INTEGRATION OF ELECTRIC VEHICLES AND RAIL THROUGH PARK-AND-RIDE INFRASTRUCTURE

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ABSTRACT

Innovation is required in transport infrastructure to meet future pressures from increasing carbon emissions, changes in power demand and limited physical space. These will need to be addressed alongside the requirement for more flexible transport options. Therefore, this study considered a possible method to mitigate these issues. The aim of this study was to determine if the electrical railway network could be successfully integrated and used to charge electric vehicle (EV) batteries at station park-and-ride facilities.

INTRODUCTION

Emission levels reduction is a key driver for governments and citizens worldwide [1]. This is having a major effect on the current travel trends and the future of travel. Trends, such as the drive towards cleaner, greener technology like Electric Vehicles (EVs) and electrification, will continue to grow as technologies develop and become more efficient and sustainable [2]. Many cities are looking at delivering car-free centres to reduce emissions, noise and temperature. This in turn will require additional ways to transport people to the heart of a city, be it by rail or bus. The ability for people to be able to make choices on where to live and work can be improved through combining transport types, creating a fully integrated network. As this integration occurs, it opens a plethora of available options in how to implement energy saving techniques and a larger infrastructure on which to base it upon, resulting in a stronger and more holistic solution [3].
Congestion is an integral cause of emissions and could be a major factor in why emission-based reduction is not set to meet government targets. Public opinion is split on EVs. This is based on the view that EV performance and availability of re-fuelling points, is lower compared to standard cars [4]. Unless this perception is changed, this will continue to be a problem and novel solutions will be necessary to change this. One such example is Vehicle-to-Grid (V2G) technology which can benefit the user as well as the grid. The potential revenue streams associated with this can instigate investment and growth in this area, therefore strengthening the capabilities of EVs and associated technology. These new avenues are not without their issues. EV batteries degrade over time, especially with repeated charges. This is a deterrent to available V2G payments as they currently do not match up in terms of the compensation to the participants of the scheme. Grid stability can also be an issue, with several new technologies being utilized on the weak parts of the network at similar times [5].
In the current climate, where regulations and legislation are reinforcing the need for green energy, EVs and their infrastructure will grow [6]. Electrification of the railways will continue as energy efficiency and customers demand for reduced journey times increases. Using an available power source (25kV Alternating Current (AC) electrified railway) located next to an existing storage facility, the use of EV park-and-ride points at a station is an interesting option that could re-use energy with minimal investment in infrastructure.

AC RAILWAY

The modelling of the station scenario is performed by the MATLAB Simulink software which utilises the given data to perform load flow and fault analysis of a system. Previous studies have been completed to simulate high load and short circuits on 25kV lines [7], replicate 2x25kV autotransformer systems [8]and evaluate the effects of high-power train loads [9]. These studies have been used alongside the relevant parameters from the Network Rail ELSSA modelling to develop an appropriate model.

Traction Power System

The model has been designed based upon 3x15km sections of route and is applicable to a four track, 2x25kV autotransformer system. The system itself is created from the following elements:
Contact and catenary wires fed at +25kV, Feeder wire at -25kV and the Earth Wire connected to earth (0V); Rails connected to earth (0V); Auto-transformer and Feeder Transformer.
Due to the close proximity of the tracks and associated wires, the individual elements cannot be considered independent and magnetic coupling is required to be taken into account. To simplify the model, it has been assumed that all conductors are parallel, and the catenary wire, which normally changes height in-between spans, is constant. Additionally, the parallel capacitances and conductance's, that would normally be modelled alongside the conductors' series resistances and inductances, have been deemed negligible. To model the railway cross-section an origin placed in the centre of the ten-foot between tracks 2 and 3 was used to show the coordinates of the wires and rails. From this, the resistance and inductance per length unit values are derived.
For the line models within 25kV AC Railway simulation these values have been multiplied by the relevant line

length within the mutual inductance blocks, see Figure 1.

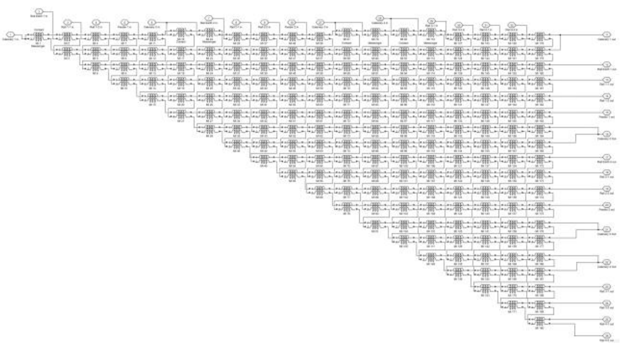

Figure 1 - Four Track Railway Line Model

The model has been developed to focus on a short section of the route for simplicity and as such is fed with a single transformer. This is modelled using the three-winding transformer block from SIMULINK, with its low voltage windings connected in series i.e. centre tapped. As the simulated railway is an auto-transformer system it is required to place this within the model. An auto-transformer block does not exist within SIMULINK although it can be adequately replicated using a linear transformer with the second winding connected to the primary winding. The initial parameters of these have been taken from the ELSSA modelling and an equivalent product chosen.

Regenerative Braking

For the regenerative braking influence of trains on the network a data-based approach has been used to reduce the modelling time required for this section of the study.
The modelling of the train would require an AC to DC convertor, specifically using insulated-gate bipolar transistors (IGBTs) and four quadrant converters to convert the AC signal to DC. This is to allow the conversion whilst absorbing sinusoidal current in phase with the voltage [9]. The regenerative braking aspect would require the model to understand the speed profiles of individual trains on the network dependent on time. Additionally, the specific positioning of the train along the line would need to be considered to understand the receptivity in terms of absorbing available excess energy.

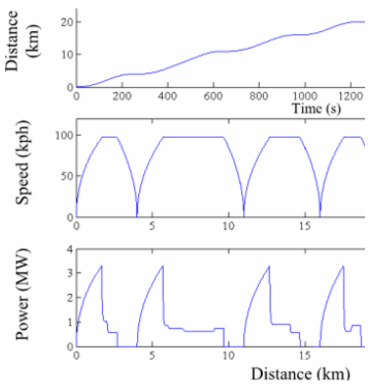

Figure 2 - Class 319/390 Speed and Power Profiles[12]

Trains will be the main source of loading on the network until the introduction of the EV charging system and have been modelled for simplicity, by a series RLC load block. This data driven approach allows the active power to be chosen per train based upon the suggested regen braking at that time compared against the required train power. The literature suggests several variations in terms of speed/power profiles, regenerative braking energy and receptivity, shown in Figure 2.
These differing values are a result of the varied rolling stock used within the railway environment. A wide range of values encompassing as many varieties as possible has been utilised to ensure all scenarios are covered [12]. Using this base data, a stochastic method to the active train power has been developed to mirror snapshots in time of real-life acceleration/de-acceleration profiles.

ELECTRIC VEHICLE PARK-AND-RIDE

EV Charging Infrastructure

In the following section, the modelling of the charging infrastructure from battery to power source will be detailed.
The first aspect of the EV charge system to be simulated is the EV car battery. There is an acceptable battery block within SIMULINK that can be utilized for this purpose. To generalize the battery type, one of the most common EVs battery parameters have been used. The Nissan Leaf has a lithium Ion battery and this has been replicated within Simulink.
To control the charge of the battery a bi-directional DC-DC converter is used. This utilizes two IGBT switches to allow continuous bi-directional power capability. The control signals used to operate this work in tandem in a buck and boost scenario. The converter works in buck-type mode when the upper switch is operated, resulting in battery current flowing from the capacitor to the inductor. When the lower switch is operated the battery current flows in the opposite direction, from inductor to capacitor, the converter working in boost mode and increasing the battery voltage is shown in Figure 3.

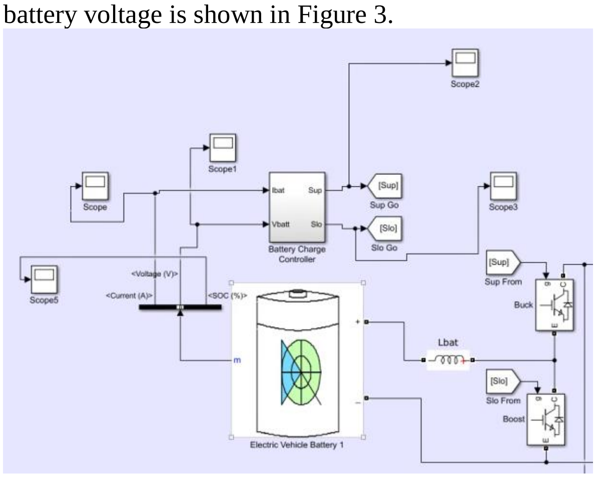

Figure 3 - Buck Boost Modelling

Alongside this, a constant current charging strategy has been implemented using the methodology depicted in Figure 4.

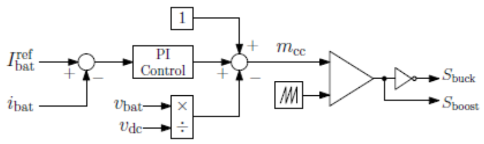

Figure 4 - Battery charge constant current strategy [10]

The boost-mode operation of the converter is defined by the output duty ratio m_{cc}. Ideally the constant current charging strategy would be used at the initial stage of charging before switching to a constant voltage strategy. This avoids sudden injection of high currents when connected to the DC bus [10]. However, for simplicity this has not been implemented within the model.
Another key component of the system is the inverter, LCL filter and its associated control system which converts the AC signal to DC. The three-phase inverter with an LCL has been replicated using the SIMULINK universal bridge block, see Figure 5.

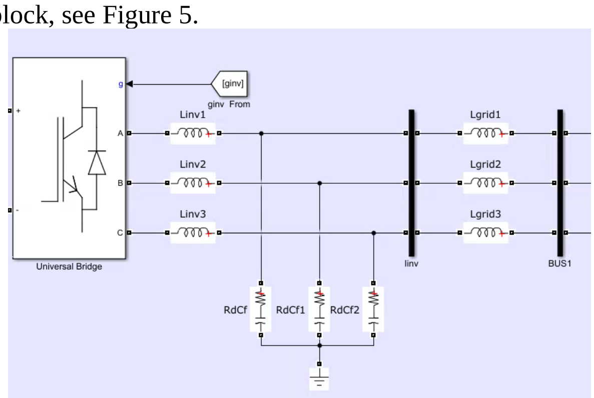

Figure 5 - Three-phase inverter and filter model

The LCL filter is used to remove harmonics linked to power factor reduction and interference. The passive LCL filter has been used rather than a simple low pass filter as it will remove 3rd order harmonics whilst keeping good harmonic attenuation and a small filter size. Careful consideration of the inductance and capacitance values is essential and depends on certain grid parameters; ripple attenuation factor, reactive power and resonance frequency.
The control methodology of the charging system depicted is dq-frame cascade control. The DC voltage at the bus is controlled by the outer loop of the d-axis whereas the q-axis outer loop uses reactive current to affect the magnitude of the AC Voltage. This reactive current is controlled by the inner loop of the q-axis. The active AC current is controlled by the inner loop of the d-axis.
The cascaded control in the dq-frame is followed by a pulse width modulation (PWM) generator to supply the required gating pulses to the IGBT switches within the inverter. This helps maintain a constant voltage at the DC bus. To improve the performance of the system, specifically during transients, dq decoupling-terms are used, these are the feed-forward voltages and gain, ωL_{inv}. A phase locked loop (PLL) is used to synchronize with the grid and negate unbalance effects. This delivers the relevant output parameters utilised within the dq-frame inverter control and uses the measured three-phase voltage at the point of common coupling (PCC) as the input.
The connection between the low voltage EV system and the medium voltage from the railway line is through a 1050kVA transformer using the SIMULINK three-phase, two winding transformer block [9].

EV Utilisation

Three scenarios have been researched to quantify the adaptability, sustainability and achievability of this solution. Within the chosen scenario and related to government legislation, 40 park-and-ride EV spaces are to be installed with "Fast" charging 230VAC, 32A, 7kW chargers to accommodate the potential for EV usage in this area.
The first scenario to be modelled is that of low EV uptake within the area combined with usage outside the core 09:00-17:00hrs, where used EV spaces will be lower. To simulate expected EV types using the 7kW "Fast" charge system, a standard NISSAN LEAF 24kWh, 7kW model has been used. Take-up of 10 spaces has been assumed as an adequate assessment of usage at this time.
The second scenario is one where uptake of EVs increases as expected and all spaces would be utilised during the core 09:00-17:00hrs. Charging of 40 EVs simultaneously will be assessed at this point.
The final scenario involves expansion of the charging facilities to utilise future upgrades to an additional 40 "Fast" 7kW chargers. This additional capacity leads to 80 EV's charging simultaneously.

COMBINED SYSTEM

Analysis and Results

Using evidence and modelling data gathered, several scenarios have been developed to understand the interaction between the systems. This interaction will be assessed against the main defining factor of voltage levels at the 25kV AC Railway before additional parameters are reviewed.
The initial assessment will take place for low levels of trains on the network with varying active powers dependant on regenerative braking applied. This will be tested alongside the three EV scenarios of low EV uptake, high EV uptake and extended EV uptake. The second assessment will take place against the same criteria but for high levels of trains on the network.

EV Charging Profiles

The EV charging aspect of the model shows various traits dependent on the state of charge of the battery and the associated system parameters. At the Vdc output of the

AC-DC converter you can see how the converter is working to output a DC signal applicable for the EV battery, see Figure 7.

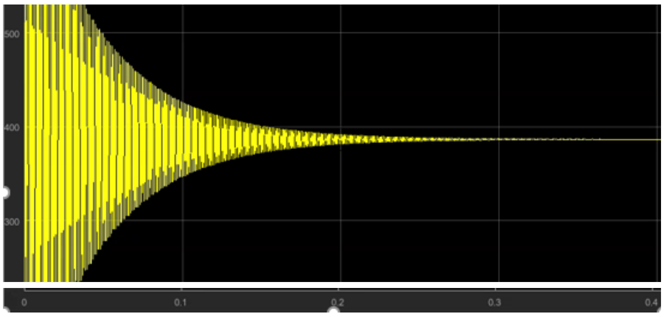

Figure 7 – Vdc Voltage Output (during charging)

The AC railway supply causes the state of charge in the battery to increase from its initial state of 50% towards full capacity. The current profile in Figure 8 shows how the EV battery reacts whilst this charging is taking place.

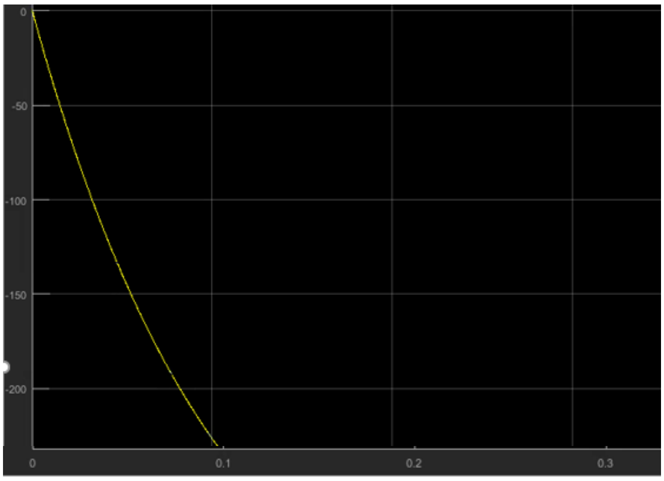

Figure 8 - EV battery current whilst charging

The current shows a steadily increasing negative current whilst the voltage at the battery increases from its nominal value by 5%. The current is represented by a negative value due to the charging taking place. If the battery was discharging, this graph would show a positive current value. If the battery is fully charged, then the voltage and current profiles differ. The nominal voltage is seen at the battery whilst the current becomes zero due to the charging deceasing.

Assessment 1 - Low Train Numbers

In the first assessment, the AC Railway model has been designed with two trains on separate lines to simulate a low train load scenario. The first train simulated has an active power 1MW and is situated on Track 3 within the first section of line, 6.25km from the feeder transformer. The second has an active power 3MW and is situated on Track 1 within the last section of line, 6.25km from the final autotransformer.

As we move down the four-track line the voltage and current profiles at the autotransformer sites differ dependent on their distance from the feeder transformer. If we use autotransformer 3 for example, at the furthest end of the line, we see the largest drop in voltage. This voltage is still well within the acceptable limits and the current profile fits with the expected results.

As the station is within the first 12.5km section this is where the EV charge connection is placed within the system. The EV uptake numbers of 10 to 80 EV cars has been simulated to understand its effect on the system during low train usage. At uptakes of 10 and 40 EVs there is minimal effect on the system however in the 80 EV scenario, the integrated system is pushed to its limits and a noticeable drop in voltage occurs. Although the voltage has dropped below the nominal at the furthest transformer, we still achieve a voltage above the mean useful levels at the pantograph. This will allow trains to run at their optimum at all speeds within the network.

Assessment 2 - High Train Numbers

In the second assessment, the AC Railway model has been designed with six trains on separate lines to simulate a high train load scenario. There are two trains within the first 12.5km section of line. One train situated on Track 1 with an active power of 5MW, the second situated on Track 3 with an active power of 2MW. Within the second 12.5km section of line there is one train situated on Track 3 with an active power of 0.5MW, and the second situated on Track 4 with an active power of 3MW. In the final 12.5km section there are two trains with an active power of 1MW, one on Track 2 and the other on Track 1.

The voltage, due to the larger presence of trains on the network, is considerably lower. This is to be expected and is still within the acceptable limits. Additionally, the current profile fits with the expected results and the voltage profile shows that it is above the 19kV lowest permanent voltage limit, see Table 1.

Ref	System characteristic	Symbol	Value	EN source	GL/RT1210
1.4	Lowest permanent voltage.	U_{min1}	19,000 V AC	EN 50163:2004+ A1:2007, clause 4.1, Table 1.	2.1.1.1
1.8	Mean useful voltage (at the pantograph) (v < = 200 km/h).	$U_{mean\ useful}$	22,000 V AC	EN 50388:2012, clause 8.3.	2.1.1.2

Table 1 - 25kV AC Railway Voltage Limits[11]

At 10 EV uptake there is negligible effect however the potential EV charging integration problems start to become apparent when the pantograph voltage and current are assessed at 40 EV uptake. The voltage level shows that the mean voltage level of 22kV is almost encroached upon in the 40 EV scenario and as such presents a potential risk to the performance of the trains, see Figure 9.

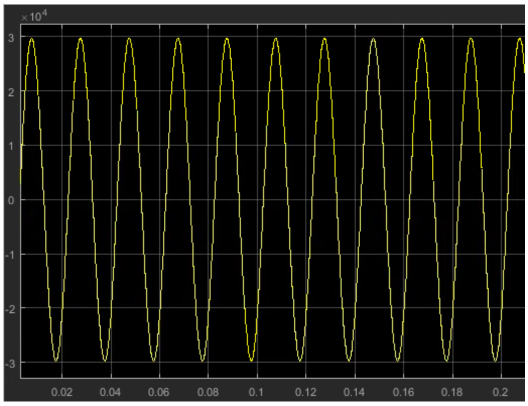

Figure 9 - Voltage profile at train 6 pantograph (High train numbers with 40 EV's charging)

When a full quota of 80 EVs is introduced, such a noticeable drop in voltage occurs at the furthest transformer that the levels decrease below the 20kV mark, see Figure 10.

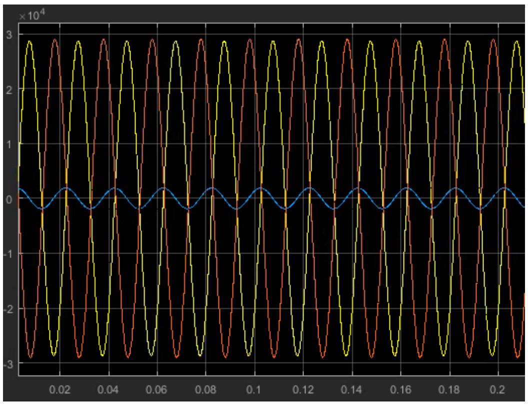

Figure 10 - Voltage at furthest auto-transformer (High train numbers with 80 EV's charging)

Although the lowest permanent voltage of the AC railway is 19kV, which the system adheres to, the voltage seen at the pantograph is below the mean useful voltage level. As mentioned, this reduction in voltage seen at the pantograph could result in poor train performance and have an adverse effect on delays within the railway and potential fines.

CONCLUSION

The possibility of charging EVs in Park and ride facilities on railway network were investigated through defining different scenarios. The results through modelling and simulation showed that a compromise is possible but the charging uptake has to be limited to allow trains to be properly powered. The AC railway voltage levels were maintained above the lowest permanent voltage value of 19kV in most cases but it was observed that in scenarios of high train numbers incorporated with extended EV numbers, a limitation in the system will be highlighted in terms of voltage drop. When both systems were functioning at their maximum, the voltage seen at the furthest train pantograph was below 20kV, this meant that train performance would be compromised. This was due to the mean useful voltage level not being achieved. The results and analysis highlighted that an integrated solution between EV and rail at park-and-ride was an achievable solution. However, the extension of EVs within the business park should not rely on the AC railway for its supply without further considerations. On this basis, the study recommended that smart solutions such as PVs on rooftop of parking area integrated with energy storage is required to be implemented to build up confidence in system. Also recommended, was for EV batteries linked to the system, to have limited charging and discharging (70-80% of the battery) to ensure charging efficiency and provide confidence in the system. Additionally, refinement of this model to include the regenerative braking aspect is required to fully represent movement of the train, energy absorption and discharge.

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