Developing a New Course about Planning and Operation of Plug-In Electric Vehicles in Smart Grid

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1. Introduction

This paper briefly presents the subjects and descriptions of the recently developed undergraduate and graduate courses about planning and operation of plug-in electric vehicles (PEVs) at State University of New York (SUNY), College at Buffalo, Buffalo, NY, US. The courses will be presented in Fall 2020 under the titles of "ENT 473: PEVs in smart grid" and "ENT 573: Planning and operation of PEVs in smart grid" for undergraduate and graduate students, respectively.

The graduate course, that is, ENT 573, includes the latest advancements in the planning and operation of PEVs in smart grid from the viewpoint of independent system operator (ISO), electric distribution company (DISCO), electric generation company (GENCO), PEV aggregator, market retailer, and end-user customer. The planning and operation problems that are studied in this course include charging station placement and sizing in electric distribution system, charging management of PEVs, demand-side management (DSM), generation scheduling and unit commitment (UC), spinning reserve provision, power loss minimization of distribution system, power market participation, and energy scheduling considering the technical specifications of PEVs. The course comprises several chapters that are introduced and described in the following.

In the first chapter, there is an introduction to the current status of energy security, greenhouse gas emissions, and global warming. Moreover, this chapter includes the governments' policies for PEVs development like tax cuts and subsidies. The current status and future of PEVs in auto-market are the other subjects of the introduction chapter.

In the second chapter, PEV technology like PEV types and standards, energy storage systems of PEVs, and concept and standards of grid-to-vehicle (G2V) and vehicle-to-grid (V2G) services are discussed.

The third chapter discusses the threats and opportunities of PEVs for electric power system, presence of PEVs in power market and ancillary services, and concept of PEV aggregator.

The fourth chapter deals with the planning problems of PEVs in smart grid like charging station placement and sizing from a DISCO's viewpoint. The planning problems are studied with the goals of power loss reduction of electric distribution system, distribution system reconfiguration, distribution feeder's congestion management, distributed generation, distribution system expansion postponement, and distribution system reliability improvement.

The operation problems of PEVs in smart grid are studied in the fifth chapter. Herein, the problems are investigated from a GENCO's and a DISCO's point of views. This chapter covers the subjects of charging management of PEVs, DSM, generation scheduling and UC, spinning reserve provision, frequency regulation, and generation system reliability improvement that are studied from a GENCO's viewpoint. In addition, the subjects like distribution system reliability improvement, power loss minimization, system reconfiguration, feeder's congestion management, power market participation, and renewables' power smoothing are studied from a DISCO's point view.

The optimization techniques that are useful in the planning and operation problems of PEVs are studied in the last chapter. These optimization techniques include heuristic optimization algorithms, artificial intelligence optimization techniques, learning-based optimization methods, linear programming, and non-linear programming.

Moreover, in the undergraduate course (ENT 473), just the concepts of the above-mentioned subjects are discussed.

Each course is considered as a regular 3-credit-hour course. Additionally, the course of "Power System Analysis 1" needs to be considered as the prerequisite course for ENT 573. Moreover, the students' learning assessment will be based on students' class participation, assignments, written exams, researches, computer simulation projects (just for ENT 573), and presentations.

2. The Reasons for Addition of the Courses to Curriculum

A considerable portion of energy consumption, carbon emissions, and global warming are related to the transportation sector. Fig. 1 shows the air pollution in Donora, PA, US, on Sep. 19, 2017 [1]. Transportation electrification is seen as one of the solutions to the above-mentioned issues, since PEVs can be charged by the clean and free renewable energy sources. Fig. 2 illustrates a charging station in SUNY Buffalo State College, Buffalo, NY, US.

On the other hand, the governments across the world are implementing tax cuts and financial incentives to accelerate the transition from the internal combustion engine (ICE) vehicles to the electric ones to achieve their own energy security and climate change mitigation goals. Fig. 3 shows the map of fuel cost savings per year for a vehicle in each state of US, when driving on electricity instead of gas [2]. As can be seen, there is a considerable potential to minimize the fuel consumption expenses. The predicted world PEV and ICE vehicle sales are shown in Fig. 4 [3]. As can be seen, it is predicted that the PEV sales will surpass the ICE car sales by 2039.

Consequently, PEVs, as the new electricity consumers, will consume a considerable portion of electricity in the near future. Therefore, students and electrical engineers need to be familiar with the planning and operation techniques of PEVs.

In the following, in Sections 3-4, some of the planning and operation problems of PEVs are presented and described in brief.

Fig. 1. Air pollution in Donora, PA, US, on Sep. 19, 2017 [1].

Fig. 2. A charging station in State University of New York (SUNY), College at Buffalo, Buffalo, NY, US.

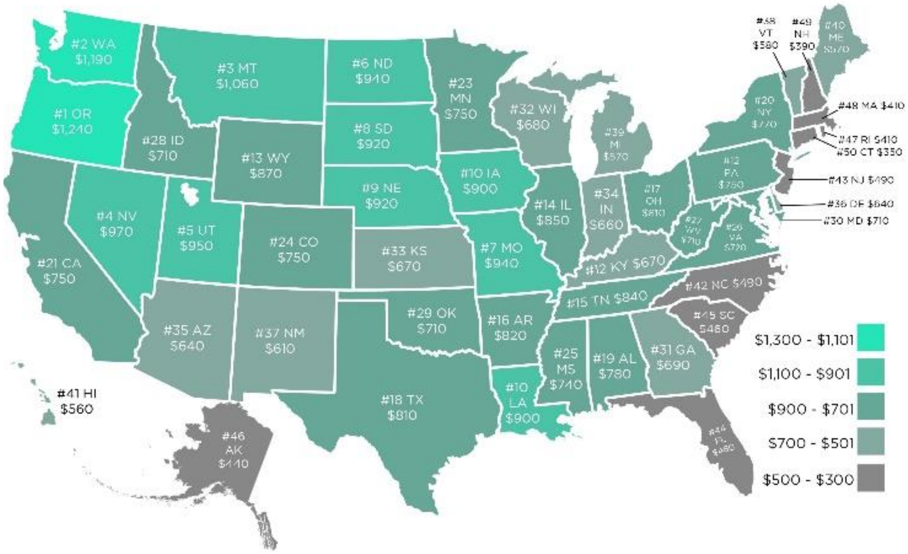
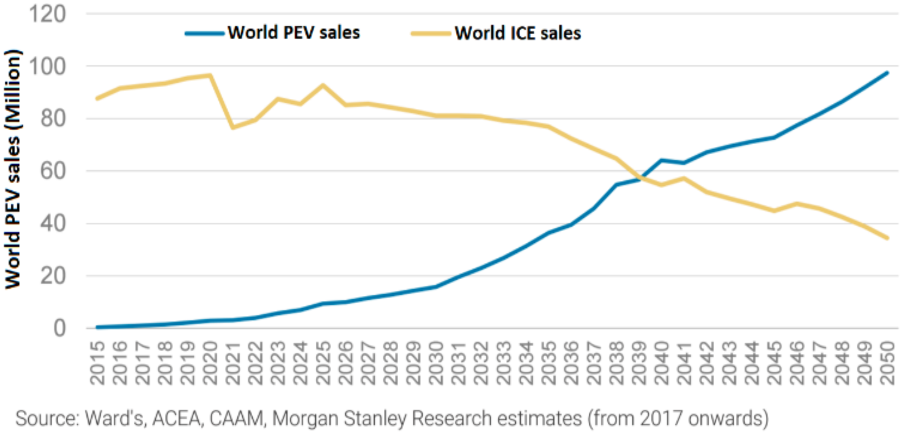


Fig. 3. Map of fuel cost savings per vehicle in the US ($/year) when driving on electricity instead of gas [2].



Source: Ward's, ACEA, CAAM, Morgan Stanley Research estimates (from 2017 onwards)

Fig. 4. A prediction about the world PEV and ICE vehicles sales [3].

3. Planning Problem of PEVs in Smart Grid

3.1. Charging Station Sizing and Placement: Cooperation with a Distribution Company

In this part of paper, the problem of charging station allocation is studied. Fig. 5 shows the electrical single-line diagram of electric distribution system under study and the hourly geographical routes of PEVs in San Francisco, CA, US [4]. The distribution system includes two medium-voltage electrical distribution feeders (F1 and F2) supplied by the 33/11 kV sub-transmission transformer. Each feeder includes a circuit breaker (C.B.) and a recloser (R.C.). Herein, just the first feeder (F1) is studied and the second one (F2) is utilized to transfer part of load of F1 to F2 during the fault occurrence using the normally open switch. The probability of transferability is considered about 60%. The system includes 28 electrical distribution buses and 27 branches. The buses supply different electricity consumers including the residential (Res), commercial (Com), and industrial (Ind) customers. Moreover, the system includes six normally close switches in the beginning of branches to isolate the faulty zone. The other specifications of system and problem have been presented in reference [4].

Minimizing the total cost of planning problem by optimal allocation of charging stations in the distribution system, while considering the economic factors such as inflation and interest rates, is the objective function of this study. Fig. 6 shows the results of problem simulation that include the optimal hourly size and location of charging stations in the typical day [4]. As can be seen, charging stations with different sizes are allocated in the specific buses of electric distribution system. Moreover, the size of charging stations needs to change during the day, and even some of charging stations do not accept any PEV in some intervals.

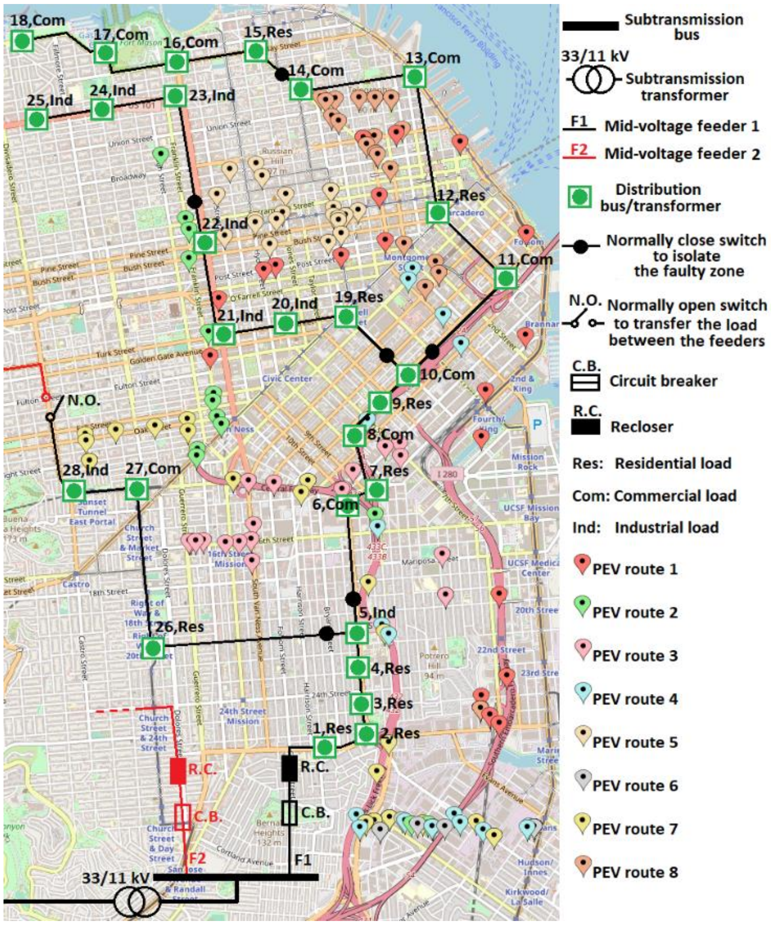


Fig. 5. The single-line diagram of electrical distribution system and the hourly geographical position of PEVs in San Francisco, CA, US [4].

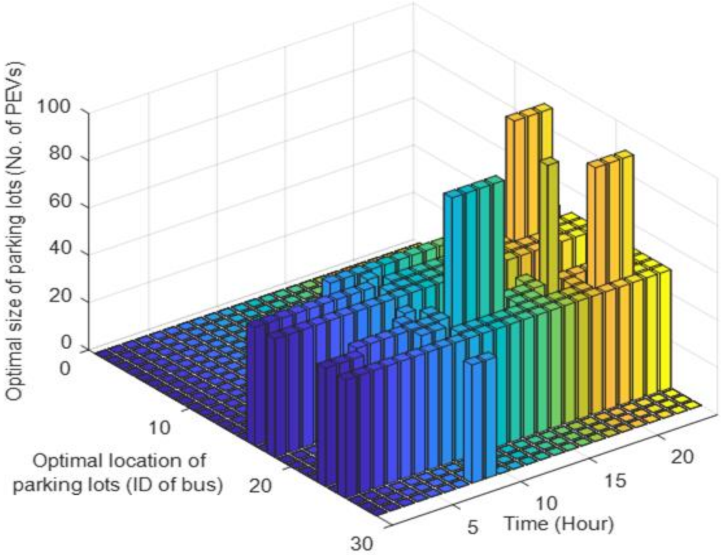


Fig. 6. The optimal hourly size and location of charging stations in the typical day [4].

4. Operation Problems of PEVs in Smart Grid

4.1. Demand-Side Management: Cooperation with an Independent System Operator

Fig. 7 graphically shows different programs of DSM and their performance. In this part of the paper, the effect of implementation of load shifting program on the demand profile of Electric Reliability Council of Texas (ERCOT) is studied. In this program, the PEV drivers are encouraged to transfer part of their charging demand from the peak period to the valley period. This type of DSM has many advantages for the ISO, like ERCOT, as well as generation, transmission, and distribution systems. Herein, the optimal value of incentive (discount on charging fee which is considered for the PEV drivers to participate in the load shifting program) and the maximum value of load factor are investigated for various PEV penetration levels (low, moderate, and high).

All the details of problem have been presented in [5]. Table 1 shows part of the problem simulation results. As can be seen, different values of incentive need to be assigned, where the more PEV penetration, the less incentive. As is noticed, the load factor of ERCOT is raised from about 92% to around 96% by optimal implementation of DSM for PEVs. Fig. 8 illustrates the hourly PEVs demand, loads demand, and total demand profile of ERCOT before and after optimal implementation of DSM for PEVs considering low, moderate, and high PEV penetration levels.

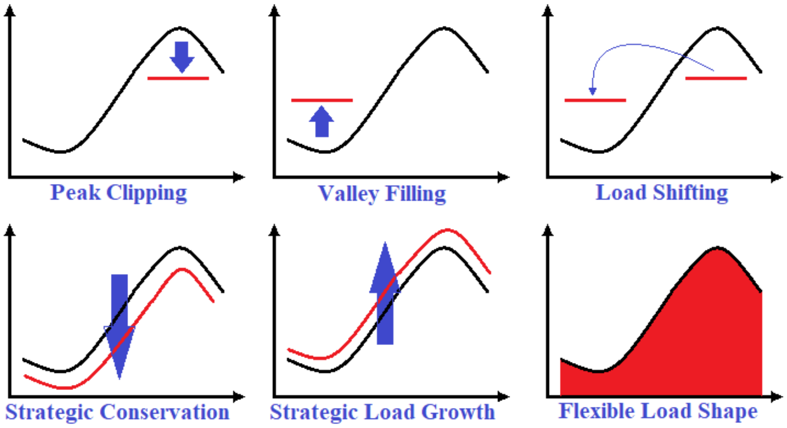


Fig. 7. DSM programs and their performance.

Table 1. Optimal value of incentive and maximum value of load factor before and after optimal implementation of DSM for different PEV penetration levels in ERCOT [5].

Outputs	DSM	Low penetration	Moderate penetration	High penetration
Optimal incentive (%)	Before	0		
	After	70	40	20
Optimal load factor (%)	Before	92.11		
	After	96.57	96.51	96.07

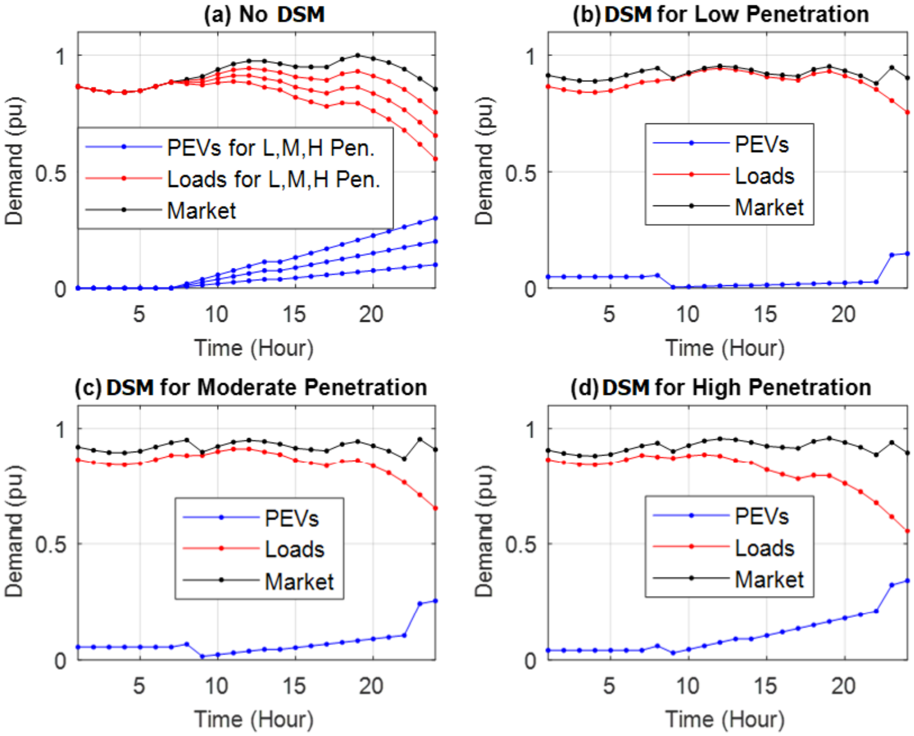


Fig. 8. Hourly demand profile of ERCOT market. (a) Demand profiles before DSM for low (L), moderate (M), and high (H) PEV penetration levels. Demand profiles after optimal DSM (b) for low PEV penetration (with 70% discount as the optimal incentive), (c) for moderate PEV penetration (with 40% discount as the optimal incentive), and (d) for high PEV penetration (with 20% discount as the optimal incentive) [5].

4.2. Minimizing Power Generation Cost: Cooperation with a Generation Company

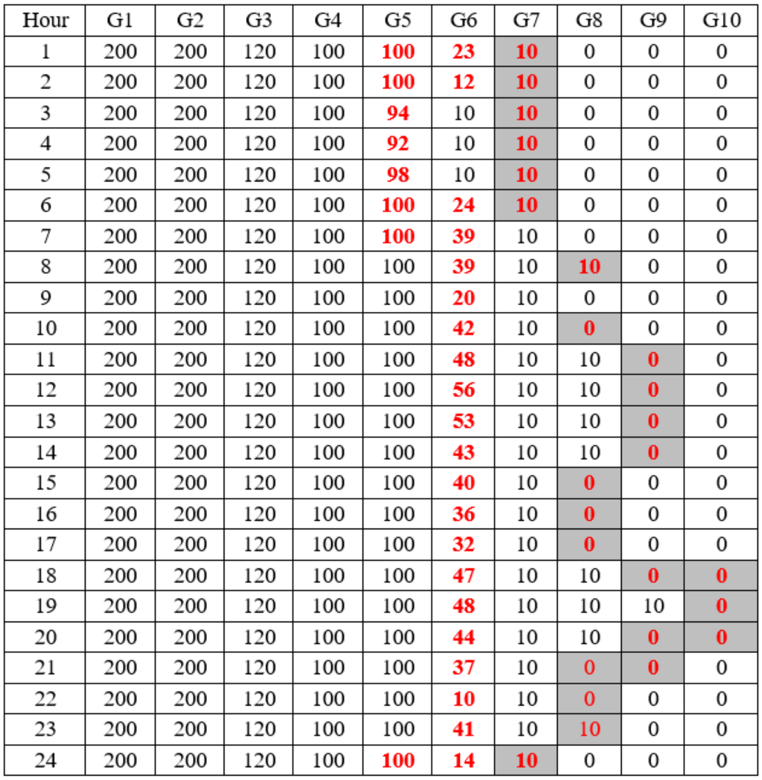
In this part of study, the PEVs are involved in the generation scheduling and UC problems to minimize the total power generation cost of a GENCO. All the details of the problem and specifications of the generation system have been presented in reference [6]. Table 2 presents part of the problem simulation results. As can be seen, the primary value of minimum total cost of problem is about 0.55050 million $/day; however, after optimal fleet management (FM) of PEVs, it decreases for any PEV penetration level.

Table 3 presents the optimal generation scheduling and commitment of generation units after optimal FM of PEVs considering a high PEV penetration level. The quantities in red color and the highlighted squares indicate the differences in the generation scheduling and commitment of units compared to the problem results without FM of PEVs, respectively. As is noticed, the generation scheduling of units G5-G10 as well as the commitment of units G7-G10 have changed by optimal FM of PEVs. The reasons for these outcomes are that the most expensive and pollutant generation units (G8-G10) have been shut down or their generation level have reduced during the peak period, and the commitment and generation level of the least expensive and least pollutant units (G5-G7) have increased during the off-peak period.

Table 2. Optimal amount of incentive and minimum total cost of problem with/without optimal FM of PEVs considering different PEV penetrations [6].

Outputs	Before FM	After FM		
		Low penetration	Moderate penetration	High penetration
Optimal incentive (%)	0	20	30	10
Incentive cost ($)	0	444	2258	902
UC cost (Million $/day)	0.55050	0.54699	0.54147	0.54250
Minimum total cost (Million $/day)	0.55050	0.54743	0.54373	0.54341
Cost saving ($/day)	-	3062	6766	7089

Table 3. Optimal generation scheduling and commitment of generation units after optimal FM considering a high PEV penetration level [6].



Hour	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
1	200	200	120	100	100	23	10	0	0	0
2	200	200	120	100	100	12	10	0	0	0
3	200	200	120	100	94	10	10	0	0	0
4	200	200	120	100	92	10	10	0	0	0
5	200	200	120	100	98	10	10	0	0	0
6	200	200	120	100	100	24	10	0	0	0
7	200	200	120	100	100	39	10	0	0	0
8	200	200	120	100	100	39	10	10	0	0
9	200	200	120	100	100	20	10	0	0	0
10	200	200	120	100	100	42	10	0	0	0
11	200	200	120	100	100	48	10	10	0	0
12	200	200	120	100	100	56	10	10	0	0
13	200	200	120	100	100	53	10	10	0	0
14	200	200	120	100	100	43	10	10	0	0
15	200	200	120	100	100	40	10	0	0	0
16	200	200	120	100	100	36	10	0	0	0
17	200	200	120	100	100	32	10	0	0	0
18	200	200	120	100	100	47	10	10	0	0
19	200	200	120	100	100	48	10	10	10	0
20	200	200	120	100	100	44	10	10	0	0
21	200	200	120	100	100	37	10	0	0	0
22	200	200	120	100	100	10	10	0	0	0
23	200	200	120	100	100	41	10	10	0	0
24	200	200	120	100	100	14	10	0	0	0

4.3. Minimizing Spinning Reserve Provision Cost: Cooperation with a Generation Company

Herein, the PEVs participate in the spinning reserve provision problem, and compete with the generation units to provide spinning reserve capacity. The details of study can be found in reference [7]. Part of the problem simulation results are presented in Fig. 9 and Table 4.

Figs. 9.a and 9.b show the hourly spinning reserve capacity in the normal condition provided by the generation units and PEVs, before and after optimal FM of PEVs (30% incentive), respectively. Moreover, Fig. 9.c illustrates the hourly amount of difference in the total spinning reserve capacity of system before/after FM. In addition, daily spinning reserve capacity percentage provided by the generation units and PEVs in the normal condition is shown in Fig. 9.d [7]. As can be seen, a considerable daily amount of spinning reserve capacity is granted to the PEVs. Table 4 presents the other simulation results of problem [7]. As can be seen, by optimal FM of PEVs, remarkable cost saving is acquired for each PEV penetration level.

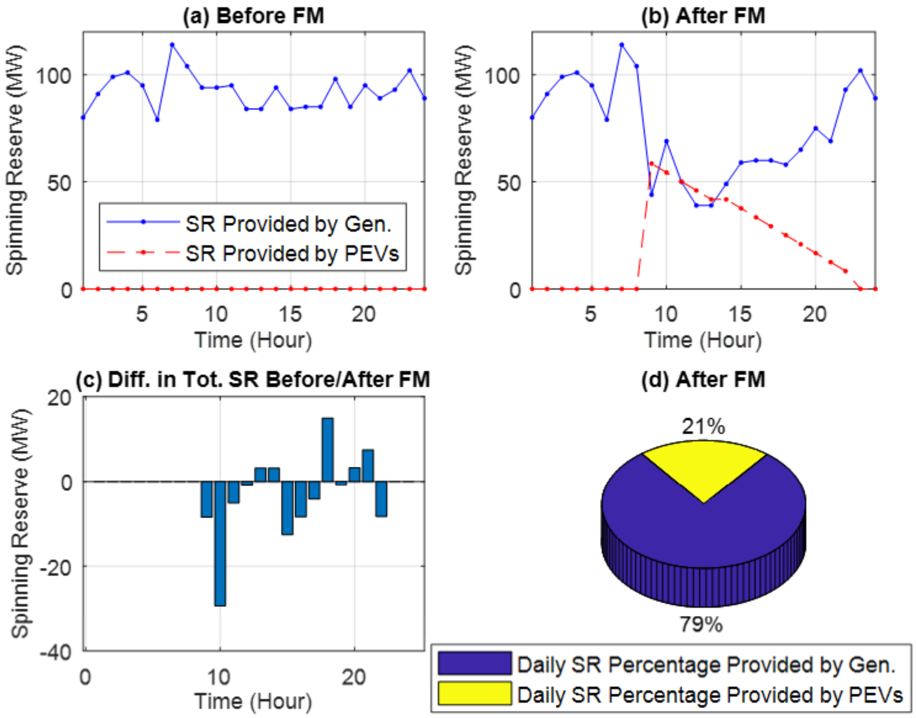


Fig. 9. Optimal hourly spinning reserve (SR) capacity (MW) in the normal condition provided by the generation units and PEVs (a) before and (b) after FM (30% incentive). (c) Value of difference (MW) in the hourly total spinning reserve capacity of system before/after FM. (d) Daily spinning reserve capacity percentage provided by the generation units and PEVs in the normal condition [7].

Table 4. Problem simulation results before and after optimal FM considering different PEV penetration levels [7].

Outputs	Before FM	After optimal FM		
		Low penetration	Moderate penetration	High penetration
Optimal incentive (%)	0	10	30	30
Incentive cost in normal condition ($)	0	169	2121	3535
Incentive cost in contingency ($)	0	2	23	39
Minimum total cost (Million $/day)	0.55050	0.54739	0.54360	0.54019
Cost saving ($/day)	-	3109	6895	10305

4.4. Minimizing Distribution System Operation Cost: Cooperation with a Distribution Company

In this part of paper, the charging/discharging pattern of PEVs is optimally managed to minimize the operation cost of electric distribution system that includes the cost terms of power loss cost, energy-not-supplied (ENS) cost, system reconfiguration cost, FM cost, and energy storage systems' (ESS) operation cost.

Fig. 10 shows the geographic and single-line diagram of electric distribution system that includes one sub-transmission substation, four distribution feeders (DFs 1-4), four initially close switches, three initially open switches, 47 distribution buses, four charging stations (installed on the 2nd bus of 1st feeder, 10th bus of 2nd feeder, 12th bus of 3rd feeder, and 13th bus of 4th feeder), four wind turbines (WT1-WT4), and four ESSs (installed on 12th bus of 3rd feeder, 13th and 15th bus of 4th feeder, and 11th bus of 2nd feeder). The other details of problem and system have been presented in reference [8].

Table 5 presents part of the problem simulation results. As can be seen, there are remarkable reductions in the value of total operation cost, energy loss, and ENS. Fig. 11.a illustrates the optimal amount of incentive proposed to the PEV drivers to let the DISCO charge (G2V) and discharge (V2G) their vehicles based on the optimal pattern. Moreover, Fig. 11.b shows the hourly amount of G2V and V2G powers in each charging station.

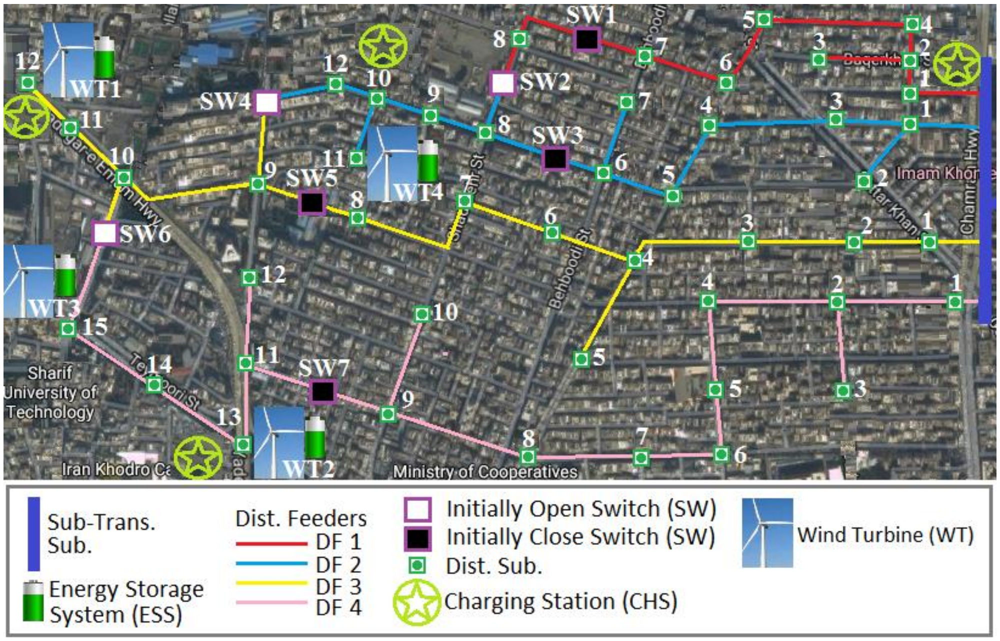
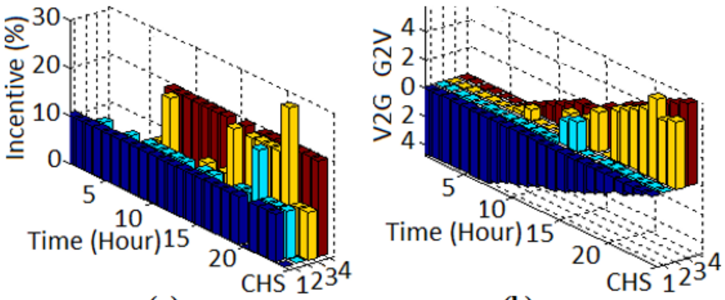


Fig. 10. Geographic and single-line diagram of the electric distribution system [8].

Table 5. Problem simulation results before and after optimal operation of system [8].

	Operation cost ($/day)	Energy loss (MWh/day)	ENS (MWh/day)
Before	18759	367.90	0.3499
After	11806	191.27	0.2932



(a) (b)

Fig. 11. (a) Optimal amount of incentive proposed to the PEV drivers. (b) Hourly amount of G2V and V2G powers in each charging station [8].

4.5. Participating in Energy Market: Cooperation with an Aggregator

In this section, PEV drivers participate in the energy market by means of an interface which is called aggregator. The aggregator has the role of interacting with both drivers and electricity market operator. All the details of problem can be found in reference [9]. Part of the problem simulation results is presented in Table 6 [9]. As can be seen, the profit of aggregator is raised from $558/day to $794/day, $951/day, and $1051/day for low, moderate, and high PEV penetrations, respectively.

Table 6. The problem simulation results considering different PEV penetration levels [9].

Outputs	Before operation	After optimal operation		
		Low penetration	Moderate penetration	High penetration
Optimal incentive (%)	0	70	40	40
Incentive cost ($)	0	139	136	228
Income ($/day)	558	934	1088	1279
Maximum profit ($/day)	558	794	951	1051
Enhancement ($/day)	-	236	393	492

5. Conclusion

In this paper, the subjects and descriptions of the newly developed 3-credit-hour undergraduate and graduate courses about planning and operation of PEVs (ENT 473 and ENT 573, respectively) at SUNY Buffalo State were presented. It was mentioned that the undergraduate course has been developed to teach the concept and basis of planning and operation problems of PEVs in smart grid. However, the graduate course aims at performing researches, studying, carrying out projects, simulating the problems, and analyzing the results of different planning and operation problems of PEVs in smart grid. Moreover, the problems need to be studied from the viewpoints of ISO, DISCO, GENCO, PEV aggregator, and end-user customer. In addition, "Power System Analysis 1" is a prerequisite course for ENT 573.

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