The improved low cost grid connected EV charging station with PV and energy storage systems

Nedim Tutkun
Electrical & Electronics Eng.
Istanbul Ticaret University
Istanbul, Türkiye
ntutkun@ticaret.edu.tr

Shamsul Aizam Zulkifli, Zarafi Bin Ahmad
Electrical Power Engineering
Universiti Tun Hussein Onn Malaysia
Johor, Malaysia
aizam@uthm.edu.my, zarafi@uthm.edu.my

***Abstract*—Recently electric vehicles (EVs) have increasingly been used for transportation due to low cost operation and less carbon emission. However, major disadvantages of EVs are charging time, range and overloading the grid, and the latter may lead to instability in the grid when a vast number of EVs are simultaneously charged from the grid. One solution to this may be to charging times and to share amount of charging power through photovoltaic (PV) and energy storage (ES) systems with minimum cost. In this study, a 20 kW grid tied charging station with PV and ES systems is designed to charge EVs with minimum cost for the hourly changing electricity price through a variety of charge options such as grid to EV, ES to EV, PV to EV, EV to EV etc. This is achieved by optimizing charge start times and facilities using metaheuristic based computational algorithms. The proposed approach worked well and results obtained are encouraging and meaningful for the case study**

Keywords— Electric vehicles; charging station; energy storage; photovoltaic; metaheuristic techniques.

I. INTRODUCTION

The rapid increase in the number of EVs on the roads has come up with a fundamental problem of fast, safe and low cost charging. The solution to this problem may be that EV owners or local authorities can install fixed or mobile charging stations with PV and ES systems on highways or in common areas of apartments. A PV system can be considered as an ideal solution for charging EVs because it can be built easily and electricity generation mostly available during daytime when electricity is usually the most expensive. However, the PV system is unable to supply constant power for EV charging due to change in solar radiation within daytime. Therefore, when PV power is lacking power required for charging an EV should be shared with other power sources such as grid, an ES system etc. Under all these conditions, charging an EV with minimal cost requires solving a complex multi-objective problem. A few studies in the literature on this subject are mentioned below.

Samir et al carried out a study about system design and practical implementation of level-2 solar powered EV charging station. The designed model is simulated in MATLAB/Simulink environment and analyzed from many aspects [1]. In another study, Chengzhe et al investigated on robust model of EV charging station considering renewable energy and storage equipment [2]. Zhou et al worked on a social cost model and calculated the total operation cost of charging stations under various distribution conditions [3]. Another investigation such as by Ahmad et al was carried out to optimally place the solar-powered charging stations and to reduce power loss and charging cost to an acceptable level [4]. Another study such as by Vanadana et al investigated on a charging station for EV integrated with an ES with enhanced grid power quality [5]. The EV and ES are connected at DC link using a bidirectional buck-boost converter. During the daytime, the EV takes power from the solar PV array while in its absence it consumes the power from the grid. Further, when the system is connected to the grid, the point of common coupling voltages synchronizes with the voltages of the grid.

In order to utilize solar PV system integrated into EV charging station, a typical PV array and ES were designed and developed in another study carried out by Dai et al in which they proposed an optimal model for EV charging station including grid-connected PV-ES systems [6]. In another investigation, Yan et al proposed an algorithm to aim to reduce operational cost by taking account the potential uncertainties, while balancing the real-time supply and demand by adjusting the optimally scheduled charging and discharging of EV and ES as well as grid supply and deferrable load [7]. The algorithm works well for unpredictable conditions and provides more incentives for EV users while lessening cost. Zia et al carried out an investigation on optimal scheduling and techno-economic analysis of EVs using solar PV powered and grid-tied charging station using the HOMER software package [8]. The proposed model also considers seasonal variation effects of power generation and the uncertainties of EV charging connectivity. Liu et al studied about the design of optimal size of PV and ES in an extremely fast EV charging station considering the coordinated charging strategy of the electric vehicles [9]. In the proposed model, the annualized cost of the extreme fast charging station, including investment and maintenance cost of PV and energy storage, cost of purchasing energy from utility and demand charge are aimed to minimize. Tercan et al investigated a study presenting an electrical, environmental, and financial results of optimum microgrid design that consist of 200 apartments, 200 electric vehicles, battery storage systems and electric vehicle charging stations powered by PV panels, considering interruption and failure scenarios [10].

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Unlike the above studies, in this study a grid-tied charging station with PV and ES systems is used to charge an EV with minimum cost under the hourly changing electricity pricing. This is achieved by optimizing charging times and facilities using metaheuristic based computational algorithms such as the genetic algorithms in MATLAB environment.

II. SYSTEM DESCRIPTION

A. Definition of Charging System

The charging system as shown in Fig. 1 considers a regular parking mode of EVs in which EVs are expected to be charged between 09.00 and 18.00 hours. The owners of these EVs use their cars go to their workplace and go back to their homes in working days. They strictly leave their cars in the parking lot before 9.00 hours and pick up their cars after 18.00 hours. The parking lot has availability to supply the required power from grid, the PV array and the ES unit and it is coordinated by an intelligent energy controller. In order to minimize the charging cost in the parking lot, an intelligent charging management system that controls the charging process of EVs. The charging time for each EV can be calculated by its arrival time, departure time and charging demand. With this input data, start time slot for charging can be optimized to minimize the charging cost of the system. Each EV in the parking lot can be charged up to 90% of its battery capacity and for the efficiency of EV batteries, vehicle-to-grid is not taken account.

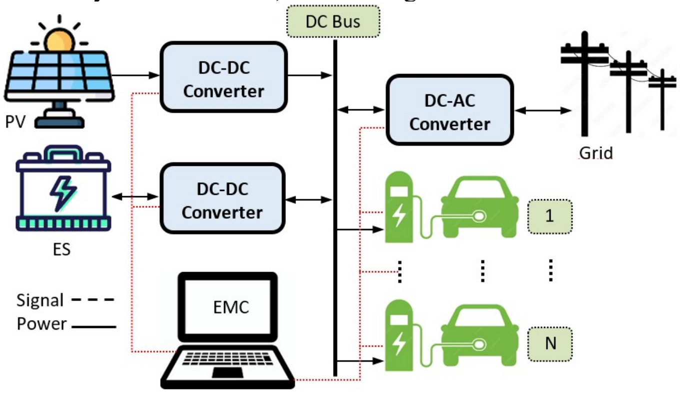

Fig. 1. PV-ES-grid charging system for EVs.

The start charging time for each EV is optimized and their minimum costs are computed based on the hourly changing electricity price. Intermittent charging of EVs within a given range from 09.00 to18.00 helps moderate both cost and power drawn from the grid. In other words, this results in minimizing the peak to average ratio (PAR) that may be considered to be another objective with the charging cost together. In the optimization process, the minimum charging time is 1 hour or 1 slot, and the EV's charging must not be interrupted during this period. The charging action for each EV can be represented by a binary number as shown in Figure 2 in which EV1 and EV2 have 3-h and 4-h charging demands.

Slot	10	11	12	13	14	15	16	17	18
EV1	0	1	0	1	0	0	1	0	0
EV2	0	0	1	0	0	0	1	1	1

Fig. 2. Binary representation of EV charging in the given time range.

It should be noted that the earliest start time for charging is 09.00 and the end time is 18.00, that is, EVs must be charged over a period of 9 slots to meet their energy demands. It should also be emphasized that each EV is charged with a constant power during each 1-h slot time. The charging system is composed of a 20-kWh ES unit, a 20-kWp solar PV array with a maximum power point tracker (MPPT), a bi-directional DC-AC converter, a bi-directional DC-DC converter with a battery management system (BMS), a bi-directional DC-DC converter, an intelligent energy management controller (EMC), the BMS nd the on-site monitoring system for charging and discharging in the ES unit under full-load conditions.

B. Operation of the Entire System

A day is divided into 24 equal spaces, and each space is called a slot. The first slot corresponds to the time interval between 0.00 and 1.00 hours. Electricity prices change hourly as shown in Figure 3 and PV power at each slot as illustrated in Figure 4 is calculated based on hourly averaged solar radiation [5]. Both day-ahead electricity price and solar radiation data are obtained from the utility and the local weather station, respectively, at 23:00 before the new day begins. If there are EVs to be charged in any slot, the power generated by the PV array is directly transferred to the EVs. If PV power is more than the power required by the EVs, the surplus power is stored in the ES system if the ES system is rechargeable, the ES system is charged and the remaining power is transferred to the grid. If there are no EVs to be charged at the station, the power generated by the PV array is directly delivered to the grid. If the power produced by the PV array is below the demanded power, the required power is first met from ES but if the ES unit does not supply the required amount of power, the lack of power is supplied from the power grid.

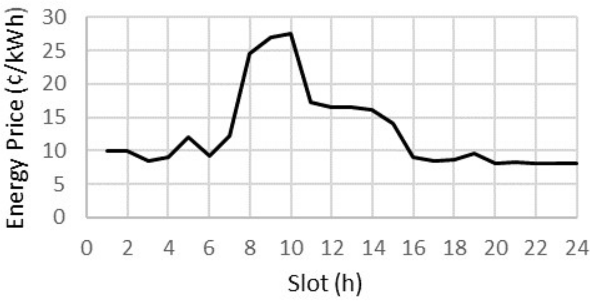

Fig. 3. The hourly changing electricity price.

Here, the most important thing to consider when using power from ES is the energy price. Because, if the energy price purchased from the utility is more expensive than the daily average energy price, the short of power is supplied by the ES unit within the allowed limits. If the opposite is the case, the lack of power is met directly from the grid. Although the ES unit is charged from the grid during slots when energy price is less than the daily average electricity price, it is used to charge EVs during slots when electricity price is more expensive than the daily average electricity price. The PV system consists of 40 half-cut 500 W panels installed on the roof of the home and includes a tracking system to ensure the maximum power generation under varying ambient conditions. As seen from Figure 4, the generated power is the highest between 12.00 and 16.00 hours [5]. Let S be a set of time slots and it can be defined by S={ 1,2,3,…,24 }. It is apparent that the power produced by the PV array mainly depends on the SR and the energy produced at slot t is calculated by:

$$E_{PV}^{(t)} = G^{(t)} S \Delta t \eta_{PV} \quad (1)$$

where $G^{(t)}$, S, Δt and η_{PV} are the amount of SR coming to the surface, surface area, time period in hours and PV efficiency respectively.

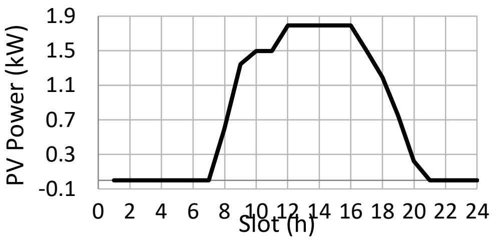

Fig. 4. PV power variation with time slot.

Energy storage capacities for EVs varied from 22 kWh to 100 kWh is given in Table 1 and they are charged by 11-kW charger at 400-VAC. EVs are subject to uninterrupted charging at the station and the charging time is minimum 1 hour and maximum 4 hours. According to the predicted scenario, the owners of EVs are people who work in offices close to the charging station and they bring their EVs to the charging station by 08.45 in the morning. These EVs are charged and made ready at the lowest cost in suitable slots for the specified period between 09.00 and 18.00.

TABLE I. THE LOAD PROFILES OF EVS

Specified Data for Charging EVs				
EVs	Capacity(kWh)	Length(h)	Demand(kWh)	Range(km)
EV1	55	2	22	395
EV2	22	1	11	190
EV3	69	3	66	415
EV4	84	3	66	582
EV5	84	3	66	582
EV6	100	4	88	560
EV7	100	4	88	658
EV8	99	4	88	500
EV9	82	3	66	481
EV10	82	3	66	476

III. MATERIAL AND METHODS

The problem definition and optimization process are particularly described from few aspects.

A. Problem Definition

As it is known, one of the primary issues in charging EVs is to maintain the charging cost as low as possible under the circumstances. This is only possible by solving an optimization problem that mainly includes 2 objectives such as the charging cost, the PAR etc. The cost is the primary objective of the optimization problem.

The cost objective function can be considered to be a fitness function that may be expressed as

$$C = \sum_{t=1}^{24} \begin{pmatrix} \left(C_{B2G}^{(t)} E_{G2EV}^{(t)} + C_{PV} E_{PV2EV}^{(t)} + C_{B2G}^{(t)} E_{G2ES}^{(t)}\right) \\ -\alpha C_{B2G}^{(t)} \left(E_{ES2G}^{(t)} + E_{PV2G}^{(t)}\right) \end{pmatrix} \quad (2)$$

where $C_{B2G}^{(t)}$ is the unit cost of energy purchased from the utility at the slot t, $E_{G2EV}^{(t)}$ is energy delivered to the EVs from the utility at the slot t, C_{PV} is the unit cost of energy delivered to the EVs from the PV array, $E_{PV2EV}^{(t)}$ is the energy delivered to the EVs from the PV array, $E_{G2ES}^{(t)}$ is the energy delivered to the ES from the utility, $E_{ES2G}^{(t)}$ is the energy delivered to the utility from the ES, $E_{PV2G}^{(t)}$ is the energy delivered to the utility from the PV array and α is the price ratio which is assumed to be 0.8 for this study. A maximum of 1 kWh of energy can be charged or discharged to/from the ES at the slot t and the charging and discharging efficiency of the ES is 0.95.

The normalized fitness function of the single objective optimization for the cost can be expressed as

$$C_T = \frac{\sum_{t=1}^{24} \begin{pmatrix} \left(C_{BG}^{(t)} E_{G2EV}^{(t)} + C_{PV} E_{PV2EV}^{(t)} + C_{BG}^{(t)} E_{G2ES}^{(t)}\right) \\ -\alpha C_{BG}^{(t)} \left(E_{ES2G}^{(t)} + E_{PV2G}^{(t)}\right) \end{pmatrix}}{C_{T_{max}}} \quad (3)$$

where $C_{T_{max}}$ is the maximum possible total daily cost of 837.4¢. Note that if the ES and PV systems are unavailable, $E_{ES2G}^{(t)} = 0$ and $E_{PV2G}^{(t)} = 0$. Since the main objective is to minimize the daily cost, Equation (3) is rearranged to construct the normalized fitness function of the daily cost that can be expressed as

$$f_{C_T} = \min(C_T) \quad (4)$$

The 2nd objective, PAR, can be calculated by dividing the maximum power demand at time slot t by the average power demand for EVs and it can be stated by

$$PAR = \frac{\frac{Max\left\{\left(\sum_{i=1}^{n} p_{EV_i}^{(t)}\right)\right\}}{P_{ave}}}{PAR_{max}}, \quad \forall t \in S \quad (5)$$

where PAR_{max} is the maximum PAR being 32.375 kW. Thus, the normalized fitness function of the PAR can be expressed as

$$f_{PAR} = \min\ (\ PAR\ ) \qquad (6)$$

It is now possible to create a single fitness function with the weighting coefficients to be selected appropriately by using the objective functions mentioned above. Thus, the combined fitness function is expressed as

$$f = \min\ \left(\ \omega_1 f_{C_T} + \omega_2 f_{PAR}\right) \qquad (7)$$

In the case of the single objective optimization, $\omega_1 = 1$ and the other weight coefficient is zero.

If the cost and the PAR objectives are simultaneously optimized, the weight coefficients should be chosen to meet the constraint $\omega_1 + \omega_2 = 1$, e.g. $\omega_1 = 0.8$, $\omega_2 = 0.2$. The weighting coefficients varied from 0.1 to 0.5 to see their effect on the objective functions. For instance, as the weight coefficient decreases, the optimal value of the objective function increases or vice versa.

B. Optimization Process

On-off control plays an important role in energy management to achieve the lowest possible charging cost for the hourly electricity price. However, in order to find the lowest cost, it is necessary to perfectly model the problem under consideration and to use a more appropriate method for it. It is apparent that the binary coded genetic algorithms (BCGA) may be more convenient technique for on-off controlled optimal energy management in particular, to charge EVs in a parking lot. The BCGA begins with a randomly created initial population with binary numbers of a pre-defined bit length so-called binary strings. The fitness of each string is calculated by the fitness function. A new population is created by selecting the strings based on their fitness values through the tournament selection. The strings in the selected population have no change with the strings in the previous population. The tournament size is limited to two strings, and since the problem addressed here is a minimization, the string that gives the smallest fitness for two randomly selected strings compared is selected and this process is continued until the number of strings in the previous population is reached. It is a fact that the average fitness of the selected population is always greater than the previous population. The selected population is then subjected to crossover, which is the most effective operator of the genetic process, to create more different strings. The crossover is differently performed from the known crossover techniques such as the single point, the two-point, uniform etc. When the two-point crossover is applied to two binary strings with the probability of 0.6, the resulting strings produce illegal strings in some cases. A special repairing procedure is used to avoid illegal strings caused by crossover is given in Algorithm 1.

Algorithm 1: A special repairing procedure to avoid illegal strings

1. Enter the two binary strings and determine the number of elements for each string.
2. If the first element of the strings is equal to 1, find the indices corresponding to the ones in the strings.
3. Create new strings of zeros in the same size of the old strings and increment the indices by 1 and set the values corresponding to these indices to 1.
4. If the last element of the string is equal to 1, find the indices corresponding to the ones in the strings.
5. Create a new string of zeros in the same size of the old string.
6. Decrement the indices by 1 and set the values corresponding to these indices to 1.
7. If (2) and (4) are not the case, generate a random number between 0 and 1.
8. If the number is greater than and equal to 0.5, find the indices of string corresponding to 1 and create a new string of zeros in the same size of the old string. Increment the indices by 1 and set the values corresponding to these indices to 1.
9. If the number is less than 0.5, find the indices of string corresponding to 1.
10. Create a new string of zeros in the same size of the old string and decrement the indices by 1 and set the values corresponding to these indices to 1.

IV. Results and Discussions

The proposed approach, developed was carried out for two main scenarios. One is that EVs are charged from the grid without using additional sources such as PV, wind turbines, fuel cells, batteries etc. The other is that EVs are charged by PV and ES systems as well as grid. Ten popular EVs on the market are selected for the proposed method to find minimum charging cost. The algorithm of the crossover applied in this study is given in Algorithm 1 [5]. After the crossover operation the reciprocal mutation is implemented on the current population with the probability of 0.1. The elitist strategy is also applied to pass the best to the next generation.

The results obtained are given in graphs throughout the section and are discussed from various aspects. Figure 5 shows EV charging from the grid at different time slots. The abbreviations GL1, GL2 and GL3 given in the graphs indicate the amount of power drawn from the grid if the weight coefficient pairs for cost and PAR are (1.0, 0.0), (0.8, 0.2) and (0.5, 0.5), respectively. Similarly, the abbreviations C1, C2 and C3 indicate daily charging costs for each weight coefficients respectively. M1 symbolizes the model of the charging station that is fed only from the grid, and M2 denotes the model of the charging station that is supplied from PV and ES systems as well as the grid.

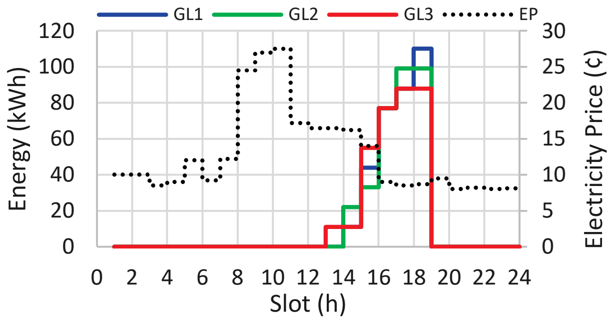

Fig. 5. Power absorbed from the grid in M1.

As seen in Figure 5, the power delivered to the load varies with different weight coefficients. In the pure cost case (GL1), the power drawn from the grid occurs in the intervals when the electricity price is lower. For instance, the power absorbed from the grid is 110 kWh in the case of GL1, but in the case of GL3 where the weight coefficients are 50% and 50%, the power drawn from the grid is 88 kWh. That is, if it is desired to reduce cost and PAR together at the same rate, some increase in cost is expected. In the optimization process, it is necessary to see the change of the fitness function shown in Figure 6 with the number of generations to see the reliability of the results obtained. If taken into consideration here, the fitness function is considered to be the charging cost. As seen from the figure, in the cases of C1, C2 and C3, it appears that the cost converges to its minimum of $32 following the 32nd generation. If the charging station is fed from the grid by supplementing it with PV and ES systems, the power drawn from the grid decreases, as seen in Figure 7. Here, while the energy drawn from the grid is 79 kWh, this value has decreased by 28% compared to previous case value of 110 kWh. This is already an expected situation. As can be seen from the graph, the energy drawn from the grid occurs in slots where the electricity price is low, similar to the first situation. This is what should happen as a requirement of the optimization algorithm.

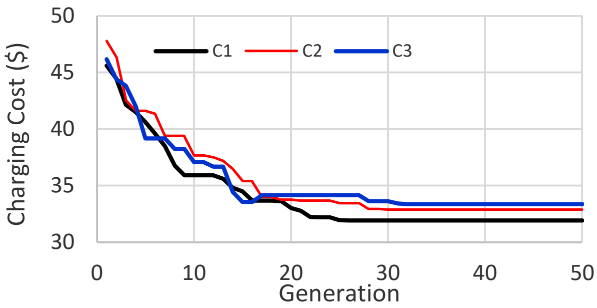

Fig. 6. Variation of the charging cost with the number of generations in M1.

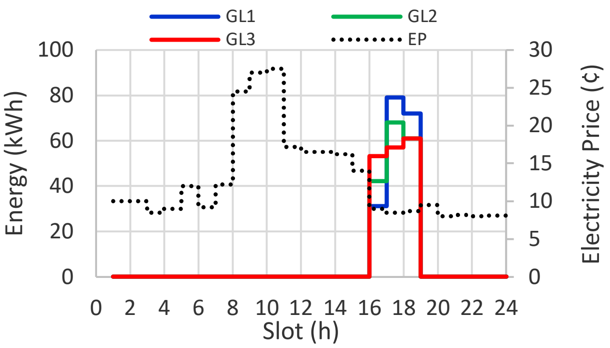

Fig. 7. Power absorbed from the grid in M2.

In the optimization process, it is essential to see the variation of the fitness function shown in Figure 8 with the number of generations to verify the results achieved. Here, the fitness function is considered to be the charging cost. As seen from the figure, in cases C1, C2 and C3, it seems that the cost converges to its minimum of $7 following the 35th generation.

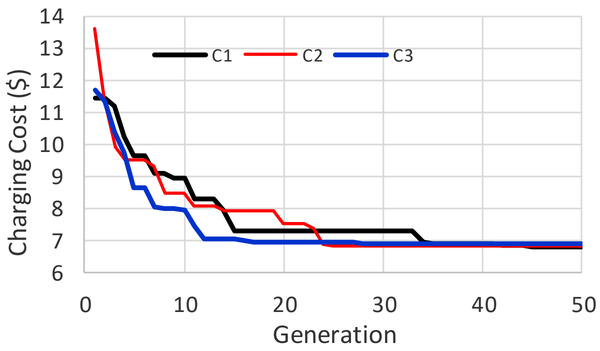

Fig. 8. Variation of the charging cost with the number of generations in M2.

When the results obtained from the two proposed models are compared based on the energy drawn from the grid as given in Figure 9, PV and ES systems significantly reduce the energy consumption. This is important in two respects. The first is that the charging station reduces the charging cost, and the second is that it prevents the power network from being overloaded. Although PV and ES systems have installation and maintenance costs, this disadvantageous situation can be tolerated due to the system life of 20-25 years.

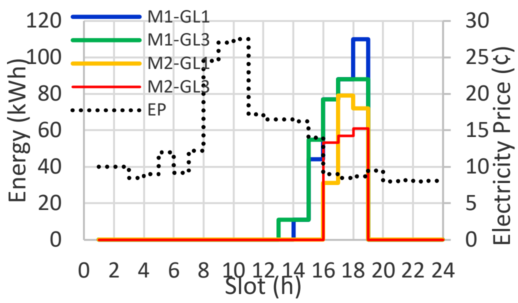

Fig. 9. Comparison of power absorbed from the grid in M1 and M2.

Conclusions

Achieving best cost minimization depends on realistically estimated day-ahead SR values and hourly EPs. The ES unit is useful and plays an important role in cost and PAR minimization. Also the PV system help decrease cost level by generating more power in periods when EPs are highest as well as preventing the grid from being overloaded.

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