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Dynamic Wireless Charging of Electric Vehicles: Supercapacitor Integration at the Service of Energy Management Optimization

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ABSTRACT

The wide deployment of electric vehicles (EVs) is mainly linked to the extensive development of charging infrastructures. Dynamic wireless power transfer (DWPT) seems to be a viable solution that deals with EV's major challenges such as autonomy. In-motion charging would improve sustainable mobility by reducing storage system weight. However, large power rates are required for such applications since energy transfer must occur quickly and must match the power requirements of various vehicles. The vehicle design, road infrastructure, and electrical network are all affected by this tendency. Power-flow smoothing is essential to eliminate pulsations generated by vehicle motion as well as power peaks caused by the WPT as part of the electrified road system, which have an impact on the total electrical load. In this paper, we present an optimal energy management scheme for the supercapacitor integration in order to meet the WPT demand and reduce the pulsation caused by EV's demand.

***Index Terms*—**Energy management optimization, dynamic wireless power transfer, electric vehicles, supercapacitor.

I. INTRODUCTION

The road transport sector is now at a major technological turning point. With the emergence of electric vehicle (EV) manufacturers, electric mobility began a new era with large-scale deployment of plug-in EV chargers and the increase of battery total efficiency [1]. The low costs of standard vehicles boosted their number, causing massive fuel consumption and exhaust emission increase, which is an important factor for the sustainable development of our country and present a serious threat [2]. Indeed, the sector's decarburization objectives for 2050 aim on the shift from combustion engine mobility to cleaner electric propulsion methods [3].

In today's era, automobiles come to be a part of many households. Types and brands are constantly being upgraded, offering more performance and driving potentials, while manufacturers offer a various range of light- and heavy-duty vehicle lines extending from petroleum-powered vehicles to all-electric vehicles (EVs) [4]. Despite the emergence and development of this technology, it is still limited by its autonomy, the method, and time required for recharging [5]. Generally, there are two technics to recharge an EV: the plug-in technology based on a regular cable connected directly to the grid done on a charging station or at home and wireless charging based on a magnetic field [6]. The wireless charging could be static or dynamic; the first one relies on charging EVs on the stop while the other one could be achieved when the EV is moving. The wireless charging is simple to use, reliable, and more resistant to damage than the conventional charging wires [7]. Furthermore, it enables a real-time supply/recharge that is entirely transparent to the user. Indeed, the ability to continuously feed the vehicle while it is in motion will relieve the user of the need to stop to recharge. This appears to be the future of transportation because it overcomes the technical barrier while also significantly reducing the vehicle's weight and cost [8]. The development of contactless battery recharging will help EVs gain traction in the transportation business.

However, the number of buyers has reached more than 10 million by 2019 [9], and the massive integration of EVs will have an impact the electrical grid due to the unpredictable charging and significant amount requirement for charging EVs [10]. In fact, EVs would have a substantial impact

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on electrical grid stability since they are charged from the grid and are "big users" of electricity at random [11]. Therefore, charging of these new vehicles must always be ensured and operated in such a way that it does not have a significant impact on power networks [12].

A previous literature [13] studied the installation of high-power capacitors both on the grid and in the vehicle. The current used to charge the vehicle's battery was reduced by 84%, and the grid connection was reduced by 81%.

Using these hybrid topologies aid in the improvement of dynamic wireless power transfer (DWPT) results [14]. A fast-responding, high-power element must be added to the grid supply [15], which will aid in achieving the ideal stability by supplying the necessary electricity and recovering the excess [16]. The insertion of a supercapacitor (SC) in the grid side reduces the impact of this technique on the electric grid [17].

A storage technology based on SCs as local power caches is being investigated to feed EVs by WPT since the DWPT' operating mechanism necessitates short-term power peaks. Through bus voltage management, SCs deployed as a buffer offer grid immunity for EV's high-power charging needs.

Dynamic wireless power transfer has been the subject of numerous studies, both theoretical and practical, with promising results in terms of efficiency and dynamic responsiveness [18]. Even then, only a few have attempted to investigate the impact of these kinds of systems on the electric grid, particularly in high-demand situations, and whether they are a good alternative or complement to static charging (wireless or plug-in) [19].

This paper aims to study the energy management of SC integration to the grid for DWPT and organized as follows: Section II provides a description of the studied system. A long-track DWPT charging system is described in Section III. A circuit model is constructed with the insertion of many SCs in parallel to the grid for feeding EV with wireless charging. Section IV introduces the optimization problem adopted for the energy management system of grid with SCs. We use MATLAB for the resolution of the problem. Finally, the results and a discussion are presented in Section V.

II. SYSTEM DESCRIPTION

Most paper and works consider the traditional network as the unique source that supply EV with WPT [20]; however, none of them have managed the energy management method for SC integration to supply EV with WPT and have mathematically defined an optimization problem, to our knowledge. For that matter, in this study:

1) we will provide a strategy to protect the electrical grid from DWPT intrusion while also supplying enough power for charging EVs at fast speeds,
2) we use SCs as local power catches to smooth the EV's demand and avoid the impact to the grid,
3) we explore the energy management optimization for the insertion of SCs on the grid side. The main topology considered, as seen in Fig. 1, consists of an electrical grid connected to a DC bus through an AC/DC inverter and SC connected to a DC bus through DC/DC converters,
4) we suggest an optimal energy management method in order to decrease the fluctuation of current flowing in/out of grid, and
5) we formulate the optimization problem to find the best solution for managing the current flow in the grid side for supplying EV with WPT.

III. DYNAMIC WIRELESS POWER TRANSFER AND THE SUPERCAPACITOR INSERTION

A. Mechanical Power

Understanding how much electricity is necessary is critical; vehicle power consumption determines the amount of power required from DWPT systems on the roadway. The amount of power necessary to propel an EV is the amount that overcomes friction forces caused by weightlessness, aerodynamics, and rolling [21]. The expression of a vehicle's power P at a particular speed can be described using (1), which takes into consideration all of these factors [22, 23]:

$$P=[C_r.M.g.\cos(-)+M.g.\sin(-)+M.a+\frac{1}{2}.\rho.s.C_x.V^2].V \tag{1}$$

where M is the total mass of vehicle, V is the relative speed, g is the acceleration of gravity, α is the vehicle tilt angle with the horizontal axis, a is the vehicle acceleration, C_r is the rolling resistance coefficient, ρ is the air density, C_x is the coefficient of penetration in air, and s is the front section of the vehicle.

B. Wireless Power Transfer Electrical Power

Fig. 2 shows the equivalent circuit diagram of an electrified road for a DWPT system, where U is the grid voltage after rectification, C_r, L_r, and R_r are the capacity, impedance, and resistance on the road side and C_{vi}, L_i, and R_i are the capacity, impedance, and resistance on the vehicle side, and $i=1, \ldots, n$. Power electronic represents all the converters inside the vehicle [24].

With the Kirchhoff's law, we could obtain (2) [25]:

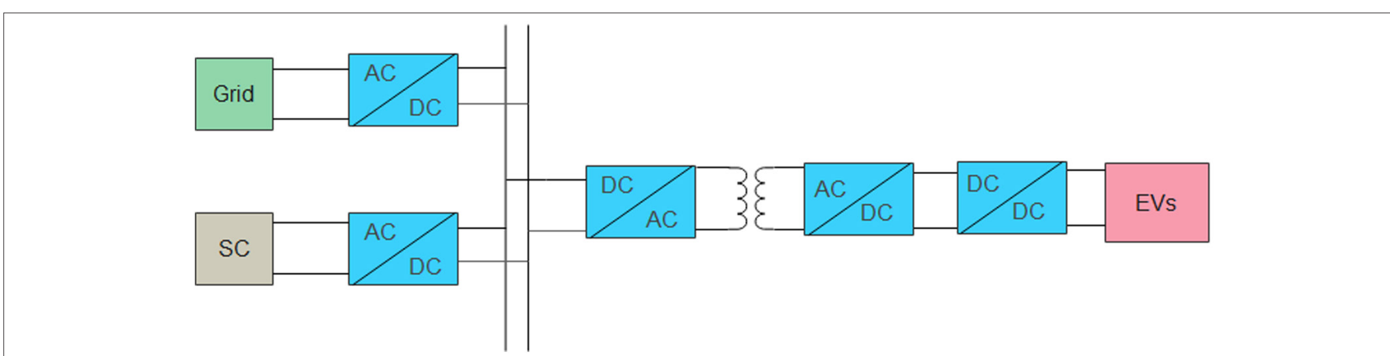

Fig. 1. System architecture.

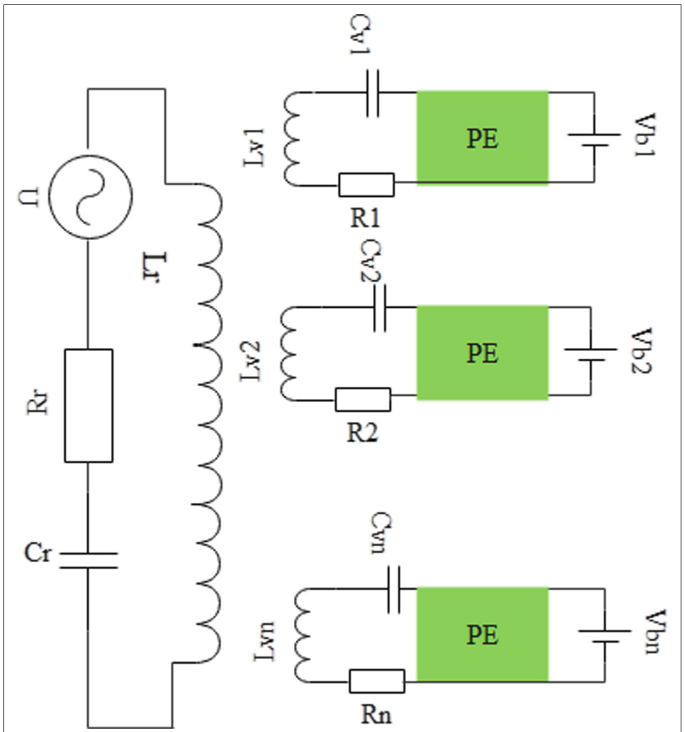

Fig. 2. Equivalent circuit diagram of long-track dynamic wireless power transfer.

$$\begin{cases} U = Z_r L_r - \sum_{i=1}^{n} j\omega M_i I_i \\ j\omega M_i I_r = Z_i I_i \left(for\ i = 1..n\right) \\ Z_r = R_r + j\omega L_r + \dfrac{1}{j\omega C_r} \\ Z_i = R_i + \dfrac{1}{j\omega C_{vi}} + j\omega L_i + R_{v_i} \end{cases} \tag{2}$$

where ω presents the operating frequency, Z_r is the impedance equivalent of the roadside, and Z_i is the impedance equivalence for the vehicle *i* (I = 1, …, *n*) assuming that the EV's battery corresponds to a load equivalent to R_{v_i}.

Assuming the system is in the resonance state, C_r, L_r, C_{vi}, and L_i for each $I = 1, ..., n$, and using the equation below, the current in the road as a function of the EV's current might be expressed as [26]:

$$L_r = \frac{U}{Z_r + \sum_{i=1}^{n} \frac{\omega^2 M_i^2}{z_i}} \tag{3}$$

$$I_{EV_i} = \frac{j\omega M_i}{Z_i} \cdot Ir = \frac{j\omega M_i U}{Z_i (Z_r + \sum_{i=1}^{n} \frac{\omega^2 M_i^2}{z_i})} \tag{4}$$

where I_{EV_i} represents the current in the *i*th EV. As a result, the charging power for each EV is:

$$P_{EVi} = R_{v_i} I_i^2 = \frac{j\omega M_i}{Z_i} \cdot Ip = \frac{\omega^2 M_i^2 U^2 R_{v_i}}{Z_i^2 (Z_r + \sum_{i=1}^{n} \frac{\omega^2 M_i^2}{z_i})^2} \tag{5}$$

To simplify this model, we assumed that all EV coils are identical and smaller in geometry than road coils and that EV behavior when crossing an electrified road is the same. The equivalent vehicle's load is Rv, and we could set R1 = R2 = … = Rn = R and M1 = M2 = … = Mn, and the equivalent charging power is:

$$P_{EVi} = \frac{\omega^2 M^2 U^2 R_v}{\left[\left(R + R_L\right) R_p + n\omega^2 M^2\right]} \tag{6}$$

C. Insertion of a Supercapacitor

Fig. 3 presents the utility *U* as the grid, a multiple SC, and the electrified road feeding the vehicle. A real-time controller that measures

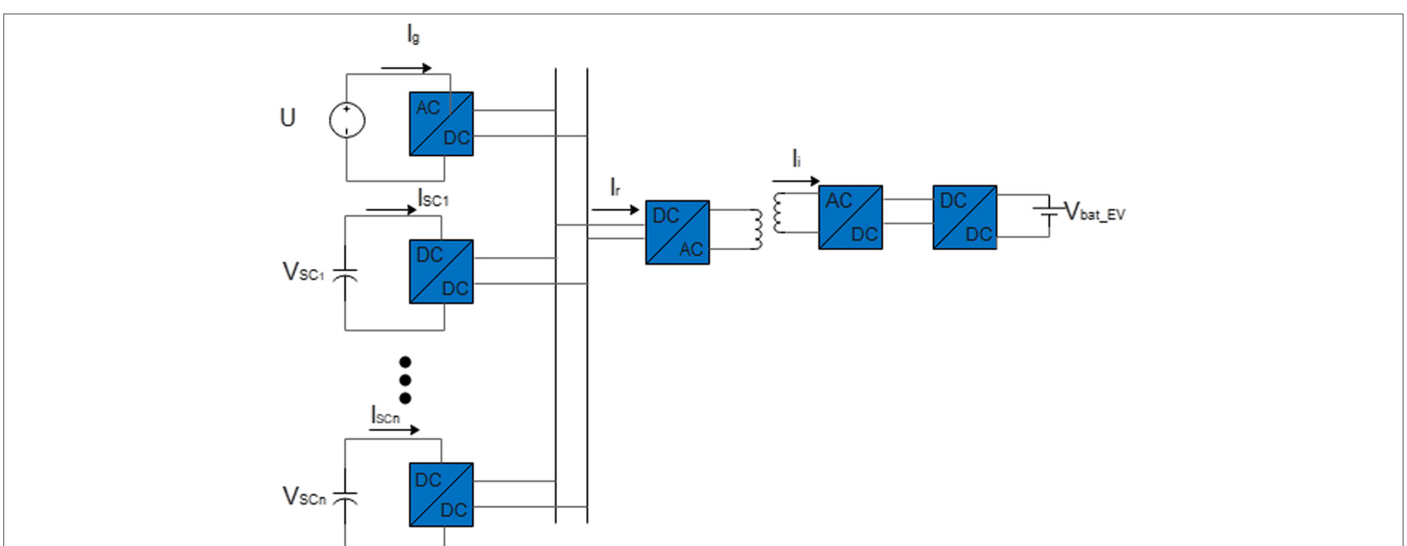

Fig. 3. Main topology considered.

current flow controls the DC/DC converters and AC/DC inverters; DC/AC inverters are used to link the electrified road to the DC bus.

According to Fig. 3, we have:

$$\begin{cases} I_g + \sum_{n \epsilon N} I_{scn} = I_r \\ I_r = K . I_{EV} \end{cases} \tag{7}$$

where n represents the number of SCs, I_g represents the grid current, and I_{scn} represents the current following in the n SC.

$$K = \frac{Z}{j\omega M} \tag{8}$$

From the two equation (7), we deduce:

$$I_g + \sum_{k \epsilon K} I_{sck} = K . I_{EV} \tag{9}$$

This work is considering a small-scale study as it emphasizes on the energy management for a single vehicle demand.

IV. APPROACH AND MODELING

A. Optimization Based on Penalty Function

This study is carried out by formulating a problem that minimizes the grid's magnitude of current fluctuation, in order to make an optimization of grid supply, with the integrations of SC current considering the energy loss induced by the SCs. The objective is to see the interest of the insertion of SCs in the grid side for supplying EV with wireless power transfer and set an optimal energy management for the system taking into account the energy loss induced by the SCs.

The group of SCs is denoted as $SC = \{sc_n / n \in N\}$, where n is the number of SCs. The grid current i_{grid}, SC current i_{sc}, and SC voltage v_{sc} are controlled dynamically by the two converters DC/DC and AC/DC. We presume that we measure voltage and current with a discrete signal in a sufficiently small sampling period.

The nth SC sc_n can be characterized by the following parameters: capacitance C_n, equivalent serial resistance (ESR) of capacitor R_{scn}, and the maximum capacitor voltage $v_{sc_n}^{max}$. Due to the ESR virtually connected with SC as described in Fig. 4, energy loss is induced in the charging and discharging of the SCs [27].

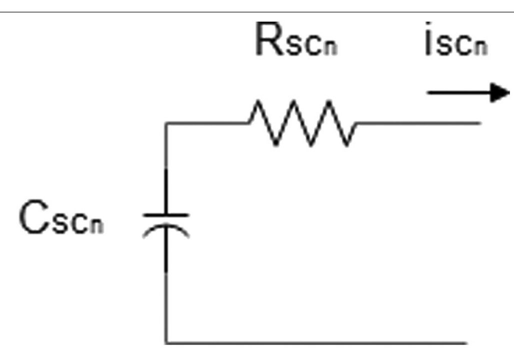

Fig. 4. Equivalent circuit of SC.

We assume that the current I_r is DC. $v_{sc_{kn}}$ can be calculated by the following classic equation:

$$V_{sc_n}(t) = -\frac{1}{C_n} \sum_{\tau=0}^{T} i_{SC_n}(\tau) \Delta \tag{7}$$

1) Formalization of the Optimization Problem

This case is designed in a way that provides an optimal command able to protect the electrical network against the high EV's current demand. To do so, the general problem is translated into a non-linear mathematical optimization problem that minimizes both the current provided by the grid and its fluctuation under the constraints of the combination of the two systems as seen below:

Problem:

$$\text{Min } \alpha \sum_{t=1}^{1200} \left(i_g(t)\right)^2 + (1-\alpha) \sum_{t=2}^{1200} \left(i_g(t) - i_g(t-1)\right)^2 \tag{8}$$

subject to

$$i_g(t) + i_{sc}(t) = i_r(t)$$

$$V_{sc_n}(t) = -\sum_{\tau=0}^{T} \left(\frac{\Delta}{C_n} i_{sc_n}(\tau) + R_{scn} \left|i_{sc_n}(\tau)\right|\right)$$

$$V_{sc_n}(1) = V_{sc_n}(T)$$

$$V_{sc_n}^{ref} = V_{sc_n}(1)$$

$$0 \le V_{sc_n}(1) \le V_{sck}^{max}$$

$$0 \le \left|i_g(t)\right| \le i_g^{max}$$

$$0 \le \left|i_{sc}(t)\right| \le i_{sc}^{max}$$

$$t \in T$$

2) Log-Barrier Function

We introduce the following log-barrier function so as to define our objective function:

$$\varphi(x,\delta) = \begin{cases} -\delta^2 log\left(1 - \left(\frac{x}{\delta}\right)^2\right) & |x| < \delta \\ \infty & |x| < \delta \end{cases}$$

Using this log-barrier function, we formulate a penalty function approximation problem [28]. It is difficult for x to be greater than δ or lower than $-\delta$ owing to the infinite penalty for $|x| < \delta$. By combining the log-barrier function to the objective function, the magnitude/fluctuation of the grid current can be restricted within a particular boundary.

The objective function for the grid current magnitude is defined by $\varphi(i_g(t), \delta_1)$ and that for the grid current fluctuation is defined by $\varphi(i_g(t) - i_g(t-1), \delta_2)$ where δ_1 and δ_2 are the parameters that decide the distribution range of x and are adjustable [29]. The formulation of can be represented as:

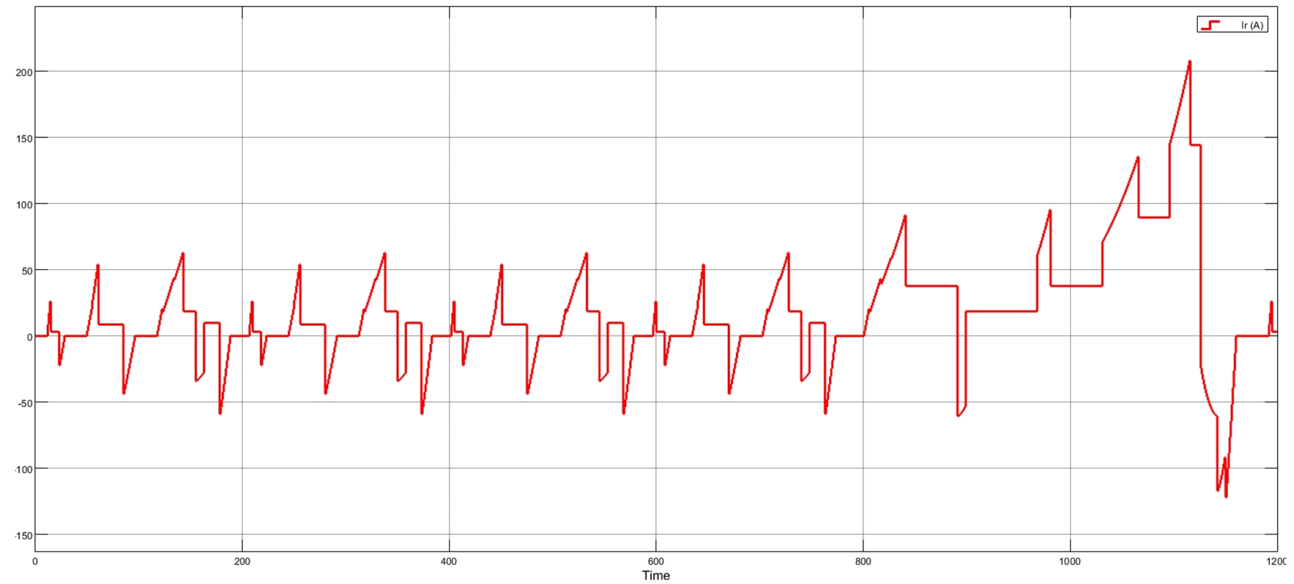

Fig. 5. Current demand by electric vehicles (in A) following the NEDC cycle.

Problem:

$$\text{Min}\ \alpha\sum_{t=1}^{1200}\varphi\left(i_g(t),\delta_1\right)+(1-\alpha)\sum_{t=2}^{1200}\varphi\left(i_g(t)-i_g(t-1),\delta_2\right) \quad (9)$$

subject to

$$i_g(t)+\sum_{n\epsilon N} i_{scn}(t)-i_r(t)=0$$

$$V_{sc_n}(t)=-\sum_{\tau=0}^{T}\left(\frac{\Delta}{C_n}i_{sc_n}(\tau)+R_{scn}\left|i_{sc_n}(\tau)\right|\right)$$

$$Vscn(1)=Vscn(T)$$

$$V_{sck}^{ref}=Vsck(1)$$

$$0\leq Vsck(1)\leq V_{sck}^{max}$$

$$0\leq\left|i_g(t)\right|\leq i_g^{max}$$

$$0\leq\left|i_{sc}(t)\right|\leq i_{sc}^{max}$$

$$t\in T, k\epsilon K$$

We consider that $\alpha=0.5$

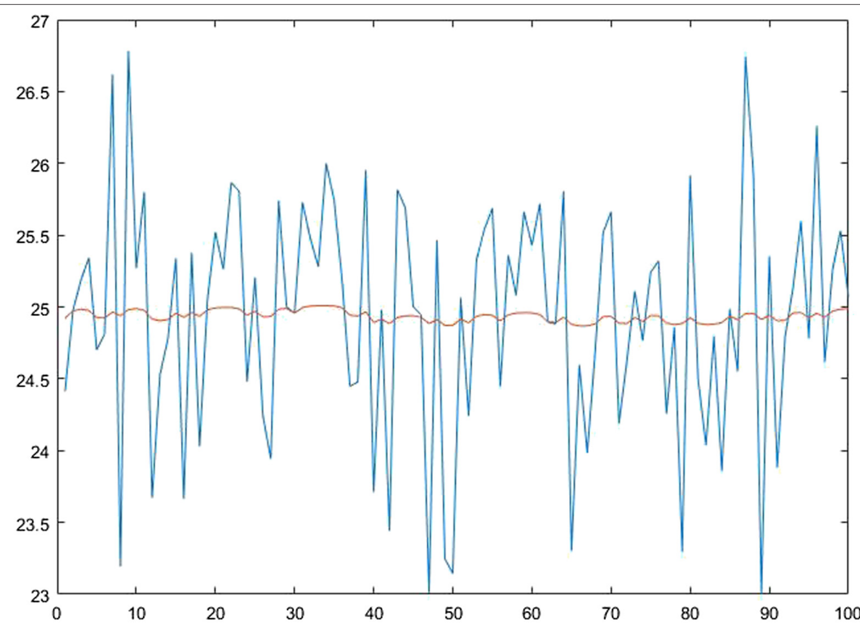

Fig. 6. Simulation result for $T=100$, the current demand (in A) following the NEDC cycle (blue), and the current supply by the grid (red).

Due to the terminology $\left|i_{sc_n}(t)\right|$, in the constraints, the formulation provided in (9) does not take the form of a convex optimization problem. This term $i_{sc_n}(t)$ could be rewritten as the sum of $i_{sc_n}^{in}(t)$ and $i_{sc_n}^{out}(t)$ as $i_{sc_n}(t)=i_{sc_n}^{out}(t)-i_{sc_n}^{in}(t)$; in this formula, $i_{sc_n}^{out}(t)$ is the current flowing out of the SC, $i_{sc_n}^{in}(t)$ is the current flowing into the SC, and both are positive. This problem would be solved based on the interior point method.

This problem is equivalent to a convex optimization problem in the matrix form as below:

Problem:

$$\text{Minimize } \alpha\varphi(I_{bat},\delta_1)+(1-\alpha)\varphi(FI_{bat},\delta_2) \tag{10}$$

subject to

$$I_g+\sum_{k\in K}(I_{sc_k}^{out}-I_{SC_k}^{in})-I_r=0$$

$$(A-I)V_{sc_k}-B_k^{out}I_{sc_k}^{out}-B_k^{in}I_{sc_k}^{in}=0$$

$$EV_{sc_k}=0$$

$$0\le V_{sc_k}\le V_{sck}^{max}$$

$$k\in K$$

where

$$\varphi(g,\delta)=\sum_t\varphi(i_g(t),\delta)$$

$$I_g=\left[i_g(1),\ldots,i_g(T)\right]$$

$$I_{SC_k}^{out}=\left[i_{sc_k}^{out}(1),\ldots,i_{sc_k}^{out}(T)\right]$$

$$I_{SC_k}^{in}=\left[i_{sc_k}^{in}(1),\ldots,i_{sc_k}^{in}(T)\right]$$

$$V_{SC_k}=\left[v_{sc_k}(1),\ldots,v_{sc_k}(T)\right]$$

$$A=\begin{bmatrix}[1,0,\ldots,0] & 0_{1x1}\\ I_{TxT} & 0_{Tx1}\end{bmatrix}$$

$$B_k^{out}=\left(R_{SC_k}+\frac{\Delta}{C_k}\right)\begin{bmatrix}0_{1xT}\\ I_{TxT}\end{bmatrix}$$

$$B_k^{in}=\left(R_{SC_k}-\frac{\Delta}{C_k}\right)\begin{bmatrix}0_{1xT}\\ I_{TxT}\end{bmatrix}$$

$$E=(1,0,\ldots,0,-1)\in R^{(T+1)}$$

$$F=\begin{bmatrix}1 & -1 & 0 & \ldots & 0 & 0\\ 0 & 1 & -1 & 0 & \ldots & 0\\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots\\ 0 & \cdots & 0 & 1 & -1 & 0\\ 0 & 0 & \ldots & 0 & 1 & -1\end{bmatrix}$$

This problem is suitable for optimizing energy supply from the grid with SCs integrated to the electrified road for the EVs' DWPT. The data considered in the simulation are exploded in the following paragraph.

B. System Characteristics

For this work, we consider an EV whose characteristics are described in Table I:

The purpose of our dimensioning is to determine the current delivered by the electrified road, required in order to cover a distance with a variable speed profile without EV's battery operation. This speed profile considered in this work is New European Driving Cycle (NEDC) cycle, composed of four repeated urban driving cycles called UCE-15 and an extra urban cycle Extra-Urban Driving Cycle (EUDC) [30]. The vehicle current I_{EV} according to the NEDC profile can be calculated by (1) and represented in Fig. 7.

V. RESULTS AND DISCUSSION

The simulation was done by MATLAB in order to establish the proposed optimization formulations and algorithm at $\delta_1=50$, $\delta_2=0.2$, and $T=1200$ s.

TABLE I. THE CHARACTERISTICS CONSIDERED IN THE STUDY

Maximum weight	1000 kg
Average speed	45 km/h
Maximum speed	120 km/h
Acceleration from 0 to 45 km/h	Less than 15 s
Autonomy	100 km
Coefficient of penetration in air C_x	0.3
Coefficients of friction C_r	0.0
Front surface	2.5 m^2
Air density	1.225 kg/m^3
Gravity acceleration g	9.81 N/kg

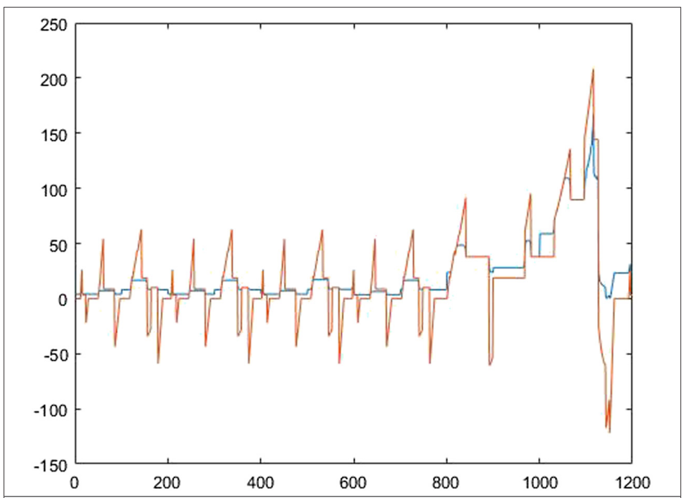

Fig. 7. Simulation result for $T=1200$.

TABLE II. CHARACTERISTICS OF SCS

SC Number	SC Type	C_n (F)	R_{scn} (m Ω)
1	BCAP0050	50	20
2	BCAP150	150	14

SC, supercapacitor.

For our small-scale simulation, we considered that the grid is connected in parallel as shown in Fig. 3 with two SCs where the characteristics are described in Table II; the current demand suits the NEDC profile [31].

The resolution of the mathematical problem considered is shown in the figure below:

The curve in blue in Fig. 7 represents the current supplied (in ampere meter) by the grid, while the curve in red represents the current's demand by the EV. The current supplied by the SCs is deduced by the difference between the two curves.

This study finally shows that it is quite possible to physically achieve such an optimization system, and it allows to protect the grid and help at the high demand, when the SC meets the instantaneous peak power, which make it possible to minimize the impact of such a technology (wireless charging) on the electrical network [32].

However, this optimization does not take into account disturbances that could affect the vehicle in its path and therefore completely modify the result of the optimization calculation. In addition, it should be completed in the large scale, taking into account an algorithm that performs real-time calculation to achieve the same objective. Moreover, more research in topology, control, inverter design, and human safety is required [33].

VI. CONCLUSION

Wireless power transfer integration into the grid seems as a challenging issue. The entire system's architecture would necessitate interoperability with various vehicle classes and speed. The DWPT's impact on the existing electrical network has yet to be determined. Since the grid charges the SCs at known power rates, the incorporation of SCs banks appears to decrease this impact. The optimization of energy management in grid with SC integration for EVs' charging with DWPT supply is investigated in this work. We discussed optimization methods for minimizing the magnitude and fluctuation for the grid supply.

Crucially, the use of SC energy can minimize the threat to the reliability of the power system, especially when there is a sudden peak power demand. The system mainly improves the following aspects:

1) utilizing the fast charging/discharging capability of SCs, and all the peak of current needed for the NEDC cycle are reduced,
2) the "quick charge and quick release" feature of SCs can help the electric network to recover huge demand during the EVs' acceleration process for example, and its recovery efficiency is higher than that of simple storage as the battery.

As a result, the suggested optimization approach is ideal for the wide development of EVs and its charging infrastructure.

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