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Load analysis of ground-powering systems for electric vehicles

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Executive Summary

Dynamic conductive road charging involves the transfer of power into moving Electric Vehicles (EVs) using sliding contacts. The power transfer mechanism can be either installed from the top of the car using overhead conductors, conducting rails installed along the road-side or ground-level systems embedded in the road surface. The ground-level power system is the preferred option as it minimizes aerodynamic resistance compared to the other two as well as being designed for operation with vehicles of various sizes. In addition, existing technologies used in trams can be modified to provide ground-level EV charging systems. This paper investigates a ground-level system for EVs driving at high-speed on a motorway. It is based on the Tracked Electric Vehicle (TEV) project where EVs drive autonomously in a platoon with short inter-vehicle distance to reduce the overall air drag coefficient of the platoon. The paper investigates the optimum length and distance for the ground-level system. A Simulink model is developed for platoons of 10 EVs powered from a converter. It is shown that, for a platoon of 10 EVs driving with an inter-platoon distance of 50 m, a conducting-bar section100 m in length is the most efficient in terms of load variation and voltage stability.

Keywords: EVSE (Electric Vehicle Supply Equipment); conductive charger; dynamic charging; load management; simulation.

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1. Introduction

Road transport contributes a third of all the greenhouse gases on the planet. It is also the most difficult source to correct. Electric vehicles (EVs) are seen as a solution when energy is provided from renewables. On highways, the power demand for EVs is highest, and as such research should focus on ideas to reduce peer demand. The most promising idea for high-speed motorway systems for electric vehicles (EVs) is called the Tracked Electric Vehicle (TEV). TEV integrates the latest technologies of dynamic road charging, autonomous driving, power distribution and smart city data in one infrastructure. The TEV system is a fully automated highway that enables vastly greater passenger carrying capacities compared with traditional highways, with about 17 lanes and zero emissions. A TEV track is a single lane with no intersections other than ON and OFF ramps, which is electrically powered with restricted-access. In the TEV system, EVs travel autonomously in platoons at speeds of 200 km/h with no overtaking. A platoon is made up of 10 EVs with an inter-vehicle distance of 0.25 car lengths, which leads to reductions in overall aerodynamic drag and hence increased overall system efficiency. Efficiency is improved further by the combination of steady speed, smooth track surfaces, low-resistance tires, streamlined car bodies, banked turns, reduced numbers of junctions and a direct supply of electrical power to the traction motors. Part of the TEV project strategy is to use mass-produced EVs. Any EV can drive on TEV, but streamlined and compact EVs are preferred weighing 907 kg, having a frontal area of 1.86 square metres and a very streamlined shape with a low drag coefficient (Cd) of 0.15 [1].

The main motivations for developing the ground-level power system are to overcome the limitations of overhead line power transfer in terms of reducing aerodynamic drag at high speeds, improving the aesthetics of cities, and to provide operation and scalability suitable for designs for both heavy-duty vehicles and passenger EVs [2]. Different ground-level track systems have been proposed and good overviews are available elsewhere [3-5]. For example, Alstom’s concept of an Aesthetic Power Supply (APS) has already been implemented for roadway power supplies to city trams since the first installation in 2003 in France. This concept has been developed for an electrified road system (ERS) for road vehicle applications and was demonstrated on a test-track in Sweden in cooperation with Volvo [3]. In railway ground-level systems, power is supplied by a single solid bus-bar located between the traction rails, known as a third rail, while the traction rails are usually used as a path for the current returning to the power supply system; however, for road vehicle applications, two conduction rails, the third and fourth rails, with sliding contacts are needed, since rubber wheels isolate the vehicle from the ground [4]. For safety purposes, all demonstrated ground-level concepts depend on relatively short sections integrated into the road infrastructure and involve different energisation methods; for instance, in Alstom APS, each section is only energized when it is completely covered by the tram [3]. For systems adapted for road vehicles, however, it would be impractical to construct segments that are shorter than small cars, and therefore segment activation is based on a safety zone around the moving EV controlled by the position and speed of the vehicle [4].

In the TEV system, since EVs drive autonomously in platoons, segmentation of conduction rails would be based on the length of a platoon, including the inter-vehicle distance, and energizing the segments will be based on a one-second time zone in front of the leading EV of the platoon, which would be 55 m long when driving at speed of 200km/h. In other words, the detection of vehicle position will be used as a condition for energizing the conduction sections [5].

This paper investigates the ground-level power system that is required in order to power EVs driving on a TEV lane autonomously at 200 km/h in platoons made up of 10 EVs with an inter-vehicle distance of 0.25 EV lengths and inter-platoon distance of 50 m. The analysis is based on the “Aesthetic Power Supply” introduced by Alstom, where power rails are embedded flush with the road surface [5, 6].

2. Power demand calculation and optimisation

In order to calculate the power demand for an EV, a Simulink model was developed that includes the most prominent resistive forces that oppose the motion of a vehicle: rolling resistance, aerodynamic drag and climbing resistance [7].

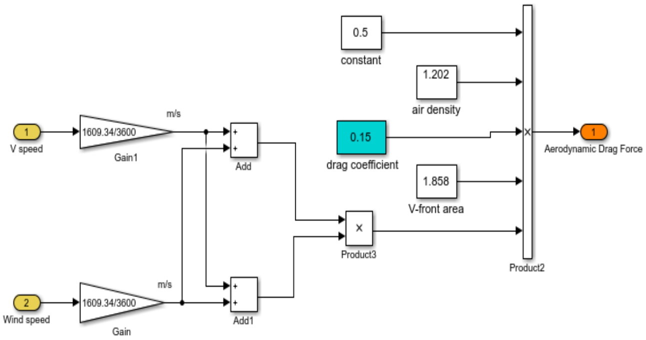

Fig. 1 Impact of EV geometry and platooning on power demand from the grid [9]

An extract from the model is shown in Fig. 1 for aerodynamic drag resistance as an example. In addition, power demand and efficiency for auxiliaries were taken into account for each component in the power drive train (inverter, motor, battery, charger, a converter for auxiliaries). This model was used to investigate and optimise the power demand from the grid when feeding platoons of EVs driving constantly at high-speed and with different inter-vehicle distances. The platoon was simulated using three different types of EVs: the Nissan Leaf, Tesla Model-3 and a TEV EV which is streamlined and therefore has a low drag coefficient [1]. The results of the simulation are shown in Table 1 and Fig. 2. As expected, the power demand is lowest for the streamlined TEV vehicle and the power requirement increases with the speed of the platoon. Table 1 also shows the impact of the platoon on power savings compared to an individual EV, which can be up to 40 % for a platoon of 10 EVs at inter-vehicle spacings of 0.25 m [8, 9].

Table 1 Impact of EV geometry and platooning on power demand from the grid [10]

Inter – vehicle distance = 0.25 EV length (1 m)	Power demand from grid (Kw)					
	Nissan leaf		Tesla Model 3		TEV streamlined vehicle	
Speed	Single	In platoon (10 EVs)	Single	In platoon (10 EVs)	Single	In platoon (10 EVs)
200 km/h (125 mph)	133	79	100	60.6	50	30.7
160 km/h (100 mph)	72	44.5	55	35.7	28	17.9
120 km/h (75 mph)	35	23	28	18.8	14	9.5

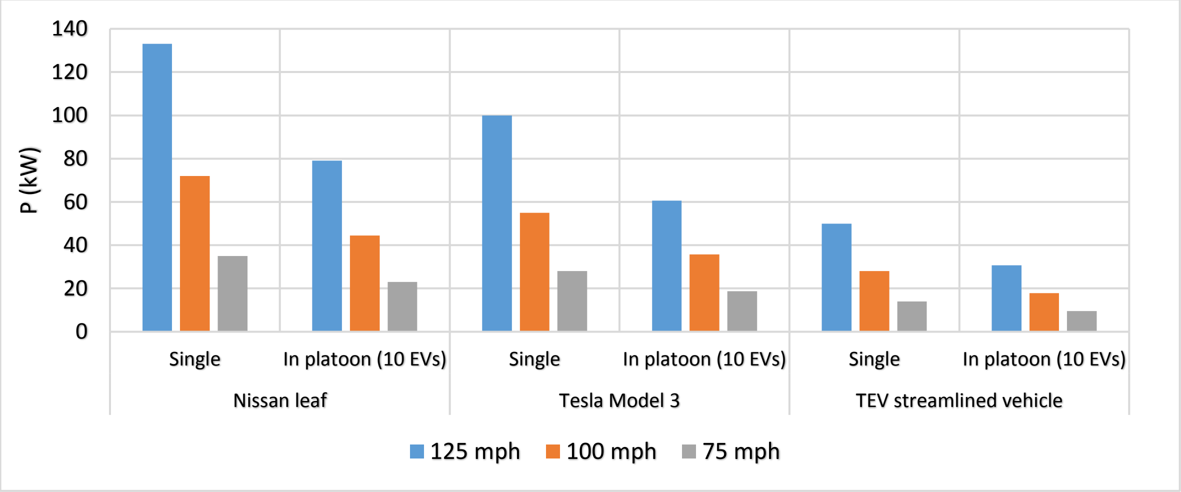

Fig. 2 Impact of EV geometry and platooning on power demand from the grid [10]

3. The power distribution of a two-way TEV track

As shown in Fig. 3, the ground-level feeder is powered from the grid by a three-phase rectifier transformer. A transformer connected to the distribution network steps-down the voltage from 11 kV to 0.75 kV. The theoretical ideal output voltage of a three-phase rectifier is:

$$V_{out} = 1.35 * V_{ll} \tag{1}$$

and therefore the input voltage to the DC/DC converters is 1 kV DC [11]. The required 750V DC for each segment is controlled using four modules of four-phase synchronous interleaved buck converters in input-parallel output-parallel (IPOP) configuration with a power level of 420 kW. Energizing the segments will be based on the one-second time zone in front of the leading EV of the platoon, which would be 55m long when driving at a speed of 200 km/h. Moreover, as long as EVs drive at steady speed, the detection of the vehicle position will only be used as a condition for activation of the conduction segments, unlike in the Alstom APS power supply system operated for a car which does not enable power supply from the road for speeds lower than 60 km/h [5].

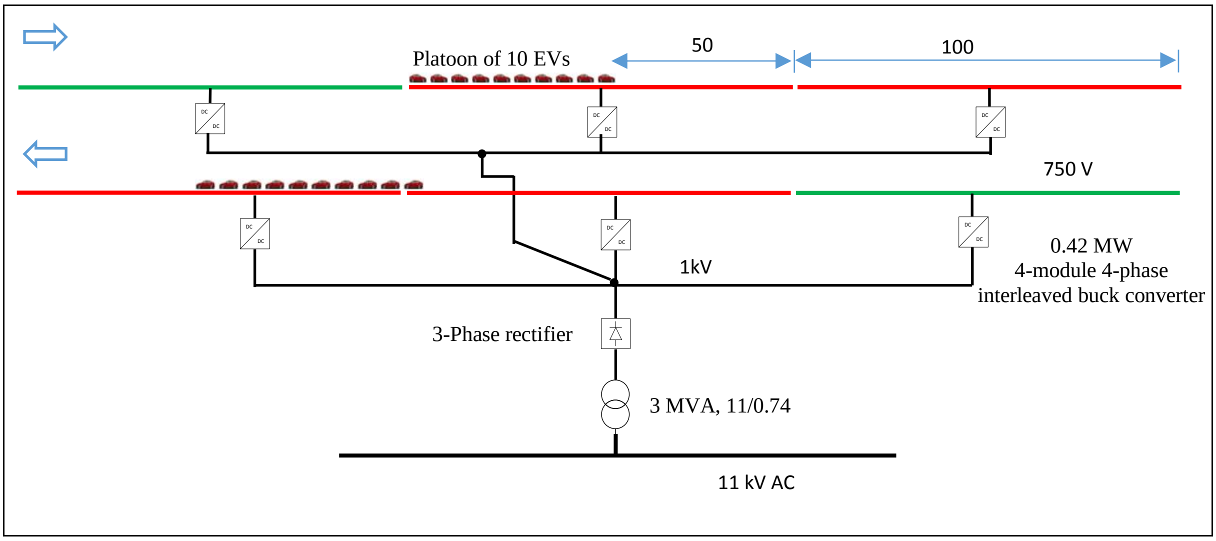

Fig. 3 Single line diagram of the TEV power distribution system

4. DC/DC converter

In power management applications, multiphase interleaved DC/DC converters are widely used due to the fact that the output current is evenly shared between a number of phases (N) resulting in lower rated inductors and switching devices and fast response, and hence high efficiency at heavy load [12]. The main advantages of the multiphase synchronous buck converter are: the current ripple cancellation effect, which enables the use of low rated passive components; the frequency of the total current ripple is multiplied by the number of parallel phases (N.f), improving the transient response, system efficiency and reducing EMI; and a phase-shedding control scheme to improve efficiency at light load [12, 13].

In the TEV system, each 100 m-segment is designed for maximum power of 420 kW at 750 V DC; therefore, with a 520-A maximum current, the design requires 16 phases to keep the individual phase currents below 40 A [14]. These phases are grouped in a four-module, four-phase interleaved buck converter, as shown in Fig. 4, where each phase has two complementary SiC MOSFETs and is shifted 90° (360°/N) from one another.

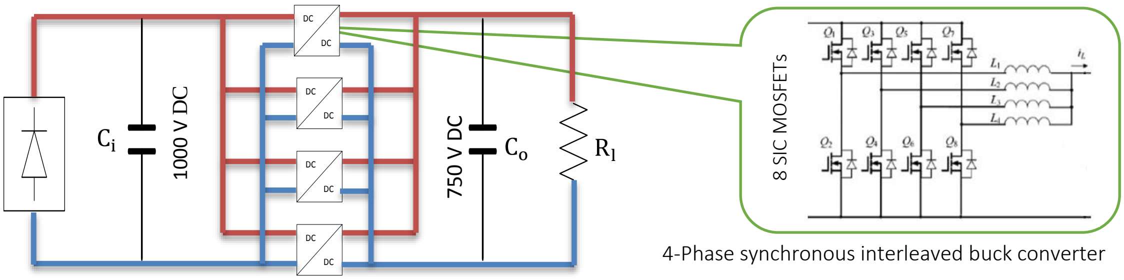

Fig. 4 Modular multi-phase interleaved DC/DC converter

Using the design criteria presented in Table 2, the passive components are designed as follows:

Table 2 Design criteria for a multiphase synchronous buck converter

Input voltage (V_i)	1000 V DC	Ripple of phase current (Δi_L)	25 %
Output voltage (V_O)	750 V DC	Ripple of output voltage (ΔV_o)	2 %
Output current (I_o)	140 A	Ripple of input voltage(ΔV_i)	3 %
Step current (I_{step})	40 A	Ripple of transient output voltage ($\Delta V_{o\ ac}$)	5 %
Switching frequency (fs)	200 kHz	Ripple of the transient input voltage ($\Delta V_{i\ ac}$)	4 %
Number of phases (N)	4	Duty cycle (D)	75 %

The output inductor value per phase is based on the specified maximum inductor current ripple and can be obtained from equation 2. It is recommended that 20 % - 40 % inductor ripple current is targeted in order to optimise the output filter performance [15]. Therefore 25 % of inductor ripple current is selected:

$$\mathrm{L_{min}} = \frac{V_o \cdot (1 - D)}{\Delta I_{L,ph} \cdot f_s} = 107.145\ \mu\mathrm{H} \tag{2}$$

The minimum output capacitance needed to handle the DC ripple can be calculated using equation 3. In this equation, $\Delta \mathrm{i_L}$ is the ripple current of a single phase of the converter [14, 15]:

$$\mathrm{C_{ripple}} = \frac{\Delta \mathrm{i_L}}{8 \,.\, \mathrm{f_s} \,.\, \Delta \mathrm{V_o} \,.\, \mathrm{V_o}} = 3.65\ \mu\mathrm{F} \tag{3}$$

The total capacitance needed to handle the maximum transient of the application is calculated in equation 4 for the load step and equation 5 for the load release [14, 15]:

$$\mathrm{C_{undershoot}} = \frac{\left(\frac{\mathrm{L_{ph}}}{\mathrm{N}}\right) . \, \mathrm{I_{step}^2}}{2. \ \Delta \mathrm{V_{o\,AC}} \,.\, \eta. \ (\mathrm{V_i} - \mathrm{V_o})} = 3.368\ \mu\mathrm{F} \tag{4}$$

$$\mathrm{C_{overshoot}} = \frac{\left(\frac{\mathrm{L_{ph}}}{\mathrm{N}}\right) . \, \mathrm{I_{step}^2}}{2. \ \mathrm{V_o} \,.\, \Delta \mathrm{V_{o\,AC}}} = 800\ \mu\mathrm{F} \tag{5}$$

In comparing the capacitance for ripple, undershoot and overshoot, the load release dictates the amount of capacitance required to maintain the output voltage. Fig. 5 shows inductor currents of the parallel four phases shifted by 90° from each other, where it is also clearly seen that the load current is equally shared between them with a value of 35 A with a ripple of 6.3 A. Fig. 6 shows that the output voltage at the full load is regulated at 750 V, which is the required output voltage of the ground-powering system.

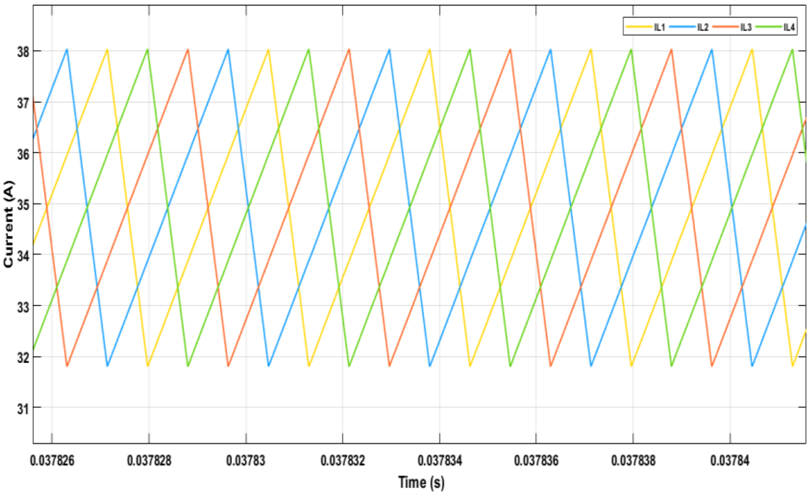

Fig. 5 Multi-phase currents of the interleaved buck converter

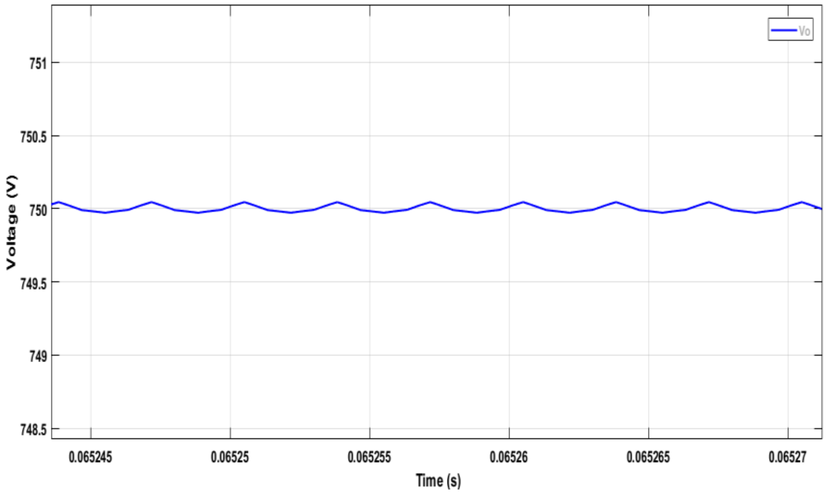

Fig. 6 output voltage of the ground-powering system

5. Simulation model

Simulations were conducted for the streamlined TEV EV driving at 200 km/h. Based on power demand calculations using a Simulink model, the power required is 30.7 kW. As in tram systems, a 750 V DC ground-level feeder powered from the distribution network is used and controlled by a four-module four-phase interleaved buck converter, and therefore each EV represents a load impedance of 18.75 Ohm. Due to platooning, the simulation requires the timing of EVs, which affects the power required. Three parameters are included in the simulation: the time delay, (t_d), which represents the time distance between each two EVs; EV travelling time (t_{EVt}); and platoon travelling time (t_{Plt}) for one length of power segment. Equations 6 to 8 describe the three timing equations:

$$t_d = \frac{l_{EV} + l_{inter}}{\nu} \tag{6}$$

$$t_{EVt} = \frac{l_{segment}}{\nu} \tag{7}$$

$$t_{Plt} = t_{EVt} + (n - 1)\, t_{dn} \tag{8}$$

where l_{EV} is the length of the EV, l_{inter} is the length of the inter-vehicle spacing, ν is the speed of the EV, $l_{segment}$ is the length of the feeder segment and n is the number of EVs in the platoon.

Based on a speed of $\nu = 200$ km/h, a vehicle length of $l_{EV} = 4$ m and an inter-vehicle length of $l_{inter} = 1$ m, the simulation results for different segment lengths ($l_{segment}$), 50 m, 100 m and 200 m, are presented in Table 3.

Table 3 Time parameters for different lengths of conducting section

Length segment $l_{segment}$	Time delay (s) t_d	EV travelling time (s) t_{EVt}	Platoon travelling time (s) t_{Plt}
50 m segment	0.09	0.9	1.71
100 m segment	0.09	1.8	2.61
200 m segment	0.09	3.60	4.41

The ground-level feeder is supplied from a rectifier transformer connected to the distribution network, and the required 750 V DC for each conduction section is controlled by a multiphase synchronous buck converter. However, in the simulation model, only the DC/DC stage has been considered while the output voltage rectifier transformer is represented by a battery of 1000 V DC. The timing block shown in Fig. 7 emulates the timing of EVs fed from the feeder according to equations 1 to 3. The simulation is conducted for three different lengths of conduction section: 50, 100 and 200 m.

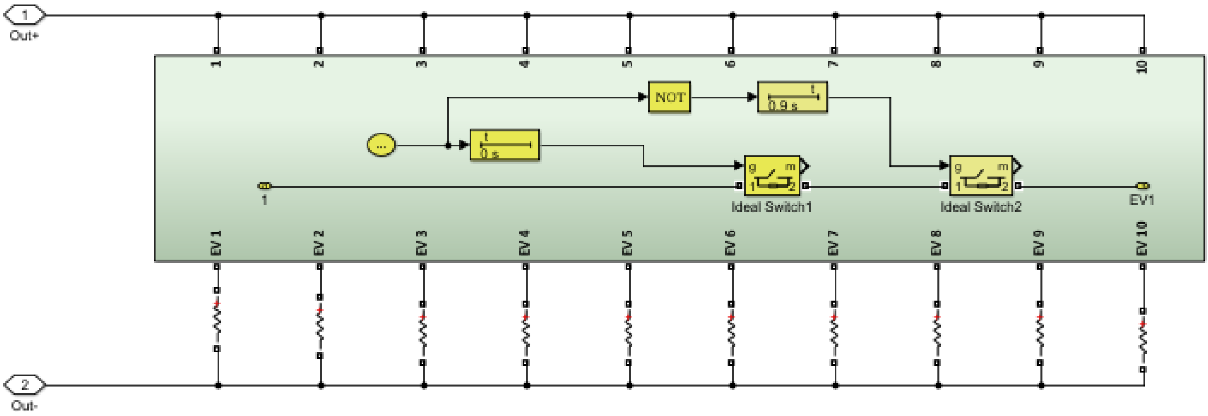

Fig. 7 Timing block of a platoon of 10 EVs feeding from the ground-level feeder

6. Simulation results

The simulation time is set at 3.60 s for all cases in order to analyse the load profile of all lengths of power segments at the same operational conditions. This time is the EV travelling time for the longest length of power segments, which is 200 m. The simulation presents a period of time of continuous driving in the TEV system at 200 km/h with different lengths of power feeder sections as follows.

6.1 Section length of 50 m:

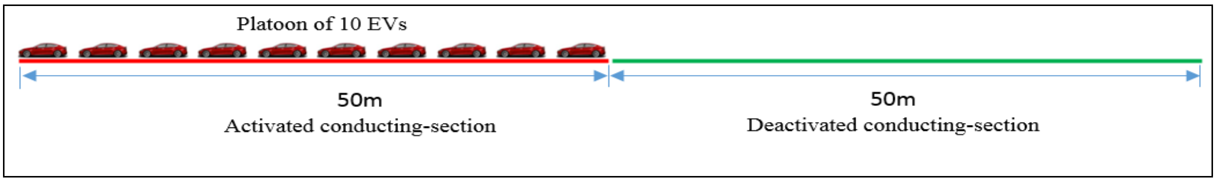

Fig. 8 Conducting sections of 50m length

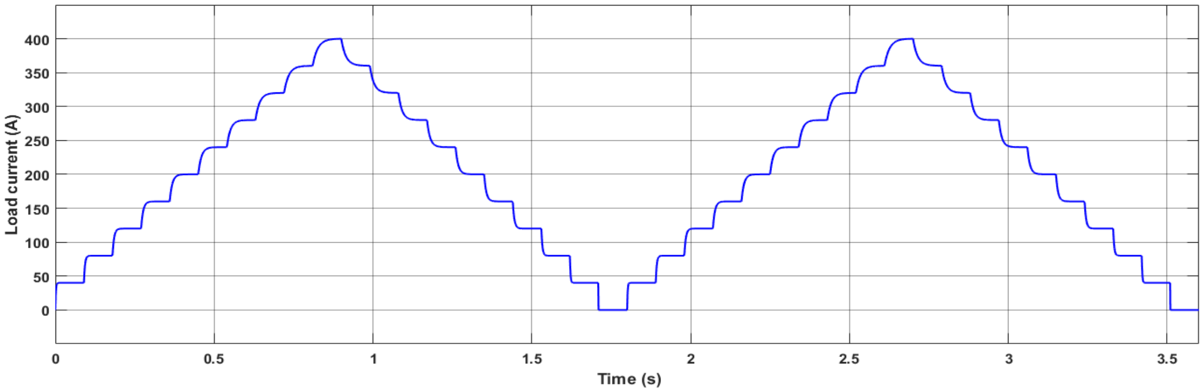

Fig. 9 Load profile of a 50-m segment of TEV track

Fig. 8 shows the car arrangement of a 10-EV platoon on one conduction 50 m length section. Fig. 9 shows the load profile for one segment of the ground powering feeder. This figure illustrates the loading and unloading of each 50 m conduction segment, where every time a new EV is fed from this segment the current shoots up until it reaches the full load current level of the segment and then EVs start leaving the section one after another. The segment load rises and falls in the same step gradient, and each step has an average current step of 40 A. As the platoon length is equal to $l_{segment}$=50 m, the maximum current of 400 A is reached at 0.9 s and lasts for a period of 0.09 s. Assuming an inter-platoon distance of 50 m, the waveform shown in Fig. 9 will oscillate at 0.55 Hz with a peak current of 400 A.

6.2 Segment length of 100 m:

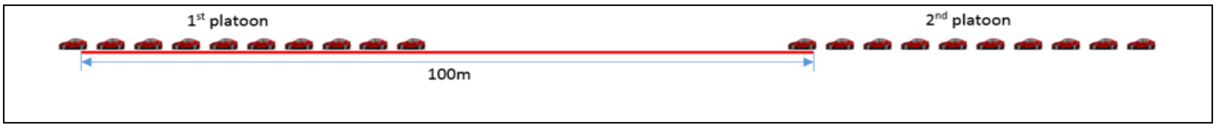

Fig.10 Conducting sections of 100m length

Fig. 10 shows the car arrangement of two 10-EV platoons. In this driving scenario, as shown in Fig. 11, the feeder will continuously provide 400 A for a duration of 2.7 s, which is much longer than that in the 50 m conduction section at 0.09 s. Also, with an inter-platoon distance of 50 m, the current will never drop to zero since, when the first car of the first platoon has left the ground supply system, the first car of the second platoon is joining it. Consequently, the load can be described as constant, at 400 A, with a transient of 0.9 s which means that the frequency of this continuous driving scenario is almost zero.

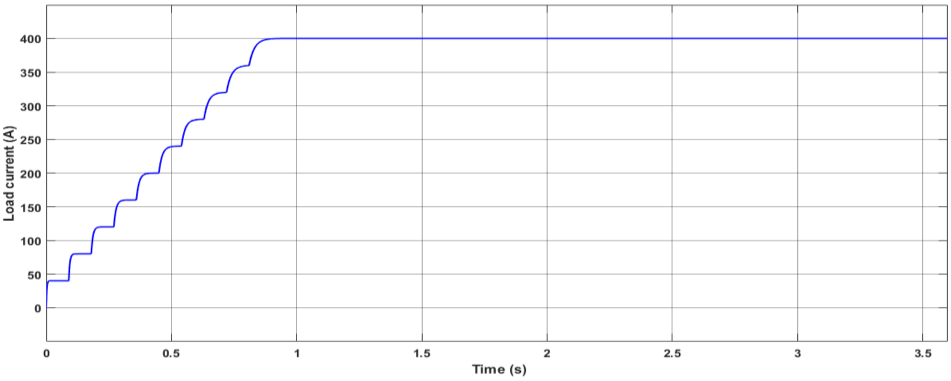

Fig. 11 Load profile of a 100-m segment

6.3 Segment length of 200 m:

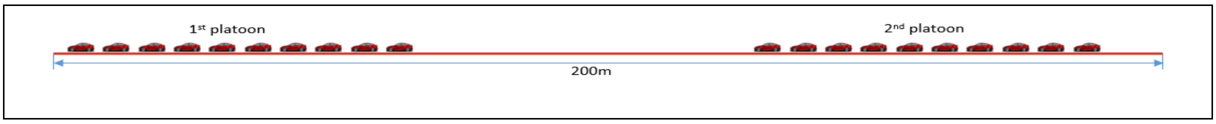

Fig. 12 Conducting sections of 200m length

In this case, two platoons of 10 EVs are sharing one feeder, as illustrated in Fig. 12. A 200 m conducting section at 50 m inter-platoon distances leads to double the load variation to 800 A, as presented in Fig. 13. This results in doubling the current handling capability of power semiconductor devices in the DC/DC converter, increasing the cooling requirement, as well as the conduction-rail sections, and power cables, which dramatically increases the cost. In addition, such a heavy load could cause a voltage imbalance between light- and full-loaded segments, resulting in current leakage between them via the sliding contacts. This could damage the conduction-rail sections and decrease the life span of the carbon sliding contacts.

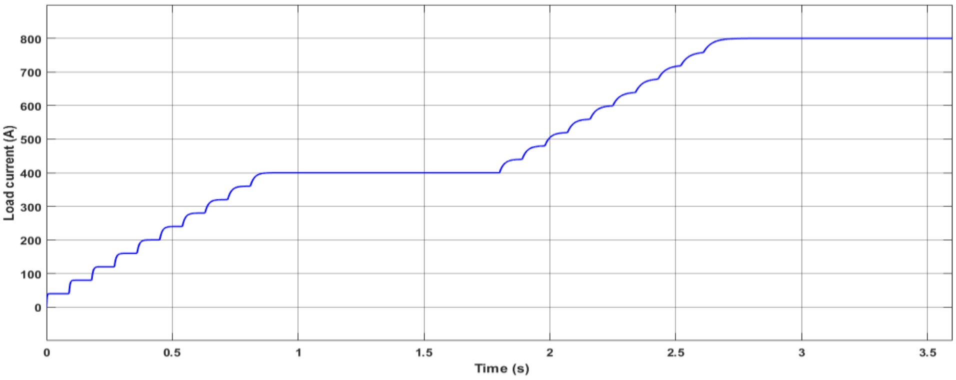

Fig. 13 Load profile of the 200-m segment

7. Conclusion

In this paper, the infrastructure of dynamic power transfer is based on segmented conductive rails integrated into the road surface, and carbon sliding contacts are used to transfer power to moving EVs. EVs drive autonomously at high speeds of 200 km/h in platoons of 10 EVs, with an inter-vehicle spacing of 1 m and inter-platoon distance of 50 m. Conduction segments of 50, 100 and 200m in length are investigated in order to determine the optimum length and distance for the ground-level powering system. Due to the higher current handling capabilities of the semiconductor devices, a segment length of 200 m is unattractive. A 50 m track requires twice the amount of DC/DC converters compared to 100 m segments, increasing the cost and complexity of the power distribution system. Furthermore, as the current frequency for the 50-m segment is 0.55 Hz compared to almost zero at 100 m, apart from the transients, the number of di/dt repetitions is much higher for 50 m, resulting in a high EMI. Therefore, conduction-section lengths of 100 m are seen as the optimum length for TEV. Despite the current handling capability and di/dt repetition, other parameters require further study such as any imbalances in energy requirements per vehicle and voltage spikes at heavy step-load changes at high speed. Future work on this system will consider such factors.

Acknowledgements

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