Smart Charge Scheduling for EVs based on Two-Way Communication

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***Abstract*— The objectives set for smart grids are as diverse as they are exciting and ambitious. Instead of overloads, bottlenecks and blackouts, smart grids will ensure the reliability, sustainability and efficiency of the Electric Vehicle Supply Equipment (EVSEs). Therefore, EVSEs and Electric Vehicles (EVs) must integrate wireless communication between them to discover the availability and make pre-reservations of charging time slots. In this paper, we propose a novel multi-objective EV Charging Slots Assignment (CSA) optimization model that, besides balancing energy usage between EVSEs, minimizes the latency time of EVs. Moreover, we integrate our optimization model to a communication protocol between EVs and EVSEs that allows a reliable reservation process, called Reliable Broadcast for EV Charging Assignment (REBECA) [1]. Then, we propose a centralized heuristic to efficiently solve our model as an offline CSA process.**

***Keywords*— Electric vehicle, broadcast, charging process, electrical vehicle supply equipment, grid, optimization;**

I. INTRODUCTION

Two-way communication technology is becoming an essential part of the smart grid landscape, tying between all component, from power generation, to energy transmission, and consumption [2,3]. With two-way communication, the smart grid has the capacity to balance power fluctuations beween production and consumption. With the advent of Electrical Vehicles (EVs), achieving a balanced capacity utilization of Electrical Vehicle Supply Equipment (EVSEs) on the road, while both satisfying charging requests of EVs, and minimizing their time to be charged, is becoming an important management issue in the grid. The grid needs, indeed, to ensure a balance between availability and efficiency.

Much of smart grid optimization processes are based on real-time information which relies on the availability of two-way communications and an advanced metering infrastructure (AMI). In the case of moving EVs, two-way wireless communications between EVs and the smart grid prior to plug-in for charging, can on the one hand, help the grid have a much accurate load forecast at EVSEs. On the other hand, the grid can help EVs by informing them on available EVSEs which can minimize their overall time-to-be served, called hereafter latency time. EVs can further benefit from two-way wireless communication, by reserving charging time-slots at their chosen EVSEs, in order to ensure predictable latency times. We define latency time, as time duration it takes a vehicle to be plugged-in at an EVSE, from the moment it requests to find an available EVSE. This included the travel time to reach the EVSE and the waiting time (in queue) to be plugged-in.

In this paper, we propose a novel multi-objective EV Charging Slots Assignment (CSA) optimization model. In particular, our proposed model, besides balancing energy usage between EVSEs, minimizes the latency time of EVs. For this, we use a scheme called Reliable Broadcast for EV Charging Assignment (REBECA) [1]. Our model coupled with REBECA is able to determine how many EVs can be efficiently served by a number of EVSEs without increasing the probability of overload on EVSEs or latency time on EVs.

Our contributions, in this paper, can be summarized as follows: (1) We propose a novel multi-objective optimization model that assigns charging slots to EVs at EVSE; the proposed model includes two objective functions and therefore provides a good flexibility; (2) we integrate a scheme that establishes robust broadcast communication between different equipment in the grid, called REBECA; (3) we solve our model using CPLEX solver [4]. CPLEX provides exact solution (i.e., the optimal solution) of the proposed model but only for small size networks in a reasonable time; and (4) We also propose a greedy search heuristic (Alg. 1) to search for a feasible CSA solution, called Charging Slots Assignment Heuristic (CSAH).

The remainder of the paper is organized as follows. Section 2 provides a brief overview of related research. Section 3 defines the CSA problem and presents a mathematical formulation of the problem solution. Section 4 proposes a resolution of the proposed model using CPLEX and heuristic algorithm. Section 5 evaluates the proposed solution via simulations. Finally, Section 6 concludes the paper.

II. RELATED WORK

Several works have highlighted the importance of two-way communication between EVs and the smart grid. One work has proposed to control EV charging start time when vehicles are already plugged-in [5]. Other researchers pointed-out to the fact that the increase in the numbers of EVs can be an opportunity to utilize their battery as a storage which can buffer time-variable renewable energy [6-7] or help in frequency regulation [8].

In [6], the author evaluated the practicality of EVs in providing a service called regulation. Regulation allows a fast response to alterations in power above and below some baseline. The authors demonstrate that, with the regulation service, EVs battery state of charge can vary in the short term, while not discharging batteries over time. The regulation work starts, however, once vehicles are already plugged-in for charging.

In [8], the authors propose that EV battery charging be managed to increase the supply of regulation service. They assume that an EVSE is already selected by EV owners to manage the EV charging power. However, we show in this work that the selection of EVSE prior to the charging process is very important and influences the grid performance in terms of latency time and management of electricity use.

Several models have been developed to characterize and optimize the operation of the grid under [9-13] various conditions. Managing varying consumer consumption levels in varying supply conditions and pricing has drawn significant attention in recent works. The role of factors such as load scheduling and market prices in driving consumer behavior and achieving energy efficiency was studied in [9] and [10]. In [10], user preferences are modeled using the concept of discomfort level within an optimization problem formulation that balances the load and minimizes user inconvenience caused by demand scheduling. In [11], an energy consumption scheduling problem is established to minimize the overall energy cost. Some researchers formulated a linear program for distribution management [12]. Authors in [13] developed an optimization model integrating real-time self-healing and uncertainty.

In our work, we use a scheme called REBECA [1] (see Figures 2-3). Because EVs charging time can be several minutes long, even at the fastest level 3 chargers, it is very useful for EVs to know the status of an EVSE prior to heading towards it for charging. For example, if all slots of an EVSE are being used, an EV will need to wait for the EVs which are already plugged-in, to complete their charging process, before being able to plugin. Wireless communication between EVs and EVSEs, while the former are on the road, allows EVs to discover the occupancy state of EVSEs and make pre-reservations of charging time-slots. The REBECA communication protocol, used in this work, allows a reliable reservation process once the choice of EVSEs has been determined. Our new CSA optimization model allows to reserve charging time slots for vehicles. CSA model is able to balance energy usage between EVSEs while maximizing the power utilization and minimizing the latency time of EVs.

III. FORMULATION

3.1 Problem description

We consider the problem of CSA in the smart grid by exploiting the tradeoffs among EVSEs load balancing and EVs latency.

Indeed, if load balancing is maximized, the supply of regulation service is indirectly increased. However, in balancing the charge on EVSEs, EVs may be directed to EVSEs which increase their latency time. Therefore, optimizing one of these criteria will affect/undermine other criteria; thus, a multi-objective approach is useful for this kind of problem. In this Section, we propose a multi-objective optimization model that offers the possibility to optimize a combination of two criteria. Further the evaluation cost of multi-objective functions is very high compared to single objective functions; therefore, appropriate heuristic must be carefully designed to resolve the problem especially for large instance of networks size.

3.2 Deployed architecture

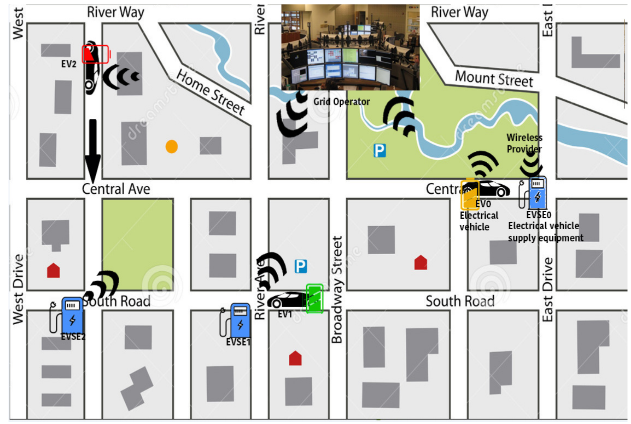

Fig.1. Architecture of an electric vehicle (EV)-based grid power management on an electrical vehicle supply equipment (EVSE)

In future, when a significant numbers of EVs will be used and will need to be plugged-in for charging on the road, it is likely that the grid operator would be contracting with EVSEs instead of single EVs. EVSEs can act as intermediary components in the grid architecture, which allow the operator to effectively manage the charging process of EVs while providing a regulation of EVs electricity use. For this, EVSEs will use two-way communication links with the grid operator as illustrated in Fig. 1.

Since the charging of an EVs is a time-consuming process (tens of minutes, even with the fastest chargers), reserving charging slots at EVs can be very useful prior to heading to an EVSE. EVs and EVSEs can exchange the reservation information by using over-the-air communication technologies such as 802.11p, Wireless Mesh Networks (WMNs) or Wi-Fi [14].

Let us formally model the smart grid of EVs and EVSEs as a directed graph as shown in Fig.2. This connectivity graph, is called $G=(V,E)$ where V represents the set of N EVs and M EVSEs, and E represents the set of edges between these EVs and EVSEs. E is therefore equal to $N*M$. $\forall\,(EV, EVSE)\in \mathrm{V}$, an edge $\mathrm{e}=(\mathrm{EV}, \mathrm{EVSE})\in \mathrm{E}$ if the distance between *EV* and *EVSE*, denoted $\mathrm{d}(\mathrm{EV}, \mathrm{EVSE})$, is smaller than the minimum range, denoted $\min(r_{\mathrm{EV}}, r_{EVSE})$, of *EV* and *EVSE* (i.e., $\mathrm{d}\,(\mathrm{EV}, \mathrm{EVSE})\leq \min(r_{\mathrm{EV}}, r_{EVSE})$) where r_{EV} and r_{EVSE} represent the radio transmission ranges of nodes *EV* and *EVSE* respectively.

The connectivity graph after charging slots assignement is denoted $G_A=(V,E,A_G)$ where $A_G=\{A_G(EV), \forall EV\in N\}$ and $A_G(EV)$ is the set of charging slots assigned to *EV*.

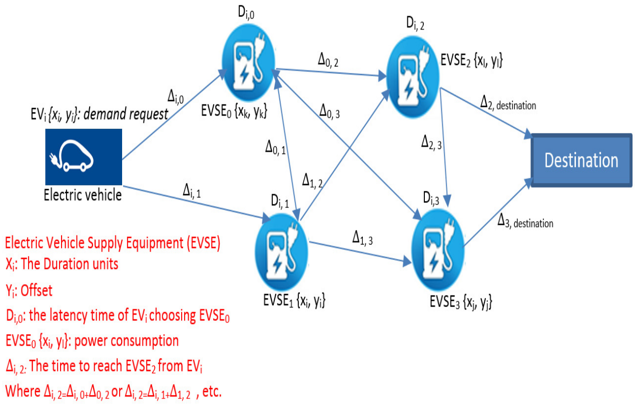

Fig.2. Connectivity graph: An example network of different paths connecting EV_i to a destination.

3.3 Broadcast communication in REBECA

We give an example of the dynamic adjustment of electricity use on EVSEs using the random access allocation algorithm of Rebeca which is illustrated in Fig.3. Thereafter, in Fig. 4, we show for the same exampling Fig.3, the corresponding sequence diagram of power discovery messages between EVs and EVSEs based on REBECA.

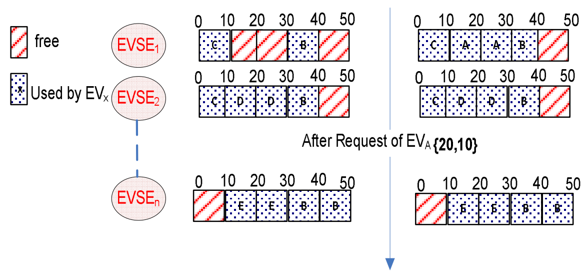

Fig.3. An example of dynamic adjustment of electricity use on EVSEs using random access allocation algorithm

Fig.3 depicts an EV_A request to M EVSEs with which it can communicate over-the-air. EV_A request comprises a couple $\{x_A, y_A\}$, where x_A designates the plugin time duration desired by EV_A, and y_A designates the duration offset desired by EV_A.. In the example, we consider that there some charging slots that are being used in EVSEs as shown in Fig.3, and some other charging slots are free. Free charging slots are advertised by each $EVSE_x$ as a set of couples $\{x_x, y_x\}$, where x_x designates the time duration of empty slots at $EVSE_x$, and y_x designated the corresponding offset.

In the example in the figures, an EVSE is chosen randomly among the set of available EVSEs. In this example, EV_A will select the random available duration among the set of feasible EVSEs, e.g., in Figures 3-4, it chooses the $EVSE_1$ since the free duration ({20, 10}, {10, 40}) is bigger than the demand of EV_A {20, 10}.

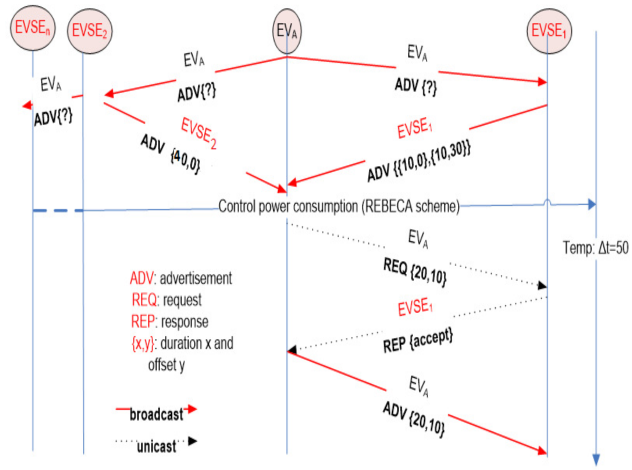

Fig.4. Sequence diagram of power discovery messages between EVs and EVSEs based on the example in Fig. 3.

Fig.4 shows the sequence diagram illustrating the interactions between a number of EVSEs and an EV. The EVSEs and EV are assumed to be in range of each other using their chosen wireless communication technology. A shown in the diagram, EV_A sends an advertisement to neighboring EVSEs asking them about their available charging time slots. Subsequently, $EVSE_1$… $EVSE_{|M|}$ advertise their available time slots as couples {x: duration, y: offset}. For example, $EVSE_1$ sends the values ({10, 0}, {10, 30}), meaning that slots {20, 10} and {10, 40} are available. Given that EV_A has a demand of 20 and that we use here a random access allocation, EV_A sends a unicast message to $EVSE_1$ with values {20, 10} asking to reserve a 20 charge duration from offset 10. Subsequently, $EVSE_1$ send back an "accept message" to EVA, updates its account of available slots, and broadcast to all EVs in the range, its new availability.

3.4 Problem formualtion

We formulate the CSA problem as a multi-objective optimization model. Table I shows the notations used to describe the model.

TABLE I. NOTATIONS PARAMETERS AND VARIABLES

P_0	The unit power
τ	The time unit deployed in a time interval
x_i	The Duration units
y_i	The offset
P_{EV_i}	Power of vehicle EV_i
P_{EVSE_j}	Power of $EVSE_j$
D	The time an EV spends in the system (latency time of EV)
Δ	The time to reach the chosen EVSE
a	The Arrival time of EV
T	The service time of EV
λ	The average rate of arrival rate of EVs
W	The time spent waiting in the queue (waiting time of EV)

μ	Average rate time of departure of EVs: the time between successive arrivals, is exponentially distributed with μ and independents of the past
$D_{predefined}$	A threshold QoS value of maximum accepted latency time in our REBECA scheme
$N(EVSE_i)$	The set of the neighboring EVSEs in the transmission range of $EVSE_i$.
$\|M\|$	The number of EVSEs
$\|N\|$	The number of EVs
$l_{EV_i EVSE_j}$	A binary connectivity parameter that assumes 1 if $EV_i, EVSE_j, i \neq j, i \leq \|N\|, j \leq \|M\|$ are connected via a wireless link; 0 otherwise
$z_{EV_i EVSE_j}$	A binary activation parameter that assumes 1 if a traffic message exists between $EV_i, EVSE_j, i \neq j, i \leq \|N\|, j \leq \|M\|$; 0 otherwise
$A_G(EV)$	The set of charging slots assigned to EV
$f_{EV_i EVSE_j}$	The traffic message broadcasted/unicasted from EV_i to $EVSE_j$ $\forall j \in \|M\|$

Accordingly, our CSA model is formulated as follows:

Objective functions

$$Min[\max_{i \neq j, j \in N(EVSE_i), i, j \leq |M|} |P_{EVSE_i} - P_{EVSE_j}|] \quad (1)$$

$$Min(D_{EV_{i, i \in N}}) \quad (2)$$

Subject to constraints

$$D_{EV_i} = a_i + T_i + W_i + \Delta, \forall i \in N \quad (3)$$

$$\tau = {e_0}/{P_0} \quad (4)$$

$$W_i = (y_{EV_i} - y_{EVSE_j}) \times \tau, \forall i \in N, \forall j \in M \quad (5)$$

$$\text{EVSE} \geq \sum_{i \in N} \text{EV}_i \quad (6)$$

$$\text{EV}_i = \{x_i, y_i\}, \forall i \in N \quad (7)$$

$$D_{EV_i} \leq D_{predefined}, \forall i \in N \quad (8)$$

$$y_{EV_i} \leq y_{EVSE\,j}, \forall i \in N, \forall j \in M \quad (9)$$

$$z_{EV_i EVSE_j} \leq S \times f_{EV_i EVSE_j}, \forall i \in N, \forall j \in M, \forall S \in R^+ \quad (10)$$

$$S \times z_{EV_i EVSE_j} \geq f_{EV_i EVSE_j}, \forall i \in |N|, \forall j \in |M|, \forall S \in R^+ \quad (11)$$

$$z_{EV_i EVSE_j} \leq l_{EV_i EVSE_j}, \forall i \in N, \forall j \in M \quad (12)$$

$$\sum_{j \in M} \sum_{i \in N} l_{EV_i EVSE_j} = 1, \forall i \in N \quad (13)$$

$$z_{EV_i EVSE_j} \leq S \times W_i, \forall i \in N, \forall j \in M, \forall S \in R^+ \quad (14)$$

$$S \times z_{EV_i EVSE_j} \geq W_i, \forall i \in N, \forall j \in M, \forall S \in R^+ \quad (15)$$

$$\sum_{j \in M} f_{EV_i EVSE_j} \leq \lambda_i, \forall i \in N \quad (16)$$

$$\sum_{j \in M} f_{EV_i EVSE_j} \geq \mu_i, \forall i \in N \quad (17)$$

In our model, the objective function (1) minimizes the charging load variance between all neighboring EVSEs to balance the energy usage. The objective function (2) minimizes the latency time of EVs.

Constraint (3) computes the latency time of a vehicle request on the road up until the time the service has been completed. Constraint (4) computes the time unit deployed in a time interval. Constraint (5) computes the waiting time of an EV. Constraint (6) ensures that the total demand in an EVSE at time t does not exceed the total capacity of the EVSE. Constraint (7) states that each EV demand is characterized by a couple of duration x and offset y. Constraint (8) prevents the latency time of an EV to violate the threshold value of maximum delay. Constraint (9) ensures that the EV demand offset is available on the requested EVSE. Constraints (10) and (11) ensure that if a message is exchanged between EV and EVSE, then the link, between EV and EVSE is active; S is a positive big value. Constraint (12) ensures that a wireless link is active only if it exists. Constraint (13) forces each EV to connect to at least one EVSE. Constraints (14) and (15) ensure that if an EV is waiting for service from an EVSE, then the link, between EV and EVSE is active. Constraints (16) and (17) define the traffic message balance equations for each EV in the smart grid.

The objective function (1) is not linear. In the following, we propose a method to linearize it. We modify the objective function (1) to

$$Min\ \Omega \quad (18)$$

Subject to the following constraint:

$$|P_{EVSE_i} - P_{EVSE_j}| \leq \Omega \Rightarrow \begin{cases} \Omega \geq P_{EVSE_i} - P_{EVSE_j} \\ \Omega \geq -P_{EVSE_i} + P_{EVSE_j} \end{cases}, \forall EVSE_i \in M, EVSE_j \in N(EVS \quad (19)$$

Constraint (19) ensures that the objective function (1) is linear and can be used during the resolution of the proposed model.

IV. SOLVING THE MODEL

In the previous section, we proposed a multi-objective model to solve the CSA problem. However, for the sake of simplicity (solving the problem using pure multi-objective optimization methods is for future work), we convert it to an aggregated form using a single objective function defined in equation (20):

$$Min(\alpha_1 \Omega + \alpha_2 D_{EV_{i, i \in N}}) \quad (20)$$

where $\alpha_1 + \alpha_2 = 1$, α_1, α_2 are positive weight coefficients.

The determination of the "optimal" values of α_1, α_2 is out of the scope of this paper; in future work, we will investigate the use of the analytical model proposed in [15] to determine these values.

4.1 Heuristic algorithm method

A heuristic algorithm called CSAH is used to provide a feasible CSA solution to the proposed optimization model. First, we determine the connectivity graph of the smart grid, and arbitrarily assign charging slots to EVs based on a random access allocation algorithm as shown in step0 in Alg.1 to get an initial solution. Second, the CSAH algorithm, carefully reassigns charging slots to EVs with the objective of selecting the smallest free location $\{x_{best}, y_{best}\}$ which is able to fulfill a demand of EV of x duration and offset y {x, y} and consequently limiting capacity wastage on the EVSE.

$$\{x_{best}, y_{best}\} = \arg_{\{x_{best}, y_{best}\}} \min\{x_i - x\} \tag{21}$$

The CSAH algorithm determines a feasible solution that is certainly sub-optimal. The rationale behind CSAH algorithm is that having small gaps in the Δt may lead to power capacity wastage. The pseudo code of CSAH is shown in Alg.1.

Alg. 1 : Heuristic CSAH algorithm

Input: random CSA, EVs, EVSEs
Output: new CSA

Step0: initialization
Build an initial/feasible solution as follows: (1) Assign charging slots randomly;

$$\{x_{first}, y_{first}\} = random\{x_i, y_i\}$$

Step1: Messages exchanges between EV and EVSEs
1.1 ADV EV_i *{(),()...}*; /* Advertisement to know available units */
1.2 ADV *EVSE {(x , y)...}* /* Advertisement of available units in *EVSE ;* where *x* is the duration and *y* is the offset*/
1.2 REQ EV_i *to EVSE* /* Request (Unicast) based on randomly selection of *EVSE* */
Step2 : Search for the smallest free location
If $P_{EVSE} - \sum_i P_{EV_i} < \varepsilon$ **then** select *EVSE ;*
Step3 : Search for near optimal solution
3.1 RESP *EVSE to* EV_i /* Response (Unicast) */
3.2 $P_{EVSE} - \sum_i P_{EV_i}$
Go to steps 1.1-1.2**;** /* Update power charging status */
If waiting time is recurred
then compute D_{EV_i}
If $D_{EV_i} \le D_{predefined}$ **then** evaluate the objective function (20)
EndWhile

V. SIMULATIONS RESULTS

To assess the quality of the solutions returned by CSAH, we compare them to CPLEX solutions [4]; CPLEX provides exact solution (i.e., the optimal solution) of the proposed model but only for small size networks; for realistic size networks, it does not return a solution in a reasonable time.

The evaluated topology is illustrated in Fig. 2 with parameters in Table II. Simulations results are produced using CPLEX solver [4] and C/C++. Simulation results are averaged over enough runs to reach a confidence of 95%.

TABLE. II. SIMULATIONS PARAMETERS

τ	0.1
Δ	5 units
Number of EVSEs	5
Number of EVs	10..130
λ , μ	1
$D_{predefined}$	100 units

It is worth to note that for low and light loads, we get results from CPLEX in reasonable time but starting from 90 vehicles, we face the problem that CPLEX does not return a solution before more than 4 hours, which is not acceptable. That is why, for a realistic network size, it is advisable to use heuristics, as our proposed heuristic CSAH, to solve the time problem.

We kept these results to assess the quality of our proposed heuristic solution CSAH and we can see easily that CSAH performs well either on low or high loads and returns solutions in very reasonable time (~700ms).

5.1 Unsatisfied vehicles where $\alpha_1 = 0$

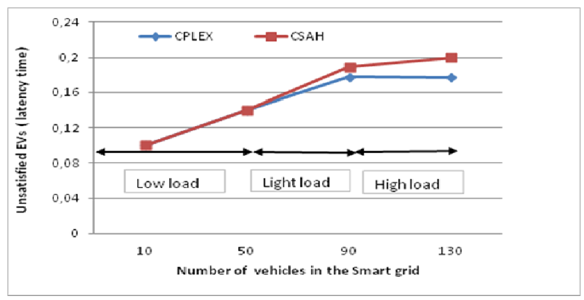

Fig.5. Performance of both CPLEX and heuristic based on latency time on EVs

In Fig.5, the quality of service (QoS) is defined as the ratio of the numbers of vehicles that get serviced with a latency that does not exceed the predefined threshold, to the total number of vehicle to be serviced. We distinguish between low, light and high network load conditions (EV number).

With CSAH method, in the low load, the QoS reaches 90%, in the light load it is reduced to 84% and in high load, it is equal to 82%.

Taking into account only the second objective function based on minimizing latency time, our method achieves very acceptable QoS. However, we notice that in high load, another criterion should be considered to improve the solution such as balancing the energy usage on EVSEs.

5.2 Unsatisfied vehicles where $\alpha_2 = 0$

In Fig.6, we take into consideration only the first objective function which is based on minimizing the charging load variance between all neighboring EVSEs to balance the energy usage. With CSAH method, in the low load, the QoS reaches 90%, in the light load it is reduced to 84%, and in high load it is equal to 79%.

We conclude that it is beneficial to consider both criteria, i.e. latency time on EVs and balancing the energy use on EVSEs. For that, in the following, we use Eq.20 to aggregate the two objective functions and to investigate the intimate relationship between these criteria.

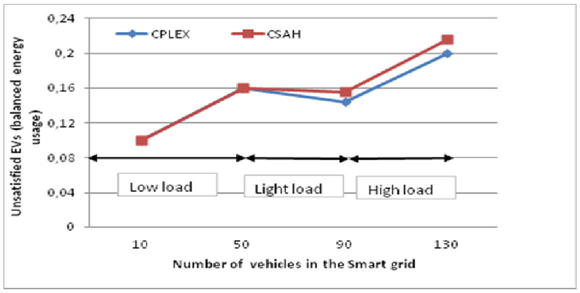

Fig.6. Performance of both CPLEX and heuristic based on balanced energy usage on EVSEs

5.3 Unsatisfied vehicles where $\alpha_1 = \alpha_2 = 0.5$

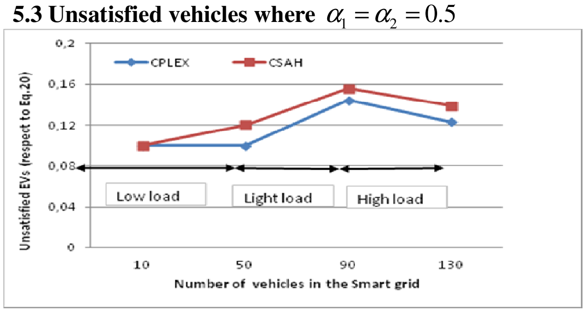

Fig.7. Performance of both CPLEX and heuristic based on latency time on EVs and balanced energy usage on EVSEs

Fig.7 shows the best results in terms of QoS, particularly in high load (e.g., number of EVs=90..130). The QoS is equal to 87% which is very desirable in dense networks.

5.4 ***The energy usage on EVSEs while*** $\alpha_1 = \alpha_2 = 0.5$

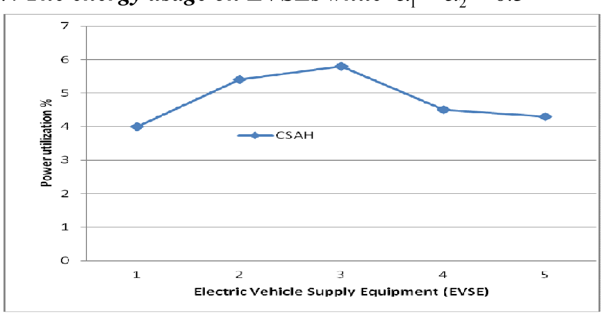

Fig.8. Power utilization in each EVSE

In Fig.8 we consider 100 vehicles. CSAH is able to reduce efficiently the variance of power in different EVSEs in the system while providing the QoS required by EVs as shown in Fig.7. As an example, the variance between EVSE (4) and EVSE (5) is equal to 4% which is desirable.

VI. Conslusion

In this paper, we propose a new unified/generalized model for the slot charging assignment problem in the smart grid. Our proposed scheme reduces the latency time on EVs, while it balances the charge usage on EVSEs.

Currently, we plan to use pure multi-objective methods to solve this problem. Moreover, we will investigate the case where the EV does not go to the chosen EVSE as previously reserved.

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