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A Hierarchical Game Theoretical Approach for Energy Management of Electric Vehicles and Charging Stations in Smart Grids

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ABSTRACT By the proliferation of electric vehicles (EVs) in power systems, it is needed to manage their demand energy within a regulated market framework. From the market perspective, integration of different market players, such as the energy producers, aggregators, and loads, could complicate the system operation and management. Therefore, an appropriate model of the market that shows the exact behavior of the system components is needed. In this paper, a new tri-level game theoretical approach for energy management of EVs and EV charging stations (EVCSs) as independent decision makers for their energy scenarios is proposed. To make it practical for a real power system, the system operator is also included in the proposed method as a master decision maker. Therefore, EVs' and EVCSs' objectives are to maximize their financial profits, while the system operator indirectly controls their energy scenarios in order to fulfill the system's technical constraints. To do so, at the highest level of the proposed method, technical goals of the system, which are related to the system operational condition, will be followed as the objective criteria. At the second level of the designed model, the EVCSs financial objectives are optimized. In the third level of the proposed method, it is tried to minimize the EVs' cost function. The method is tested on an IEEE 9-bus standard system, and the results show a superior performance of the proposed energy management system (EMS) compared with the conventional EMS methods in terms of technical and financial objectives. In this way, it is shown that in the case of considering only one aspect of the system, either financial or technical, the other aspects of the system may not be satisfied. Hence, it is essential to consider both the financial and technical aspects of the system simultaneously, in order to operate the system optimally and securely.

INDEX TERMS Energy management system, electric vehicle, electric vehicle charging station, tri-level game theory.

NOMENCLATURE

A. ABBREVIATIONS

EV	Electric Vehicle
EVCS	Electric vehicle charging station
SO	System operator
EMS	Energy Management System
Tri-level game	A game including three levels
Bi-level game	A game including two levels
PV	Generator bus
PQ	Load bus
NE	Nash Equilibrium

B. SYMBOLS

σ^i	Mixed strategy chosen by player i
u^i	Payoff value of the player i
U_{EV}	Objective function of the electric vehicle
U_{EVCS}	Objective function of the electric vehicle charging station
$s_j^i j^{\text{th}}$	Strategy chosen by player i
S	Space of the possible pure strategies in the game
β^i	Optimal payoff value of the player i

p_{EVCS}	Electricity price set by electric vehicle charging station
x_{EV}	Consumed load by electric vehicle
N	A set of players in the game

I. INTRODUCTION

Restructuring of the power system and rethinking innovation in emerging energy markets have resulted in new paradigms for energy management systems (EMSs). In smart energy systems, not only the supply side but also the loads are controlled based on the system's information in order to meet one or more objectives [1]. Considering Electric Vehicles (EVs) as mobile electric load/storage devices, the high penetration of EVs poses new challenges in operation management of smart energy systems [2].

The energy management problem of the power system is well known as an optimization problem in related literature [3]–[6], which can be solved by different optimization techniques. On the other hand, by increasing the penetration of EVs in the system, the EMS of the power system including the EVs becomes one of the main concerns of both the system operators and industry [7]. From the EV producers point of view, technical aspects, which influence the EV battery such as deep-discharge in addition to the cost of the large battery, are the main concerns [8]. Therefore, an appropriate energy management design of the EVs battery can help to improve the life cycle of the system [9]. In order to protect the EV battery, different control strategies are developed, which are classified and discussed in [10]. On the other hand, system operators consider the EVs as mobile energy components, which can consume and inject energy into the system at different points of the grid. This fact provokes the energy management of the EVs in the grid a more complex problem in the EMS point of view compared to the conventional EMS with fixed loads [11]–[13]. The challenge of EMS design for EVs can become worse as both the electrical load and the grid show uncertain behavior [14]. Introducing EVs into power markets may increase the electricity consumption. In this way, studying EVs impact on power systems may be divided into two main categories: 1) Economic evaluation, which may be related to peak load shaving and load valley filling [15]–[18], and 2) Assessment of EVs impact on technical power systems' features, such as energy loss, frequency control, reactive power compensation [19]–[21].

EVs may be assumed to be as independent decision makers, which are able to decide where to be connected to and how much energy is received from the grid. Although a high penetration of EVs in power systems may cause new challenges for EMSs, by applying appropriate operation management and control methods, the system behavior may be improved [22]. Basically, an EV owner may act in order to minimize his/her cost function. On the other hand, the electricity supplier, which is another independent decision maker, may set higher electricity prices to make more money and maximize its profit. In this double-sided energy market environment, the EMS may be considered as a game among EV owners and the grid operator or their related agents [23].

Introducing the game-theoretical approach provides opportunities to involve system components such as loads and energy sources into the EMS problem [24]–[26]. In this way, the load side management can be obtained by involving them into the game [27]. What is followed in most game-theoretical approaches is to design a structure of a game in which every player tries to maximize its own profit as well as optimizing the whole system objective. In this way, one or some Nash Equilibrium points is defined as the objective point of the game in which the game may eventually converge to it [28].

To address the problem, many attempts have been devoted in respect of analyzing and modeling of the EMS in order to achieve an optimal EV charging strategy [23], [29]–[32]. In [29], a game-theoretical approach for EMS is developed in order to schedule EVs' demand energy and aggregator's profit. In this attempt, both cooperative and competitive game approaches are studied to model the EVs strategies. In [30], an aggregator is considered as a leader which sets the electricity price, while EVs act as followers, which decide how much energy to purchase from or sell to the aggregator. In this approach, it is shown that cooperative models lead to higher system stability compared with competitive models in the presence of uncertain demands. In [23], a non-cooperative leader-followers game between the Smart Grid (SG) and groups of EVs is designed. To do so, the SG sets the electricity price based on the estimation of EVs' response. Then, EVs decide the energy consumption based on the electricity price.

Unlike [23], [29], and [30], which mainly represent one-leader-multi-followers EMS strategy for EVs, in [31] and [32], multi-leaders-one-follower strategies are represented in order to evaluate EMS of EVs from different points of view. In [31], EV aggregators are considered as leaders, while system operator is considered as the follower, which tries to minimize the operation cost. In [32], a competitive game among Electric Vehicles Charging Stations (EVCSs) is designed in order to maximize their profit. In the same work, it is assumed that EVs are uniformly distributed in a given area and choose where to charge based on the electricity price and their distances to the EVCSs.

Researchers in [33]–[35] have developed a multi-leader multi-follower game in order to manage the energy among EVs and EVCSs. In [33], at an upper level, EVCSs compete with each other in order to maximize their utility. At a lower-level, EVs may cooperate with each other and act as a group to negotiate to charge a price to the upper-level in order to minimize their energy costs. In [34], another multi-leader multi-follower game among the EVs and EVCSs are developed, where EVs compete among each other to minimize their costs. EVCSs are also competing against each other in order to maximize their profits. In [35], EVs are considered as leaders and EVCSs are assumed to be the followers. Determining which player is the leader and which one is the follower should be defined in the game rules. EV may be defined either as a leader of a follower based

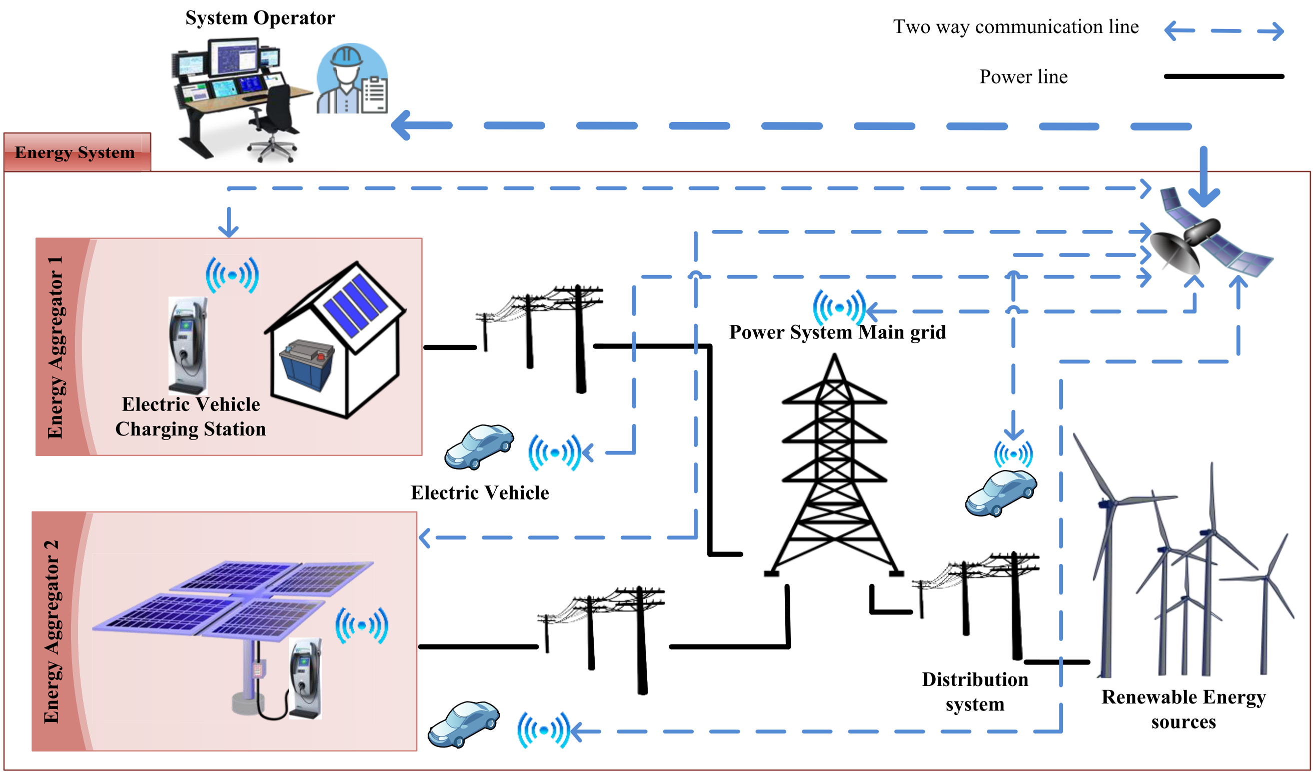

FIGURE 1. Power system graph including electric vehicles, electric vehicle charging station, and the system operator.

on the game rule. To the best authors' knowledge, none of the aforementioned works considered the EMS for EVs and EVCSs as a hierarchical game, and simultaneously optimize the system operator's objective.

In this paper, a three-level game theoretical approach is designed for EMS in order to optimize the system operator's objective in addition to maximizing the EVCSs and EVs utility functions. Therefore, at the highest level (Level 1), the system operator will try to distribute loads among the system by applying indirect control signals. Then, in a lower-level (Level 2), EVCSs will try to maximize their profit by providing more power with higher prices. At the lowest level of this tri-level game (Level 3), EVs will choose where to charge, based on their position and the EVCS's electricity price. The whole scope of the grid is shown in Fig. 1. The novelty of this work are listed as follows:

- Three-level game is designed in order to consider EVs, EVCSs, and the system operator. The system operator attends the game by applying its incentive program, while EVCSs compete to absorb more EVs to increase their benefit. In the lowest level of the game, EVs choose where to be charged and how much energy to consume in order to maximize their benefits.
- Financial optimization in addition to technical goals are both considered in the objective function of the proposed method. This is considered as a multi-objective optimization problem, which both involves financial and technical objectives.
- In simulate a more realistic case, energy aggregators are defined as independent energy sellers, which are able to set the electricity price independently. This inevitably makes the game more complex, which is a leader-followers/leaders-followers Stackelberg game. This is discussed in details in Section III.A.

In the proposed method, the system's technical constraints in addition to players' financial benefits are considered in one single game. A master-slave relation is defined between Levels 1 and 2 and Levels 2 and 3 respectively, where the system operator acts as a master for EVCSs in the upper two levels and EVCS takes the master role for EVs in the lower two levels. System operator controls loads (e.g. EVs) in an indirect manner. This means that, by participating in the game, direct load control methods such as costly load shedding and load curtailment are not necessary.

The basic power system of the proposed method is designed in DigSilent software and the game is solved in GAMS. Then, a co-simulation tool between the mentioned platforms is established to simulate a real market environment.

The following sections are defined as follows: Smart game theoretical-based EMS is defined in Section II. In Section III, the proposed method for designing tri-level game EMS of EVs, EVCSs, and the system operator is introduced in detail. Then, in Section IV simulation results together with the performance evaluation of the proposed method is illustrated. Finally, Section V presents a concise summary of the results along with the major conclusions.

II. SMART ENERGY MANAGEMENT SYSTEMS

In this Section, the game theoretical-based EMS will be explained. To do so, first, the concept of leader-follower game theory is presented.

A. STACKELBERG GAME PERSPECTIVE

To model a game in a mathematical language, first, the game components may be defined. Each game includes some players, strategies, payoffs, and rules. In every game, each player has some actions, and each player may choose an action in order to reach its goal. Eventually, the game may converge in a point, called Nash equilibrium point, in which no player may be interested in changing its action. A game may have either no Nash equilibrium point or some [36].

Stackelberg game is a kind of game in which players may act with a sequence. This kind of game is popular in energy systems [37]. The leader is defined as a player which may dominate other players by its strategy. Followers are those who act in respect to the leader's strategy.

A game among some players may be modeled as an optimization problem. Assume there are n numbers of players, e.g. player 1, 2…and n. A finite game may be introduced by a finite ordered list of elements as shown below:

$$\Gamma = \left(N,\ \left\{S^i\right\}_{i\in N},\ \left\{u^i\right\}_{i\in N}\right) \tag{1}$$

where S^i and u^i indicate space of strategies and payoff function of player i, respectively. N presents a set of players in the game. The space of possible pure strategies in game Γ is the product of all players' space strategies, as follows:

$$S = \prod_{i\in N} S^i \tag{2}$$

Let define σ^i as a mixed strategy of player i. A mixed strategy of player i is a probability distribution over the space S^i. The Nash equilibrium may be defined as a mixed strategy (σ^*) in which no player may gain a better payoff by only changing its strategy and leave other players' strategies fix. This is illustrated as follows:

$$\sum_{i\in N}\left(u^i\left(\sigma^{*-i},\sigma^i\right)\right) \le \sum_{i\in N}\left(u^i\left(\sigma^*\right)\right) \tag{3}$$

in which $\sum_{i\in N}$ is space of all mixed strategies of player i. $u^i\left(\sigma^{*-i},\sigma^i\right)$ denotes the payoff of a mixed strategy when all players except player i choose the Nash equilibrium point. Let define β^i as the optimal payoff to player i. To find the optimal payoff to player i, the following optimization problem may be introduced:

$$\begin{aligned}
&\min\ \beta^i - u^i(\sigma)\\
&s.t.\ u^i\left(\sigma^{-i}, s_j^i\right) - \beta^i \le 0, \quad \forall j = 1,\ldots,m^i\\
&\qquad \sum_{j=1}^{m^i} u^i(\sigma) = 1, \quad 0 \le u^i(\sigma),\ \forall j = 1,\ldots,m^i
\end{aligned} \tag{4}$$

where $u^i\left(\sigma^{-i}, s_j^i\right)$ is the payoff of player i in which it chooses the jth strategy.

To find the Nash equilibrium for the game Γ, an optimal solution for all players may be included in the objective of the optimization problem as follows:

$$\begin{aligned}
&\min \sum_{i\in N} \beta^i - u^i(\sigma)\\
&s.t.\ u^i\left(\sigma^{-i}, s_j^i\right) - \beta^i \le 0, \quad \forall j = 1,\ldots,m^i\\
&\qquad \sum_{j=1}^{m^i} u^i(\sigma) = 1, \quad 0 \le u^i(\sigma),\ \forall j = 1,\ldots,m^i
\end{aligned} \tag{5}$$

It is proved in the literature that for every finite game with a Nash equilibrium, there is a feasible optimum solution [36], [38].

B. GAME-THEORETICAL APPROACH FOR ENERGY MANAGEMENT OF EVs

In this Section, the game-theoretical approach applied in EMS is explained. To present the game in mathematical format, game components may be defined. In this manner, there are two types of game players: EVs and EVCSs. The EVs' strategy is to determine the value of energy bought from EVCSs and which EVCS they may choose. On the other hand, EVCSs' strategy is to set a price for the electricity. Talking about the rules for this game, first, each EVCS announces its price without knowing other EVCSs' strategy in choosing the electrical price. This means that EVCSs compete with each other in order to obtain more financial benefits. In another scenario, EVCSs may be aware of other EVCSs' electricity price. In this regard, they cooperate with each other in order to achieve more profit.

In this scenario, EVs act as followers, while EVCSs are leaders. Then, EVs may choose where to be charged and how much energy they may buy from the EVCSs.

To determine the EVs' payoff, it should be noted that each EV owner may be more satisfied if the car gets more charged. The reason is that by absorbing more energy, one may drive further in distance in addition to long-term recharging is needed. Then payoffs may be a non-decreasing function in respect of energy consumption as follows:

$$\frac{\partial U_{EV}}{\partial x_{EV}} \ge 0 \tag{6}$$

where U_{EV} and x_{EV} are payoffs of each EV and the load consumption, respectively. On the other hand, the relationship between the consumption load and the level of satisfaction is not linear. As more energy is consumed, the level of satisfaction gets saturated as follows [23]:

$$\frac{\partial^2 U_{EV}}{\partial x_{EV}^2} \le 0 \tag{7}$$

In addition to the aforementioned characteristics regarding the payoff of EVs, it should be noted that consuming energy may be paid by EVs. This means that EVs do not wish to buy expensive electricity. Therefore, the level of satisfaction may be decreased by increasing in the value of the electricity price. Mathematically,

$$\frac{\partial U_{EV}}{\partial p} \leq 0 \tag{8}$$

where p is the electricity price consumed by the EV. In the case that there are some energy producers, each EVCS may introduce its own electricity price. There are also some other items that affect the desirability of the EV to be charged in an EVCS. Traveling cost including the distance of the EV from the EVCS and traffic jam in addition to waiting time at the station may be considered in the EV payoff function [23]. Although these factors can be included in the objective function of the EV, without losing the generality and for the sake of simplicity, they are neglected in the EV payoff function. Considering (5)-(7), the following equation may be considered as the payoff function of each EV:

$$U_{EV} = a_1 \cdot x_{EV} - a_2 \cdot x_{EV}^2 - p \cdot x_{EV} \tag{9}$$

where a_1 and a_2 may have some fixed or variable values, yet they should be positive in order to satisfy (5) and (6). It is important to choose an appropriate value for a_1 and a_2 in order to model the accurate behavior of the EVs, as they may affect the level of satisfaction in the EV. a_1 is related to the capacity of the EV's battery. Higher values for a1 shows higher battery capacity of the EV, which means that more energy is required for the EV to approach its maximum fulfillment. In addition, a_2 indicates the different behaviors of the EV owners. For example, when the battery of the EV is almost empty, then EV owners desire to charge its EV battery more than the time that it is almost full. In this case, one single EV can behave differently based on its desired energy consumption. By choosing a different value for a_2, the various satisfaction level of the EVs with an equal battery capacity will be reached. This is shown in Fig. 2.

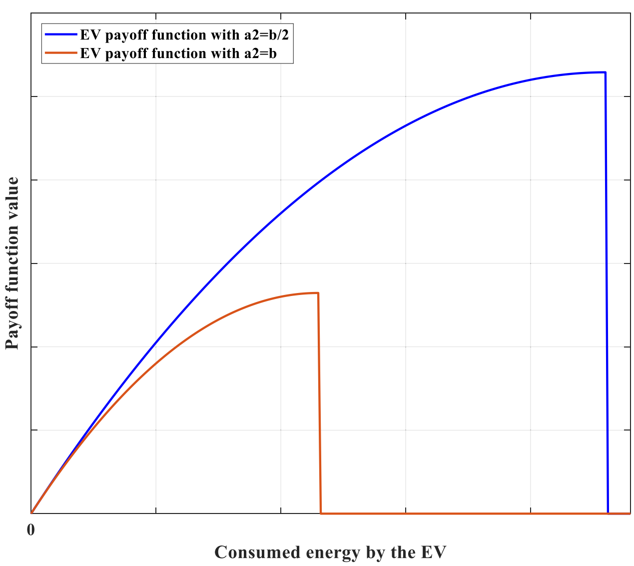

FIGURE 2. Payoff function for one single EV with different values of the a_2. The (b) is a constant positive real value.

To determine payoff for the EVCS, the effects of two variables may be assessed: the value of the electricity price and the amount of energy to be sold. If there are some EVCSs in the grid, they may cooperate with each other or compete in order to maximize their profit independently. In the former scenario, one single objective function can be defined to include all EVCSs' payoffs. In the latter, each EVCS tries to maximize its own payoff with/without considering other EVCSs' actions. In the more advanced scenario, each EVCS may learn how other players act. Then, it may modify its action in the next iteration of the game.

A very simple payoff for an EVCS can be presented as:

$$U_{EVCS} = p_{EVCS} \sum\nolimits_n x_n \tag{10}$$

in which U_{EVCS} and p_{EVCS} are the payoff and the suggested price introduced by the EVCS. In this way, by increasing its suggested electricity price, each EVCS may increase its payoff. On the other hand, the electricity price is introduced in the payoff of the EVs as a negative factor. Then, if the electricity price increases, EVs may try to consume less energy, which means $\sum_n x_n$ may decrease. Consequently, U_{EVCS} may decrease.

At the highest level related to the operational conditions, the system operator may implement some incentive programs in order to reach its goal. Here, the incentive program is defined by paying money to EVCSs that are located far from the load center or reducing their taxes in order to motivate them to sell the energy with less electricity price. In this way, the EVs will be encouraged to purchase the energy from the mentioned EVCSs, which are not located in the load center. This makes the system load to be distributed in the system, hence operational constraints of the system (in this case voltage magnitude of the bus bars) will be satisfied.

To mathematically model the abovementioned discussion, the objective function of the system operator and its constraints need to be modeled. To do so, the objective of the system operator is to minimize its cost (economic incentive), which it pays to the EVCSs. On the other hand, its constraint is to keep the bus bars voltage magnitude with their boundaries. The objective of the system operator can also be related to some other constraints of the system such as line current. Here, without losing the generality of the method, the constraint of the optimization problem of the system operator is chosen to keep the bus bar voltage magnitudes with their boundaries, while this could be some other aims of the system. In addition, the line current limits are supposed to be considerably high in order to not be violated in the model. Therefore, the formulation of this level is shown as follows:

$$\begin{aligned} &\min\ \textbf{Cost F}. = \sum_j p_{SO_j} x_j, \quad \forall j = 1, \ldots, m \\ &s.t.\ |V_i| \geq D, \quad \forall i = 1, \ldots, b \end{aligned} \tag{11}$$

Where p_{soj} is the incentive electricity price dedicated to the j^{th} EVCS with x_j amount of energy for m number of EVCS. In addition, $|V_i|$ is the voltage magnitude of the i^{th} bus from

b number of buses, which should be more than a marginal value, D.

With all this in mind, the whole problem can be introduced as a leaders-followers game as follows:

System Operator (leaders):

$$\min \ \textbf{Cost F}. = \sum_j p_{SO_j} x_j, \quad \forall j = 1, \ldots, m$$
$$s.t. \ |V_i| \geq D, \quad \forall i = 1, \ldots, b$$

EVCSs (leaders for EVs and followers for the System Operator):

$$\max \ U_{EVCS_j} = \left(p_{EVCS_j} - p_{SO_j}\right) \sum_n x_n$$
$$s.t. \ \sum_n x_n \leq C$$
$$p_{EVCS \geq 0}$$

EVs (followers):

$$\max \ U_{EV} = a_1 \cdot x_{EV} - a_2 \cdot x_{EV}^2 - p_{EVCS} \cdot x_{EV}$$
$$s.t. \ x_n \geq 0 \tag{12}$$

Equation (12) shows that each player has its own objective function. To solve the optimization problem of (12), backward methods can be employed. In this regard, first followers' objective function is optimized. In this step, electricity price is considered as a constant value. Then, energy quantity is determined based on the value of the electricity price. Next, EVCSs' objective function is optimized. In this step, energy quantity is replaced by the value determined in the last step. This means that the leader (e.g. EVCS) already knows about the follower's (e.g. EV's) decision, which gives the EVCSs the advantage of reaching a better point in the optimization problem.

III. DESIGNED TRI-LEVEL GAME FOR EVs, EVCSs, AND THE SYSTEM OPERATOR

In this section, first, the logic of the designed game is described. Then, the mathematical model of the proposed method will be explained.

A. LOGIC OF THE DESIGNED GAME

Regarding the payoffs of the players and their decision variables, there are three levels of players in the proposed method: Level 3: EVs; Level 2: EVCSs; and Level 1: System operator. For each level, a different objective function is defined as follows:

- Level 3: EVs

At this level, EVs compete with each other in order to minimize their cost function. Their decision variables may be choosing where and how much to be charged. Each EV may be unaware of other EVs decision. Although prediction of other players action can lead to a better decision making for each individual EV, this is not the subject matter of this paper. To do so, it is recommended that the last actions of the other players are involved in each EV's objective function.

- Level 2: EVCSs

At this level, EVCSs try to maximize their profit by selling more energy at higher prices. On the other hand, as there are some EVCSs distributed in the system, EVs may choose more desirable EVCS with a reasonable price. The value of desirability is determined by the EVs' need. For example, an EVCS near to the city center may be more desirable compared to the one, which is placed on the suburbs. The variable, which is controlled by EVCSs is their electricity price.

- Level 1: System Operator

This is the highest level in the hierarchical game for the EMS. One of the main goals of the system operator is to keep the system working all the time considering operational features such as power quality, stability, etc. On the other hand, EVs charging behavior may affect the system condition negatively, like increasing distribution transformer losses, voltage deviation, etc. [39], [40]. In this paper, the effect of EVs on system nodal voltages is studied. Other system characteristics may also be considered as an objective of the system operator, which it is out of the scope of this paper.

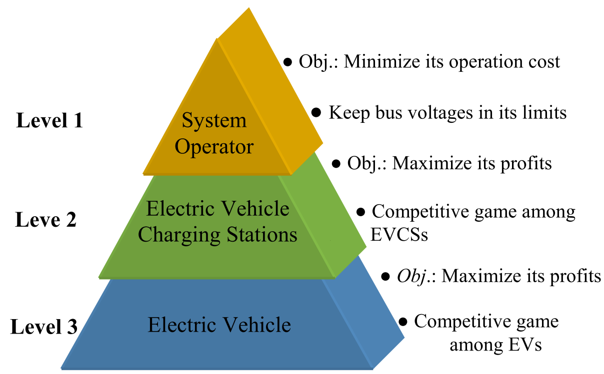

FIGURE 3. Architecture of the hierarchical game theoretic approach of energy management for EVs, EVCSs, and the system operator.

The whole process of the tri-level game theoretic approach for EMS is illustrated in Fig. 3. Therefore, the game starts with the highest level (Level 1), e.g. system operator. In this step, system operator checks if the system variable (voltage magnitude) is in its desired limits. If all bus voltages are within their limits, the system operator will not apply any penalty to EVCSs' decision. On the other hand, if some voltage deviations occur, the system operator will apply an indirect control method in order to make its followers to change their decisions. To do so, the EVCS, which causes voltage drop, may pay a surcharge. As a consequence, the EVCS may wish to sell less energy in order to pay less surcharge. Then, the voltage may be restored to the allowed range.

In the second step of the game, EVCSs try to maximize their economic profit. As the numbers of EVs is limited, EVCSs have to compete against each other to attract more EVs in order to sell more energy. The only action which may be controlled by EVCSs is the electricity price. As it is assumed that each EVCS acts independently, they have no information about the others' actions. Therefore, each EVCS sets its own electricity price. To maximize its profit, every EVCS has to consider all possible conditions in order to find out what the best action is. In this manner, different conditions should be considered by EVCSs: 1) What is the best electricity price if all EVs are charged in the considered EVCS? 2) What is the best action if only some EVs choose to be charged in the considered EVCS?

In step three of the game, EVs may compete with each other in order to pay less money with more satisfaction degree. Their decision variables are choosing the desired EVCS to be charged in addition to determining the amount of energy to be consumed. They may have no information about other EVs' decision. To make the competition fair, all EVs are assumed to act simultaneously in respect to their decision ([41], [42]. As each EVCS may provide a limited amount of energy, EVs which make more profit for the EVCS may be charged there. In this regard, the EVs compete with each other by determining the optimum amount of energy and the best EVCS; i.e. the EVCS which provides cheaper energy blocks in comparison with other EVCSs. The optimum amount of energy may be calculated by the objective function of the EV.

B. ALGORITHM OF THE DESIGNED GAME

To present the algorithm of the tri-level game, it should be noted that each leader (upper-level) knows how its followers (lower-level) may act in response to its strategy. Therefore, action series follows a top-down process, while the three-level optimization process is done in a bottom-up fashion as shown in Fig. 4. This means that, first of all, the optimization problem for the EVs is solved considering

EVCSs' action as a constant. Then, EVCSs optimize their profit based on the information determined in the last step.

After determining the optimal value for the objective function of the EVCSs, the system operator may use the lower level information to optimize its own payoff. This technique is called backward induction technique to find a Nash equilibrium point in leader-follower games, as shown in Fig. 4 [43].

The process of optimization begins in EVs and ends with the system operator. The hierarchical optimization process is illustrated in the algorithm shown in Table 1.

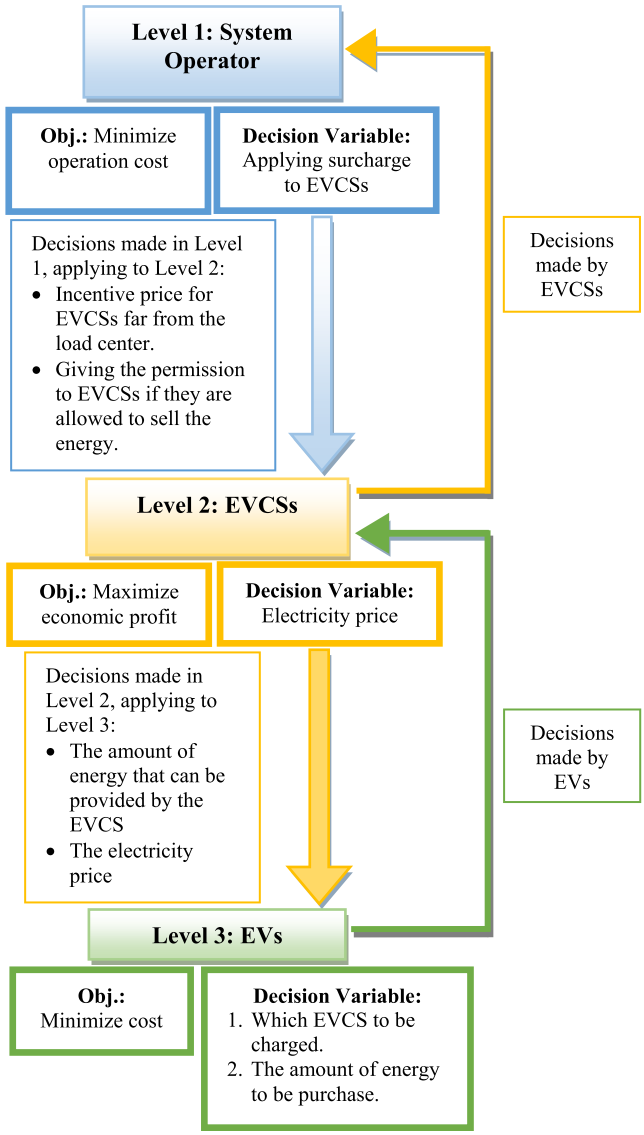

FIGURE 4. Backward induction technique to find a Nash equilibrium point in leader-follower games for the proposed method.

IV. SIMULATION RESULTS

To evaluate the proposed method, three scenarios are considered: 1) Blind scenario; in which there is no information exchange among EVs, EVCSs, and the system operator. 2) Conventional EMS including a bi-level game; in which EVs and EVCSs receive and send information among each other. Yet, the system operator is not included in the game. 3) The proposed method; in which a tri-level game is introduced for the EMS.

The IEEE 9-bus standard system as shown in Fig. 5 is used as a testbed for verifying the proposed method, which is mainly used for system-level studies. The DigSilent software is used for simulating the electrical network. In addition, GAMS programming software is used for doing the optimization process.

A. SCENARIO 1 (BLIND SCENARIO)

In this scenario, EVs have no information about the electricity price. Therefore, they will charge their battery based on their battery state-of-the-charge, and the closest EVCS. It is worth mentioning that the EVs will still try to optimize their benefit, although this is not a game among EVs or EVCSs. The reason is that each player makes its decision based on its own benefit and no information from other players. In addition, player's decision has no effect on the other players' decisions.

It is further assumed that the load center is located at Bus 5 and Bus 6. In this circumstance, some EVs will be charged at Bus 5 and some of them will choose Bus 6. For this scenario, the player's objectives are not modeled,

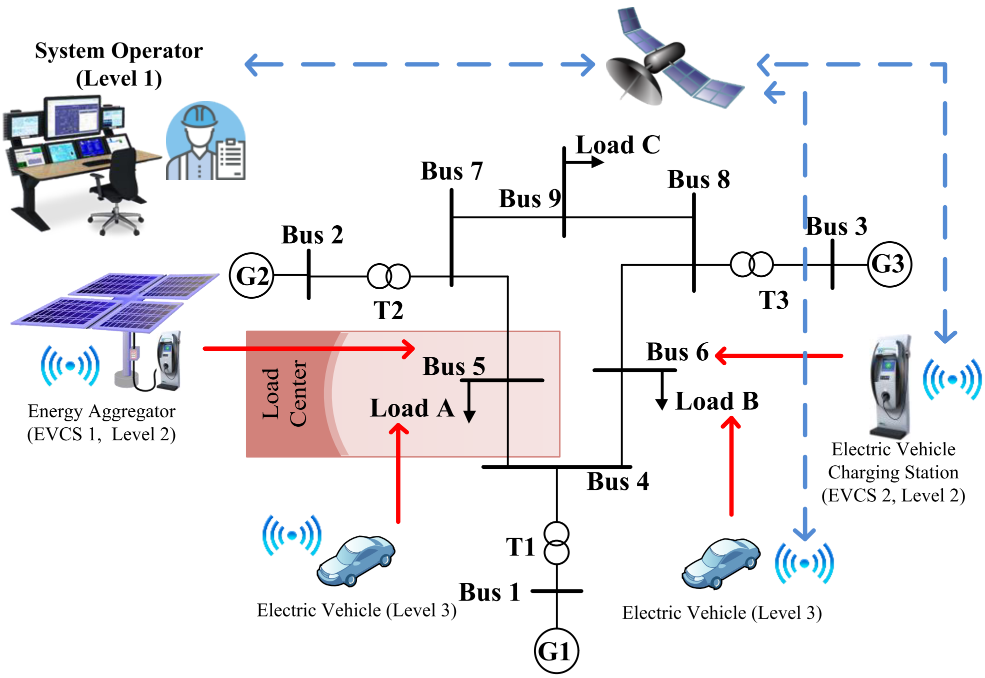

FIGURE 5. IEEE 9-bus system, considering Buses 5 and 6 as EVCSs.

TABLE 1. Three-level algorithm for the proposed method.

Step 1. Solving EV's optimization problem

1.1 Optimize each EV's objective function.

1.2 Insert EVs' decision (the amount of energy consumed by each EV without considering electricity price) into EVCSs optimization problem as inputs.

Step 2. Solving EVCS's optimization problem

Optimize each EVCS's objective function based on the amount of energy consumed by EVs.

Apply decisions (electricity prices) made by EVCSs to EVs.

Repeat Step 1 and 2 until no player changes its decision.

Step 3. Solving System operator's optimization problem

3.1. If the system operation limits are violated, apply the surcharge program into EVCSs, and go back to Step 2.

3.2.1 Check if all system variables are in their boundaries.

If all variables are in their boundaries, stop the optimization.

but randomly distributed in the system in order to have a better feeling of the next two scenarios. Therefore, active power in Bus 5 and Bus 6 are equal to 165 MW and

TABLE 2. IEEE 9-bus voltage magnitude in a blind load scenario.

Bus No.	Bus Type	Voltage magnitude (p.u.)
1	Slack	1.040
2	PV	0.949
3	PV	0.955
4	PQ	0.989
5	PQ	0.923
6	PQ	0.954
7	PQ	0.951
8	PQ	0.944
9	PQ	0.963

125 MW, respectively. It is worth mentioning that also these values are much bigger than an EV, which its scale is in some kW, it makes sense when an integration of EVs are considered. Therefore, an aggregation of the EVs are considered as the load. Table 2 shows the load flow results in which bus voltage magnitudes are indicated. Bus voltage magnitude is a key characteristic of the system which can help the operator to keep the system stable. Therefore, it is used in order to indicate either the system runs in a safe mode or not.

Let the marginal point of the voltage magnitude be equal to 0.925 p.u. It is worth mentioning that this value may differ in different systems with some other operator's objectives. As it is indicated in Table 2, the voltage magnitude of Bus 5 is below the marginal point (0.93 p.u.). It means that if EVs try to charge their battery based on their preferred location, there may be an operational challenge in the system. In the next parts, the effect of introducing a game to the system players will be presented. It will show that all games do not necessarily have benefit for the system operator. Therefore, including the system operator as a leader in the game will improve system operational mode in addition to players' benefit.

B. SCENARIO 2 (CONVENTIONAL EMS WITH A BI-LEVEL GAME)

In this scenario, a game among EVs and EVCSs are developed based on economic benefit. System's operational conditions are not included in this stage. Each EV tries to spend less price for the same value of the energy. This makes a game among EVCSs in order to attract more EVs. As it is assumed EVCSs have no information about each other's suggested price, then EVCSs (located in Bus 4 and 5) try to maximize their profit by setting the highest possible value of the electricity.

This bi-level game is considered as a Stackelberg game. Here, the EVCSs act as leaders and EVs are considered as followers. According to the backward induction technique explained in the previous section, the optimization starts from Level 2 and continues to the Level 3; see Fig. 4. Level 1, as it is related to the system operator, is not included in this scenario. Therefore, this scenario is a special case of scenario 3, which is not necessarily the best possible equilibrium point (will be discussed in the next part).

Here, two EV types are considered as the aggregation of the EVs. This means that EV 1 presents a group EVs and decide for them as an aggregator. Each EV try to optimize its own objective function. It does not necessarily mean that EVs are charged in the EVCS in which electricity price is cheaper. Indeed, the EVCS that suggests the lower price and is closer to the load center will attract EVs; see Table 3. Here, although EVCS 1 suggests a higher price for the unit MW, it still attracts both EV aggregators. The reason is that EVCS 1 is more desired for EVs based on their objective function. The tendency of each EV to each EVCS is called the desired function. Here, each EV has two desired functions. For simplification, the desired function for EVs are indicated as follows:

$$\begin{aligned}
&EV_1's\ desired\ function\ in\ respect\ to\ CS_1\\
&\quad = 10 \cdot x_1 - x_1^2 - p_1 \cdot x_1\\
&EV_1's\ desired\ function\ in\ respect\ to\ CS_2\\
&\quad = 10 \cdot x_1 - x_1^2 - p_2 \cdot x_1\\
&EV_2's\ desired\ function\ in\ respect\ to\ CS_1\\
&\quad = 12 \cdot x_2 - x_2^2 - p_1 \cdot x_2\\
&EV_2's\ desired\ function\ in\ respect\ to\ CS_2\\
&\quad = 9 \cdot x_2 - x_2^2 - p_2 \cdot x_2 \qquad (13)
\end{aligned}$$

Accordingly, if all EVs try to be charged in EVCS 1 in order to optimize their objective function, the voltage magnitude at Bus 5 (EVCS 1) will dramatically fall; see Table 4. This is not acceptable regarding the system operational constraints. According to Table 3, Bus 5 voltage magnitude is not only improved but also decreased in comparison with Scenario 1.

TABLE 3. EVs and EVCSs transaction information in scenario 2.

Items	Load info.	Explanation	Electricity price
EV 1	36.25 MW	Charged in EVCS 1	-
EV 2	46.25 MW	Charged in EVCS 1	-
EVCS 1	82.5 MW	More desired for EVs	2.75 unit per MW
EVCS 2	0 MW	Less desired for EVs	2.125 unit per MW

TABLE 4. IEEE 9-bus voltage magnitude in a two-level scenario.

Bus No.	Bus Type	Voltage magnitude (p.u.)
1	Slack	1.04
2	PV	0.950
3	PV	0.959
4	PQ	0.990
5	PQ	0.921
6	PQ	0.960
7	PQ	0.952
8	PQ	0.946
9	PQ	0.967

C. SCENARIO 3 (THE PROPOSED METHOD)

In this scenario, the system operator also participates in the game as a leader for EVCSs. In addition, EVCSs act as leaders for the EVs. This means that the system operator controls the EVs indirectly. In this way, all players including energy consumers, energy providers, and system operators, will be involved in EMS. It is worth mentioning that by applying the tri-level game, no player is forced to make a decision, or is directly controlled by any other player.

To include the system operator in the game, its objective and decisions should be determined. The objective of the system operator is to maintain bus voltage magnitudes within the allowed range, for instance, upper than 0.93 p.u. and lower than 1.06 p.u. Its decision variable is the amount of incentive applied to EVCSs. This incentive strategy is widely used in economic problems. With all this in mind, the system operator tries to balance the load among EVCSs. By doing so, it is expected that the voltage magnitudes in all buses are maintained within the limits.

Table 5 shows the voltage magnitude of buses regarding the Scenario 3. What can be concluded from this table is that all bus voltages are more than 0.93 p.u., which is desired from the system operator point of view.

The system operator's objective is achieved by applying the incentive method. This means that system operator introduces an economic incentive to EVCS 2, which is the less desired EVCS from the EVs viewpoint. By increasing the

TABLE 5. IEEE 9-bus voltage magnitude in Three-level scenario.

Bus No.	Bus Type	Voltage magnitude (p.u.)
1	Slack	1.04
2	PV	0.954
3	PV	0.958
4	PQ	0.991
5	PQ	0.930
6	PQ	0.954
7	PQ	0.956
8	PQ	0.948
9	PQ	0.966

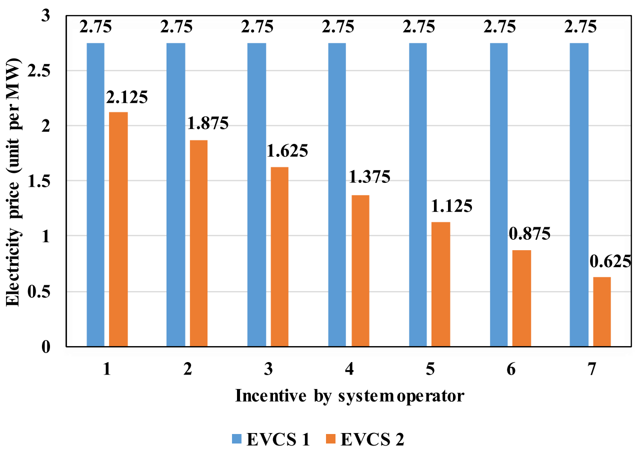

FIGURE 6. Suggested electricity price by EVCS 1 and EVCS 2, considering system operator incentive strategy.

incentive value, EVCS 2 can provide the electricity at less price to its customers, i.e. EVs. This decrease in electricity price by EVCS 2 will continue until some EVs tend to be charged in EVCS 2 instead of EVCS 1. This decrease in electricity price is shown in Fig. 6. The blue and column show the electricity price introduced by EVCS 1 and EVCS 2, respectively. As it can be seen from Fig. 6, electricity price introduced by EVCS 1 maintains fixed through different incentives introduced by the system operator. On the other hand, by increasing the economic incentive for EVCS 2, the electricity price introduced by EVCS 2 will decrease. There will be an equilibrium point in which EVs tend to be charged at EVCS 2 because of its cheap electricity price. By doing so, loads will be shifted from EVCS 1 to EVCS 2, which distributes the load among the power system.

By introducing an incentive strategy from the system operator, the EV type 1 and 2 are distributed between EVCS 1 and EVCS 2. This is shown in Table 6. In this table, it is also shown that while EVCS 2 is less desired in respect of EVs, as it introduced much less electricity price compared to EVCS 1, some EVs will tend to be charged at EVCS 2.

In summary, by designing an appropriate game in the system, all parties' objective functions will be satisfied, while in the case that only EVs and EVCSs are considered in the game, operational challenges will be caused for the system operator.

TABLE 6. EVs and EVCSs transaction information in scenario 3.

Items	Load info.	Explanation	Electricity price
EV 1	36.25 MW	Charged in EVCS 2	-
EV 2	46.25 MW	Charged in EVCS 1	-
EVCS 1	46.25 MW	More desired for EVs	2.75 unit per MW
EVCS 2	36.25 MW	Less desired for EVs	0.625 unit per MW

This can be seen by comparing results in Scenario 2 and Scenario 3.

V. CONCLUSION

In this paper, a hierarchical game-theoretic approach has been used in order to solve the EMS problem for EVs, EVCSs, and the system operator. In this game, EVs acted as EVCSs' followers, while at a higher level, the system operator played as the leader for EVCSs. The system operator objective is to meet the system security constraints. To do so, it applies a surcharge program to its followers, which are EVCSs. At the second level EVCSs try to maximize their benefits by selling more energy to EVs at a higher price. The input for the EVCSs are the incentives from the system operator and the amount of energy consumed by EVs. By solving the EVCS optimization problem, electricity prices are set by each EVCS. Then, at the lowest level, EVs try to minimize their cost. They apply the electricity prices set by the EVCSs into their objective function and try to choose the lowest offered price and more desired EVCS. It is shown in the results that the more desired EVCS is not necessarily the EVCS with the lowest offered price. It was shown that if the system operator's role is neglected in the game, this may cause operational challenges. In this way, the main outcomes of this paper are as follows:

1) In order to apply a game-theoretic approach for EVs in the energy market, it is recommended to include system technical constraints in the EMS. Unless the system operational state variables may be out of their boundaries in order to satisfy the economic benefits of the EVs.

2) By applying a surcharge program introduced by the system operator to the energy aggregators, state variables of the system can be controlled in the market platform indirectly.

By using the proposed method, economic profits and operational challenges of the system components were modeled simultaneously. Therefore, both aspects of the system were improved.

Future works can be directed to the following aspects: First of all, there are some other technical points of the system such as line current limitations and power quality effects of the EVs in the main grid, which can be included in the system operator's constraints. To do so, transmission system operator can be involved into the game as the leader for EVCSs in order to satisfy line current limits. This will introduce a tri-level game with multi-objective optimization problem in each level. Although this may seem more complex, it is a more realistic problem. Second, the game can be designed in different ways in order to evaluate the best possible game-theoretic approach structure from the point of components view. For instance, the cooperation and competition game can be compared for the EVCSs in order to evaluate that in what circumstance they will be more satisfied.

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