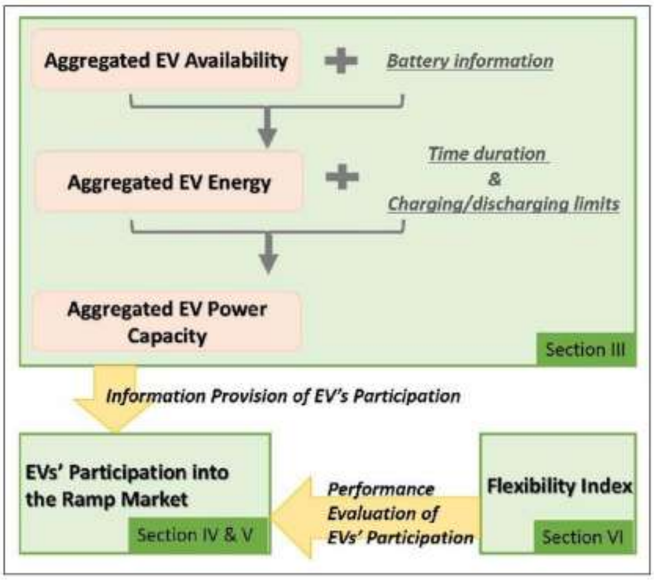

Fig. 2. Relationship among different sections

There are more research of the flexible ramping product. References [20]–[23] discuss the impact of the flexible ramping product on operation as well as power system reliability and flexibility. Congcong *et al.* [24] proposed a new principle to determine the amount of ramp capacity needed. Thatte *et al.* [25] and Wang and Hobbs [26] compared the performances of the flexible ramping product model, traditional dispatch model, stochastic model, and robust model. However, few efforts have been devoted to discuss Hybrid Electric Vehicles provision of the flexible ramping product

III. Problem Formulation

The focus of the optimal energy storage system sizing problem for a 12 months duration is proposed as in (1)

$$Min\ IC + OC \tag{1}$$

$$IC = ICP_B P_B^R + ICE_B C_B^{\max} \tag{2}$$

$$OC = \sum_{s=1}^{NS} p_s \sum_{t=1}^{NT} \sum_{h=1}^{NH} \sum_{i=1}^{NG} [F_i(P_{ith}^s) I_{ith}^s + SU_{ith}^s + SD_{ith}^s] + \sum_{s=1}^{NS} p_s \sum_{t=1}^{NT} \sum_{h=1}^{NH} \rho_{th} P_{M,th}^s. \tag{3}$$

Smartgrid and Base Constraints

$$\sum_{i=1}^{NG} P_{ith}^s I_{ith}^s + \sum_{i=1}^{NR} P_{rth}^s + P_{B,th}^s + P_{M,th}^s + LS_{th}^s = P_{D,th}^s \tag{4}$$

$$|P_{M,th}^s| \le P_M^{\max} UY_{M,th}^s \tag{5}$$

$$0 \le LS_{th}^s \le P_{D,th}^s. \tag{6}$$

The electrical power balance equation ensures that the power generated from local units, power generated (consumed) by energy storage system, and the power imported (exported) from (to) the main grid would meet the hourly grid load. A load shedding constraints were added to the power

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balance equation if the available generation from the grid units and the main grid could not supply the load. The energy storage system power, is greater than zero when the storage is discharging, negative when charging, and zero when energy storage system is in idle mode.

The primary grid power is positive when the power is imported from the main grid, negative when the power is exported to the main grid, and zero when the grid operates in islanded mode. The demand is obtained using load forecasting techniques and is considered constant in each scenario.

The power imported (exported) from (to) the main grid is limited by equation (5), where the associated contingency state is included in this constraint to represent the state of the line connected to the main grid in each scenario. Shedding of load is limited by the smartgrid hourly load in each scenario equation (6). Constraints on thermal power for every scenario at day at hour are proposed as follows:

$$P_i^{\min} I_{ith}^s U X_{ith}^s \le P_{ith}^s \le P_i^{\max} I_{ith}^s U X_{ith}^s \quad (7)$$

$$P_{ith}^s - P_{it(h-1)}^s \le UR_i(1 - y_{ith}^s) + P_i^{\min} y_{ith}^s \quad (8)$$

$$P_{it(h-1)}^s - P_{ith}^s \le DR_i(1 - z_{ith}^s) + P_i^{\min} z_{ith}^s \quad (9)$$

$$\sum_{k=h}^{h+UT_i-1} I_{ith}^s \ge UT_i y_{ith}^s \quad (10)$$

$$\sum^{h+DT_i-1} (1 - I_{ith}^s) \ge DT_i z_{ith}^s. \quad (11)$$

Adding to these useful constraints, fuel and emission constraints could be considered for each thermal unit as well as the grid. The proposed unit constraints include hourly operation of units and in detail consider the inter-temporal constraints of each thermal unit. In addition to thermal units, the renewable units are considered in the model. A long-term forecast would determine the generation pattern of each renewable unit, which would be considered as a constant in the load balance equation. A scholastic method (based on historical data) or simulation approach could be used to forecast the input behavior of the generation source.

IV. NUMERICAL SIMULATION

Smartgrid is analyzed to show the performance of the proposed method. The characteristics of grid generators, including 4 thermal units and 1 wind unit, are shown in Table I. The considered ESS for installation in the grid has annualized power and energy investment costs of 40 $/kW/year and 11 $/kWh/year, respectively. The capacity of the line connecting the grid to the grid is 10 MW, which limits the power transfer between the grid and grid. The wind speed distribution is modeled by a Weibull probability distribution function with a mean speed of 5.5 m/s and a shape parameter of 2.

To model component outages as well as wind speed, 500 scenarios are generated. The scenario reduction is applied which reduces the number of scenarios to 5 as shown in Table II. It is assumed that the grid load will not increase in future years, so a one year scheduling horizon is considered. The reliability criterion is 0.1 day/year.

To further investigate the impact of the ESS size of the grid cost and reliability, the problem is solved for a variety of ESS sizes. The results are provided in Figs. 2–4, which depicts the grid total cost as a function of ESS rated power and capacity. The ESS rated power is increased from 1 to 5 MW, with a step of 1 MW, and the ESS capacity is changed from 1 to 8 times the rated power. So, the horizontal axis represents the minimum number of hours that ESS can reach its maximum capacity.

By increasing the ESS size the investment cost is linearly increased as shown in Fig. 2 and the grid operating cost is reduced as shown in Fig. 3. A larger ESS requires higher power import (as well as local generation) in low price hours, thus increasing the cost of power import. On the other hand, a larger ESS increases the power export to the grid at times of high electricity prices and also reduces the units generation cost. Therefore, it would result in reduced operating costs.

Table 1: CHARACTERISTICS OF GENERATING UNITS

Unit No.	Bus No.	Cost Coefficient ($/MWh)	Min. Capacity (MW)	Max. Capacity (MW)
1	Gas	27.7	1	5
2	Gas	39.1	1	5
3	Gas	61.3	0.8	3
4	Gas	65.6	0.8	3
5	Wind	0	0	1
Unit No.	Min. Up Time (h)	Min. Down Time (h)	Ramp Up (MW/h)	Ramp Down (MW/h)
1	3	3	2.5	2.5
2	3	3	2.5	2.5
3	1	1	3	3
4	1	1	3	3
5	-	-	-	-

Table 2: PROBABILITIES OF REDUCED SCENARIOS

Scenario	1	2	3	4	5
Probability	0.714	0.121	0.075	0.039	0.051

It is inevitable that inconvenience may occur to EV drivers due to EV participation in the electricity market. Therefore, incentive mechanisms become indispensable to encourage EV involvement. Those incentive mechanisms can also apply in the case of EV providing the ramp product.

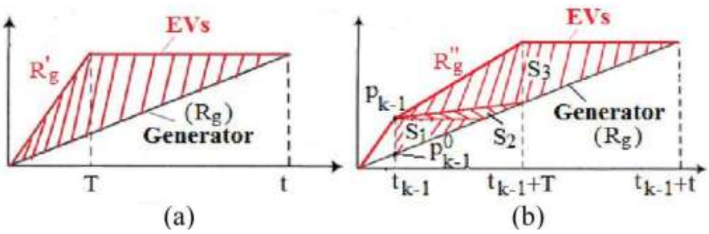

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Fig. 3. Illustration of EV cooperation with conventional generators. (a) Scenario 1. (b) Scenario 2.

V. EXPERIMENT AND RESULT

A. Calculation of the Equivalent Ramping Rate Although it is hard for EVs to provide sustainable power like conventional generators, they can ramp up or down very quickly if needed. For those generators with relatively low ramp rates, the cooperation with EVs can enable them to improve their ramp capabilities. The basis of EV improving generator's ramp rate is to utilize EV ramp capacity until the generator can catch up with the new generation point, as illustrated in Fig. 3. The red shade denotes the energy provided by EVs and the black line denotes the operation of the conventional generators. T is the time base for the ramp product. Three factors exert restriction on the equivalent ramp rate.

B. 1) the available energy that EVs can charge or discharge; 2) the maximum power EVs can provide; and 3) the generation limit of the conventional generator. If we take the process of ramping up for example, the first scenario shown in Fig. 3(a) lies in the situation when EVs do not discharge, or EVs are charging at the very beginning. The constraint caused by EV energy capacity can be expressed, which means the area of the red triangle is less than the aggregated EV available energy, and the corresponding maximum ramping rate is presented.

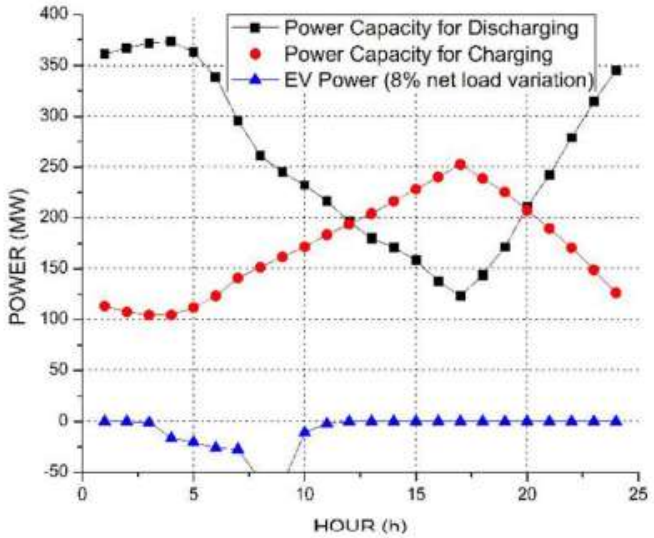

Fig. 4. EV aggregated power capacity and power during one day

Ever since the flexible ramping products were proposed, several studies have been conducted to evaluate power system flexibility. It is pointed out that generator' ramp capacities, which enable the system's flexibility in dealing with uncertainty and variation, are not independent of each other. We propose to use the probability that the system fails to meet the ramp requirement, fail to ramp probability (FTRP-up and FTRP-down), to assess the flexibility based on certain market clearing results, under which circumstances, the correlations among generators' ramp capacities can be greatly reduced

Impact of EV Cooperation With Conventional Generator There are mainly two factors resulting in the differences between EVs cooperation with the conventional generator and their direct participation. First, EVs will have less capacity to provide the ramp product, if cooperating with the conventional generator first. This could lead to more reservation on ramp capacities for other generators in the system. Second, the cooperation with the conventional generator can help exploit EV ramping capability, and this is well exhibited in Fig. 5.

The upper part of Fig. 5 is quite similar to Fig. 3(a), and in order to obtain the equivalent ramp rate R_g, the energy equal to S_1 will be needed from EVs. However, if the cooperation is not enabled, energy that equals to $S_1 + S_2$ will be needed from EVs to achieve the same equivalent ramp rate. Less energy from EVs is required to achieve the desired ramp rate with the cooperation. This might not be the case if the situation illustrated in Fig. 3(b) happens.

However, the ramp capacity will be rarely called in reality owing to the fact that a high uncertainty event will not happen that often. Therefore, the situation illustrated in Fig. 3(b) rarely happens. Due to the further utilization of EV ramp capability, the cooperation shows some further advantages over EV direct participation in the ramp market. The improvement will be more obvious when the net load uncertainty and variation are increased. Meanwhile, the cooperation shows a potential to help make more profit for both EVs and the designated generator, as illustrated in Table.

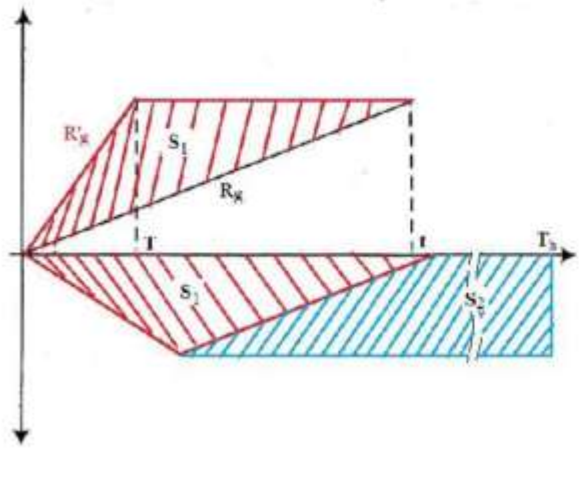

Fig. 5. Difference between EV cooperation with the conventional generator or not.

This analysis assumes that the profit rate is 3% for both EVs and the generator. Such increase in profit can be an incentive for the widespread use and development of EV charging/discharging stations. In addition, the following discusses the impact of EV participation in the ramp market from EV side. During the simulation, we found that although EVs take the majority in the ramp product, they seldom get called to provide energy back to the system, as illustrated in Fig. 5.

Therefore, EVs, in most cases, serve as a backup for dealing with huge uncertainty and variation. This attribute is beneficial for EV operation, since.

1) They do not have to discharge quite often.

2) Their capability of fast ramping up/down can be rewarded accordingly.

3) Their charging can be optimized and charging cost can be reduced

VI. Discussion

ESS would increase the grid reliability by reducing load shedding and improve the grid economics by storing energy at low price hours and generating the stored energy at high price hours. It might also help defer the need for additional grid investments to meet the grid peak load. Specific features of the proposed optimal ESS sizing problem are listed as follows:

TABLE V
TOTAL BENEFIT FOR EVs AND THE GENERATOR

Benefit ($)	Net load Uncertainty and Variation			
	1%	2%	3%	4%
No cooperation	15263	15642	22717	25106
With cooperation	15311	15646	22748	25992
Benefit ($)	Net load Uncertainty and Variation			
	1%	2%	3%	4%
No cooperation	47340	60839	74016	100474
With cooperation	47465	61086	77840	111070

— Optimal ESS sizing: The optimal ESS size in a grid is found which minimizes the total grid cost during the scheduling horizon and satisfies predefined reliability criteria. A planning problem is solved while considering short-term operation constraints. This coordination would offer practical and efficient solutions for the grid planning.

— Economic benefits: Despite high capital investments, the ESS provides economic benefits for grid. ESS offers low cost power to local loads and reduces the need for local generation or energy import from the main grid.

— Reliability consideration: A stochastic approach is used to calculate the grid reliability criterion which employs the Monte Carlo simulation for the modeling of random component outages. The proposed approach considers the grid operations in the base case and contingencies. Load curtailment is enabled in the model to ensure the feasibility of the obtained solution and further determine grid reliability index. ESS provides a viable opportunity for satisfying desired levels of reliability in a grid and could be considered as a quick and efficient solution to the grid reliability problems.

— Practical results: The presented results provide an insight on the application of ESS for improving the economics and the reliability of grids. A variety of energy sources, such as thermal and renewable units, could be included in the model.

— Computational efficiency: The reliability consideration would add additional binary and continuous variables to the planning problem. An efficient MIP model was proposed to find the solution in a reasonable time.

VII. Conclusion

In this paper an accurate model for calculating the optimal ESS size in a grid was proposed. The approach utilized an expansion planning problem, where the ESS investment cost and grid operating cost were taken into account. The reliability index of the system was calculated to ensure reliable operation of the grid by satisfying reliability criterion. An MIP formulation was proposed to effectively calculate the reliability criterion within the optimization problem, resulting in accurate reliability assessment of the grid.

Numerical studies revealed that a larger ESS does not necessarily provide larger economical benefits. There exists an optimal point that the ESS should be installed, where larger ESS sizes might impose higher expansion costs to the smartgrid.

The main contributions of this paper are as follows.
1) Analytical estimate of EV aggregated charging/discharging power capacity taking into account EV stochastic mobility and drivers' behavior.
2) Exploration of EV potential in improving the ramp rate of conventional generators through cooperation.
3) Proposed models to involve EVs into the flexible ramp market, for both EV direct participation and cooperation with generators, with EV charging need and charging/discharging efficiency considered.
4) Proposed new indices to evaluate the power system's flexibility under certain market clearing results.
5) Numerical experiment conducted to understand the impact of EV participation in the ramp market on the system's reliability and flexibility as well as on EVs themselves. The limitation of the proposed market model is the lack of integration of other ancillary services such as reserve, regulation, etc. The possible extensions would be.
1) Improve the market model by integrating other ancillary services.
2) Estimate the aggregated EV availability by nonhomogenous Markov model.
3) Economically evaluate the cost of EVs providing the ramp product.
4) Study the incentive scheme for EV participation in the ramp market.

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