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Grid Impact Studies from Dynamic Wireless Charging in Smart Automated Highways

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***Abstract*—Autonomous and electrified mobility are two key developments expected in the next decade to improve the efficiency and reduce carbon footprint of transportation. As electric vehicles (EVs) increase on the roads, one of the issues that needs to be addressed is range anxiety. To mitigate this problem and for seamless integration of EVs, dynamic wireless charging is an attractive solution. In this paper, a few case studies are considered in a smart autonomous highway to understand the impact of dynamic wireless charging on grid dynamics. The studies show that the grid voltages vary significantly due to the dynamic wireless power transfers (DWPTs), if connected to the existing grid. The variations in the grid voltage can reduce power transfers, increase grid instability, and cause inadvertent protection triggers. The inadvertent protection triggers can reduce the reliability of the connected grid. These problems highlight the need for modern grid infrastructure to support DWPT systems.**

I. Introduction

The adoption of electric vehicles (EVs) today is impeded by range anxiety and the lack of adequate charging infrastructure. These issues can be overcome through roadway electrification, which includes the installation of dynamic wireless power transfer (DWPT) systems on the roads. The DWPT systems can reduce the commute time with respect to static wireless charging. The reduced time is a result of not requiring to stop for charging vehicle batteries. The DWPT systems have been studied in literature on low-speed urban infrastructure [1]–[3]. However, most of the travel on urban roads happen over short distances, which do not provide a significant challenge to the adoption of EVs. For most short-distance commute, there is likely to be an opportunity to recharge at the destination without the need for dynamic charging. With most of the long-distance travel happening on highways [4], DWPT infrastructure on highways can play a significant role in reducing range anxiety.

High-power DPWT systems will be necessary for roadway electrification to provide sufficient energy to the EVs. The challenges associated with high-power DWPT systems are increasingly being overcome based on the recent developments [5]. One of the other challenges associated with roadway electrification with high-power DWPT system is the grid infrastructure that is required.

There have been some previous studies to understand the impact of DWPT systems on grid or vehicle [1], [6]–[9]. The economic benefits derived from vehicle-to-vehicle coordinated charging is studied in [6]. The economic co-simulation of traffic-grid is considered in [7] for various electric vehicle (EV) penetration levels to maximize social welfare using a standard IEEE 3-bus and 30-bus systems superimposed on road networks. Quasi DWPT systems were studied in [8] to quantify WPT infrastructure requirements in urban infrastructure. The quasi DWPT systems were considered to have been implemented on the roads near the traffic signals. Various studies were performed to understand the state-of-charge (SOC) variation of the vehicle batteries under different charging profiles and coil misalignments. The effect of DWPT systems on grids at a higher time-scale of minutes was studied in [9]. The support from solar photovoltaic systems and battery storage systems to reduce the power variations were considered in [9]. Several approximations were applied in [9] to study at the higher time-scales such as the first-order approximation of the smoothing that solar photovoltaic systems and battery storage systems can provide. High-fidelity models need

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to be developed to justify the assumption, which has not been considered. Drive-cycles based optimal placement of DPWT systems in highways and urban roadways was studied in [9]. Economic studies were performed in [1] to compare static and dynamic WPT charging of buses under urban drive-cycles. These studies do not consider using electro-magnetic transient (EMT) analysis to quantify the impact of pulsating power required by DWPT systems on grid voltage, which is critical to maintain reliable operation of the grid.

In this paper, EMT studies are performed to quantify the impact of DWPT systems on the grid. These studies are used to understand the grid infrastructure requirements to reduce the voltage variations in the grid. The reduced voltage variations can improve the stability of grids and avoid inadvertent protection triggers. To perform these studies, the vehicle energy use needs to be quantified as described in Section II. The vehicle traffic data in a smart autonomous highway and the corresponding DPWT system infrastructure required to support charge sustaining mode of operation is described in Section III. In the charge-sustaining mode of operation, the SOC of the battery in the vehicle does not change while on traveling on highways. Connected and autonomous vehicles (CAVs) are assumed to be plying in the smart autonomous highways with CAVs being expected to revolutionize transportation in the coming years. The DPWT system model is provided in Section IV. The grid infrastructure and the various scenarios considered to support the DWPT system is explained in Section V. The results of the vehicle traffic and grid EMT co-simulation for the various scenarios are presented in Section VI and the results are concluded in Section VII.

II. Vehicle Energy Use

Vehicle energy use determines the average power required from the DWPT systems on the highway. As derived from expressions in [10], [11], vehicle mass M, velocity v, rolling friction μ_r, road grade α, aerodynamic drag $C_\mathrm{d}A$, tractive efficiency η_eq, and regenerative braking efficiency η_br are included in (1).

$$\bar{P} = \frac{1}{T}\int_0^T \left\{ \left(\left(\frac{\mu_\mathrm{r} + \sin(\alpha) M g}{\eta_\mathrm{eq}} \right) v(t) + \frac{C_\mathrm{d} A v(t)^3 \rho}{2\eta_\mathrm{eq}} + \frac{\delta M a(t) v(t)}{\eta_\mathrm{eq}} \right)^{P>0} + \left(\left(\mu_r + \sin(\alpha)\right) M g \eta_\mathrm{br} v(t) + \frac{C_\mathrm{d} A v(t)^3 \rho}{2} + \delta M \eta_\mathrm{br} a(t) v(t) \right)^{P<0} \right\} dt, \quad (1)$$

where $\bar{P}$ is the average traction power consumed, a is the acceleration, ρ is the density of air, and δ is the mass correction coefficient.

By splitting up the time periods with positive and negative power, the different efficiencies present when the CAV does positive wheel work or regenerative braking are considered in (1). For now, these efficiencies, η_eq and η_br, are assumed to be constants. In future work, the variation of the efficiency of CAV electric drivetrain depending upon the operating point, as it does with current EVs, may be considered.

Using (1), the energy needs for vehicles on a stretch of highway or interstate can be estimated using average annual daily traffic (AADT) counts, freight weight, and velocity data from microwave radar stations and vehicle trajectory surveys from past years. Although CAV traffic patterns may differ from past ones, they are considered as a representative pattern with other sources having shown that a DWPT system can be spatially optimized to match the tendencies of traffic in an area [12]. Currently, the total and relative numbers of weight classifications vary widely by location and time of the day, and the energy usages of each vehicle depend furthermore on individual driving style preferences.

TABLE I: Simplified Vehicle Models and Constant Speed Results

Light Duty Model		Heavy Duty Model	
Parameter	Value	Parameter	Value
M	1700 kg	M	33201 kg
E_bat	30 kWh	E_bat	320 kWh
$C_\mathrm{d}A$	0.72 m	$C_\mathrm{d}A$	7.88 m
L_vehicle	4.445 m	L_vehicle	17.37 m
P_aux	3 kW	P_aux	6 kW
Power Use at Constant Speed (Not Including Auxiliary Power)			
55 mph	12.93 kW	55 mph	145.26 kW
70 mph	23.39 kW	70 mph	251.41 kW
80 mph	33.04 kW	80 mph	359.12 kW

In this paper, the constant-speed worst-case power usage, as a representative case, by a light-duty and heavy-duty vehicle model have been calculated and can be found in Table I. The weight chosen for the heavy-duty vehicle model is based on a common gross weight seen by interstate weigh stations. Additional loads, not used for vehicle propulsion like the auxiliary power values, are derived from equivalent HVAC loads at low ambient temperatures [13].

Fig. 1: Smart autonomous highway case-study showing EV and wireless charging coil locations.

III. Roadway Electrification

In this section, the DWPT system requirements are quantified based on assuming the charge-sustaining mode of operation. Based on the charge-sustaining mode of operation, the following power balance equation is defined:

$$\bar{P} + P_{\text{aux}} - P_{\text{sys}}\epsilon_{\text{road\%}}\frac{L_{\text{vehicle}}}{L_{\text{sys}}}\eta_{\text{coupler}} = 0, \qquad (2)$$

where P_{aux} is the auxiliary power consumption, P_{sys} is the DWPT power transferred, $\epsilon_{\text{road\%}}$ is the DPWT system coverage percentage with respect to the road length, L_{vehicle} is the length of the vehicle, L_{sys} is the length of DWPT coupler, and η_{coupler} is the efficiency of the DWPT system. Based on (2), the power rating of DWPT systems can be obtained with given vehicle data and DWPT system coverage percentage.

TABLE II: Road Electrification Data

Parameter	Information/Value
Distance of road	30 mi
Vehicle type on road	Light-duty
Speed of vehicles	70 mph
Length of each vehicle	16’
Distance between two vehicles (measured between centers of gravity)	4 16’
Penetration of EVs	100 %
Coil/Track length	8’

The cases studied in this paper assume 100% penetration of light-duty EVs. Previous studies from real traffic data have shown 91.5% and 75.5% penetration of light duty vehicles in urban and rural inter-states, respectively [14], justifying the 100% penetration of light-duty vehicles. As the cases studied here are in a smart automated highway, the vehicles are assumed to be at constant distance from each other and to be traveling at a constant speed of 70 mph. The speed is determined based on the speed limit in a majority of highways in the US. The data is summarized in Table II.

The coverage of wireless charging coils and their corresponding power rating are determined based on an optimization to reduce the overall cost of roadway electrification. The efficiency of DWPT systems is assumed to be 80% and the energy transfer is further reduced due to trapezoidal power transfer profile, rather than rectangular power transfer profile. The power transfer profile is the power transferred as a function of time from the DWPT system to the vehicle battery as the vehicle passes over the DWPT system. Using the aforementioned data, the results of the optimization have shown that a 50% coverage of 82.5 kW rated DWPT systems can maintain charge-sustaining mode of operation for light-duty EVs. The DWPT system coils/tracks are assumed to be equidistant from each other, as shown in Fig. 1.

IV. DWPT System Model

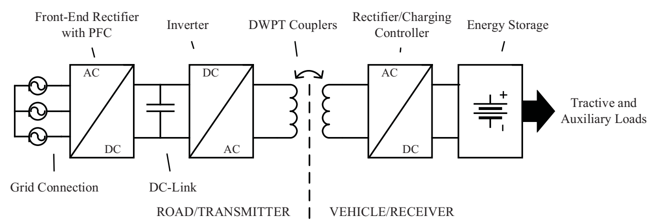

Fig. 2: DWPT system with active front-end (AFE) rectifier.

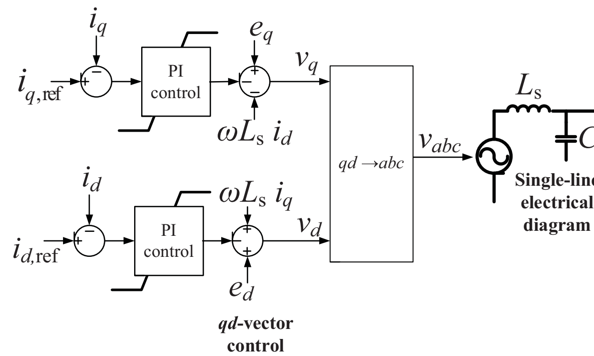

Fig. 3: DWPT system model.

The hardware architecture of the DWPT system used in this study is shown in Fig. 2. The DWPT system uses an AFE rectifier. The AFE rectifier provides greater system stability compared to a diode-bridge rectifier as it can provide reactive power support and connect to weak grids, which are important for large-scale implementation of DWPT systems on highways. The AFE rectifier is controlled based on the qd vector current control using proportional and integral (PI) controllers. The controller is summarized by the following equations:

$$v_q = -K_{\text{p}} \left(i_{q,\text{ref}} - i_q \right) - K_{\text{i}} \int \left(i_{q,\text{ref}} - i_q \right).dt + e_q - \omega L_{\text{s}} i_d, \tag{3a}$$

$$v_d = -K_{\text{p}} \left(i_{d,\text{ref}} - i_d \right) - K_{\text{i}} \int \left(i_{d,\text{ref}} - i_d \right).dt + e_d + \omega L_{\text{s}} i_q, \tag{3b}$$

where e_q, i_q, $i_{q,\text{ref}}$, are the grid-side q-axis voltage, current, current reference, respectively, and e_d, i_d, and $i_{d,\text{ref}}$ are the corresponding d-axis quantities. The q-axis is aligned with grid-side phase-a voltage. The PI controller gains in (3) are K_{p} and K_{i}, respectively. The qd axes current references are generated from the active and reactive power references, respectively. When the grid-side voltage is controlled, the d-axis current reference is generated based on a droop control of the q-axis grid-side voltage.

The DWPT system model is based on state-space averaged model of the AFE with the feedback control. The model is summarized in Fig. 3.

V. Grid Infrastructure & Scenarios

The grid infrastructure required to support DWPT systems is explained in this section along with the various scenarios considered. The basic infrastructure to support the DWPT systems is shown in Figs. 4-5. The standard IEEE 9 bus 3 generator 230 kV transmission system is super-imposed over the considered 30 mi road section, as shown in Fig. 4(a). The 3 load buses in the IEEE 9 bus system are converted to connect to the detailed sub-transmission - distribution - low-voltage grid and DWPT systems. The sub-transmission system is based on 4-feeder 5-node 32 kV system, as shown in Fig. 4(b). The distribution system is based on the 5-node 4.16 kV system, as shown in Fig. 5. The nodes in the sub-transmission and distribution systems have been assumed to be simple radial systems to keep the cost of the required infrastructure low. Each node in the distribution system is connected to 8 active DWPT systems connected to 480 V low-voltage system (or, LVNTS test network). With each active DWPT system rated at 82.5 kW, the low-voltage system processes a maximum of 660 kW based on the vehicle penetration assumption in Section III. The low-voltage system transformer is rated at 1 MVA 4.16 kV/ 480 V, the distribution transformer is rated at 6 MVA 32 kV/ 4.16 kV, and the sub-transmission transformer is rated at 25 MVA 230 kV/ 32 kV. The basic infrastructure explained here is considered

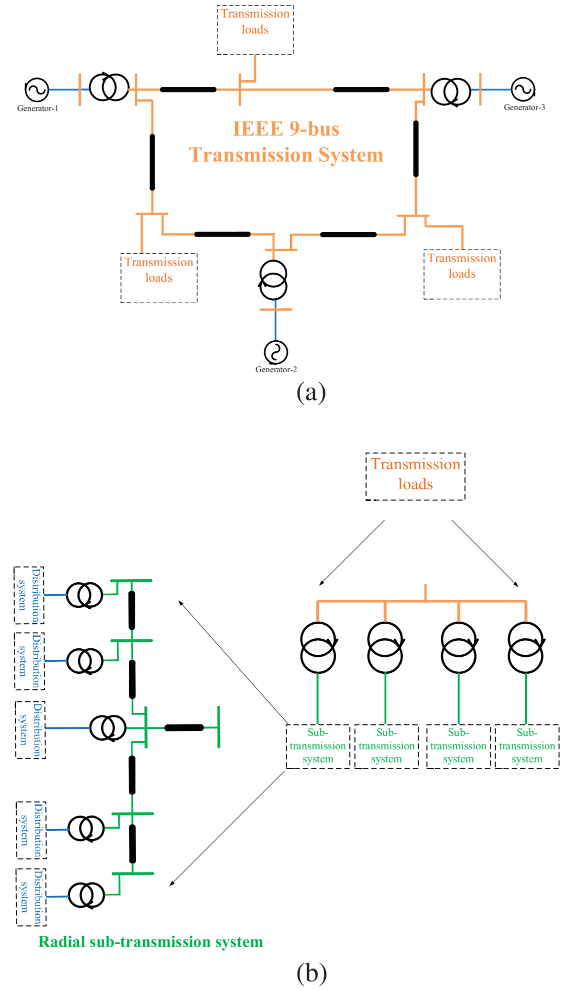

Fig. 4: Grid infrastructure to support DWPT systems in Scenario-1: (a) Transmission system, and (b) Sub-transmission system.

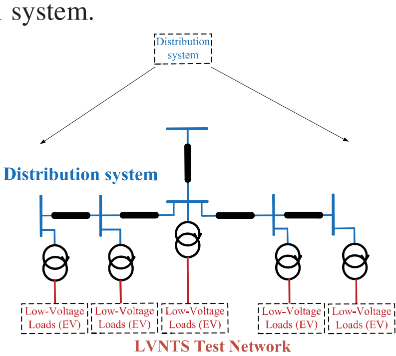

Fig. 5: Grid infrastructure to support DWPT systems in Scenario-1: Distribution and low-voltage systems.

as Scenario-1. The voltage rating of the distribution and low-voltage systems are based on commonly available voltages in these systems and the power flowing through these systems. The sub-transmission system voltage is determined so as to avoid voltage instabilities caused by

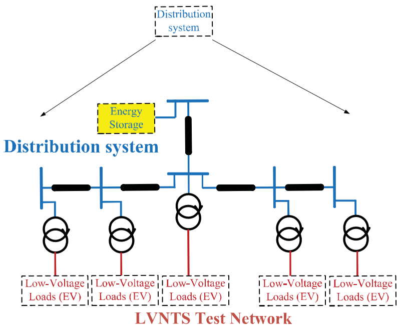

Fig. 6: Distribution system with distributed energy storage in Scenario-2.

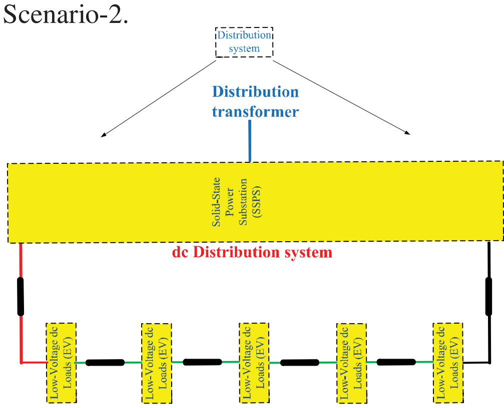

Fig. 7: The dc distribution system connected to the distribution transformer through solid-state power substation in Scenario-3.

the DWPT system loads.

In Scenario-2, distributed energy storage is connected to the secondary side of the distribution transformer to avoid the pulsating DWPT system power being transferred to the distribution and sub-transmission systems. This scenario is shown in Fig. 6. For distributed energy storage, either battery packs or ultra-capacitor modules could be used. Ultra-capacitors, however, may not be feasible due to the number of cells or modules that must be connected in series in order to be compatible with the voltage of the connected ac system. The associated costs with a high number of cells or modules make ultra-capacitors economically infeasible. Although it will offer higher energy densities, lifetime of battery packs could be a concern if they are not sized properly. Hybrid battery/ultra-capacitor energy storage systems can potentially provide the best performance in terms of cost, energy and power density, and lifetime.

In Scenario-3, a dc infrastructure is considered to reduce the voltage variability without inclusion of energy storage. The dc infrastructure is connected to the distribution transformer through a solid-state power substation (SSPS). The SSPS, here, converts 4.16 kV ac system to

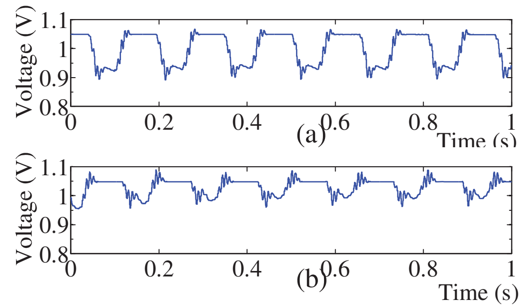

Fig. 8: Normalized voltage in a sub-transmission bus in Scenario-1: (a) Without smart inverters, and (b) With smart inverters.

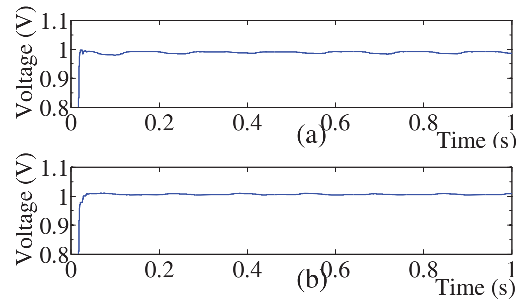

Fig. 9: Normalized voltage in a sub-transmission bus in Scenario-2: (a) Without smart inverters, and (b) With smart inverters.

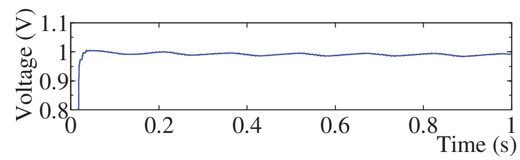

Fig. 10: Normalized voltage in a sub-transmission bus in Scenario-3.

8 kV dc. The 8 kV dc line is connected to up to 40 active DWPT systems. The SSPS requests only the average power required by the DWPT systems, with the pulsating power restricted to the dc system. The corresponding scenario is shown in Fig. 7. In this scenario, the AFE in the DWPT system is no longer required and the dc-link of the DWPT system can be directly connected to the dc distribution infrastructure.

VI. Simulation Results

The DWPT systems' use case for the various scenarios defined in Section V has been provided in Section III. In Scenario-1, there are two studies performed: (i) DWPT system connects to the basic infrastructure, and (ii) DWPT system consists of smart inverters that can provide Volt-VAr support to the basic infrastructure. Similar studies are performed in Scenario-2 with non-smart and smart inverters considered connected to the energy storage. The final study is performed on Scenario-3 with dc distribution infrastructure. The normalized voltages at the sub-transmission buses for each of these scenarios and studies are shown in Figs. 8-10. In the base-case shown in Fig. 8(a), the voltage varies by up to 20% with the transients associated with DWPT system loads. With the introduction of smart controls on the DWPT system AFE, the voltage variation is reduced by up to 50%, as may be noticed in Fig. 8(b). The study results from Scenario-2 shown in Fig. 9(a) and (b) shows up to 90% reduction in the voltage variations. The advantages of optimum placement of energy storage and smart controls are clearly shown through the reduced voltage variations. The final study on dc infrastructure shows the benefits of SSPS with varying dc-link voltage that results in insignificant impact on the sub-transmission system voltages from the DWPT system loads as shown in Fig. 10.

A preliminary comparison of the cost of the Scenarios-2 and -3 indicate that the dc infrastructure is likely to be cheaper than incorporation of energy storage. This comparison is based on the higher costs associated with expensive energy storage compared to dc distribution infrastructure. The dc distribution infrastructure will require an SSPS that can handle variable dc-link voltages and maintain a stable ac-side voltage and frequency in the ac grid.

VII. Conclusion

The impact of smart automated electrified highway on the grid is studied in this paper using EMT studies. These studies provide insights in to the variation of the grid voltage due to DWPT system loads. Three different scenarios are studied to determine the best grid support infrastructure required to support DWPT system loads. Based on the study results, it appears that a combination of smart control and energy storage or dc distribution infrastructure is adequate to maintain grid stability. The cost of dc distribution infrastructure is expected to be cheaper than the costlier energy storage, but would require a flexible SSPS. The flexible SSPS should be able to connect a variable dc-link voltage to an ac grid with stable ac-side voltage.

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