

Design of the contact-less battery charging system for the people-movers at the Whakarewarewa Geothermal Park

G. A. Covic Member IEEE, G Elliott, O. H. Stielau, R. M. Green¹ and J. T. Boys Fellow IPENZ

Electrical and Electronics Engineering, The University of Auckland, Private Bag 92019, Auckland 1, New Zealand

¹Wellington Drive Technologies, 12A Vega Place, Mairangi Bay, Auckland New Zealand

Abstract

This paper describes a contactless power transfer system to provide intervention free battery charging to specially designed low-weight electric vehicles for use at Whakarewarewa Geothermal national park. This system was commissioned in 1998 and is unique in concept and design. It allows around 20kW to be supplied to the electric vehicles via a non-contact ICPT (inductively coupled power transfer) system when parked at loading platforms. The charging is transparent to the driver and passengers, requiring only that the driver park in a designated (but non-critical) location so that the charging unit can sense the vehicle and begin power transfer and battery charging if required. Four charging bays (buried under the ground) are provided, allowing opportunity charging throughout the day. This minimises the necessary on-board batteries, and therefore the vehicle weight, while still allowing the vehicles to be operated continuously. The system continues to operate successfully in this corrosive environment with minimal down-time.

Keywords: Contact-less energy transfer, Electric vehicles, Battery charging

1 Introduction

As part of a major redevelopment of the thermal park at Whakarewarewa, near Rotorua, New Zealand, a people-mover system was commissioned. The people-mover is necessary because the redeveloped park is extensive, with many areas being difficult for visitors to access in reasonable time. It was expected that this people-mover system would contribute significantly to the overall visitor experience at the site.

Wampfler A.G. in Germany were responsible for designing and developing an appropriate solution for the people-mover drive train working through Auckland UniServices with technology supplied by the Electrical Engineering department of the University of Auckland. Several important aspects were considered. First, the site is an area of considerable natural beauty, with an interesting history of human habitation. Visitors must be free to concentrate on the features of the site, without intrusion from the workings of the people-mover itself. Secondly, the terrain and ground conditions within the thermal area are difficult in several respects, so that the physical size and weight of the vehicles must be kept down. Thirdly the system should be environmentally friendly to prevent damage to the ecological nature of the site. Finally, the system should operate with minimum user intervention.

An electric people-mover meets all of the important site requirements; however traditional systems suffer from significant restrictions in terms of charging and maintenance of on-board batteries, limited service range and high weight. Another important consideration is the hostility of the site to electrical and electronic equipment due to the high levels of sulphur dioxide, which, when combined with moisture in the air, produces sulphuric acid. These obstacles can be overcome, but at high cost rendering the system commercially impractical. On the other hand, if internal-combustion engines were used problems would arise due to unacceptable levels of pollution, noise and maintenance.

The proposed solution was to develop a people-mover powered by an ICPT power supply system [1] in conjunction with sealed maintenance-free lead-acid batteries. ICPT systems permit

power to be transferred to vehicles without contact or operator intervention. Sealed AGM (absorptive glass mat) lead-acid batteries are attractive as they minimise maintenance and do not vent gas under normal charging so safety hazards are avoided. This system is the first loosely coupled ICPT battery-charging system, at this power level, in the world. Other systems such as [2-4] are designed for either much lower power levels or more restrictive operating conditions.

The paper discusses the key aspects of the project and details the development of the ICPT pickups used on the vehicle, the vehicle control electronics and the ICPT charging system.

2 The Site Requirements

The Whakarewarewa geothermal park, located in Rotorua, has long been a place of spiritual significance to the local Te Arawa Maori people. Due to public interest in the geothermal activity, the original geothermal park was opened to visitors, centred around the Pohutu geyser. In 1995 a large section of the site was developed to open up new previously unseen areas to the public. A people-mover was deemed necessary because parts of this new area were considered sacred so that visitors were not allowed on foot. With the expected rise in visitor numbers the people-mover was expected to carry around 600 people per hour over a circuitous track roughly 1.8km in length [5] having several interesting features:

- The area is mildly active geologically: geysers, mudpools, fumeholes etc. are present and are major attractions. These features constrain the route, and more importantly the permissible weight, of the people-mover.
- In areas specifically designed for visitors, the people-movers must share a narrow (2.4m wide) track with pedestrians.
- Large variations in passenger loadings are encountered throughout the day.
- The site operates for ten hours per day, all year, although extensions to operating hours are intended.

The close proximity of vehicles to pedestrians, the off-road, closed-circuit nature of the route, and the requirement of a relatively small vehicle width (1.5m) make electrically-driven vehicles an attractive option. However, an analysis of the energy requirements for passenger transport around the route [5] showed that each vehicle could consume approximately 2.4kW-hr or more per hour of operation (depending on vehicle selection and loadings). This level of energy requirement is beyond the capacity of an electric vehicle operating with only a single charge per day, particularly when taking into account vehicle weight restrictions. Consequently, in order to service the site using conventional electrically operated vehicles either an expanded fleet size (allowing some vehicles to be charged while others were working), a battery exchange scheme, or fast battery recharging would be required. Modern ICPT systems can now be designed to supply the needs for site-specific people-mover applications. Such equipment “changes the rules” for sites like Whakarewarewa, because electrical power can be supplied to the vehicles on a continuous, semi-continuous or intermittent basis, without any operator intervention, or maintenance of any kind.

3 Choosing an appropriate ICPT system

A typical ICPT system may be envisaged as shown in Fig. 1. It consists of two mutually coupled independent electrical systems. The primary (stationary) part of the ICPT system produces an essentially constant current I_1 in the transmission inductance L_1 using a suitable resonant power supply. The transmission inductance can be physically constructed in the form of a track or charging coil; and often, primary compensation in the form of a tuning capacitor is necessary to minimise the VA rating of the supply [6,7]. The pickup (secondary) can physically move with respect to the track or charging coil and is mutually coupled to the transmission inductance when in close proximity. Here a compensation capacitor is also often required, to enhance the power transfer capability. A switched-mode controller is normally used to control the power flow from the pickup coil to produce a stable DC power source as required for a motor controller or other loads.

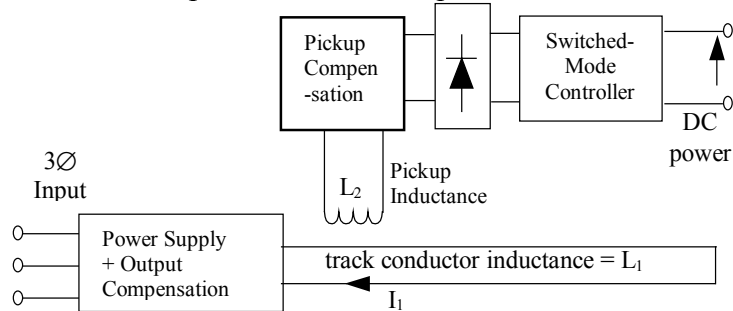


Fig. 1: A Tuned ICPT System

While it might appear that an ideal solution is to eliminate the batteries altogether by using a continuous track system, there are inherent problems. The ground is unstable, and therefore over time the track conductors are likely to move, making pickup alignment difficult. A power supply designed for the peak power requirements would be required, but is not cost effective. A track-powered system would cost more than NZ\$600,000 for Litz wires plus power supplies, whereas batteries for five vehicles cost around NZ\$20–25,000. It is not possible to have zero battery operation, as vehicle operation would then be constrained to powered sections of the road, which is undesirable considering the nature of the site.

An alternative is to reduce battery weight by adding several charging stations along the track where opportunity charging can take place. Assuming the power used to negotiate a complete circuit can be replaced in an acceptable time before beginning the circuit again, the batteries need contribute only around 10% of the gross weight of the vehicle, rather than 40% as in conventional electric systems. If the charging bay is positioned at the passenger transition bay, the time required to off-load one set of passengers and load the next group of passengers can be used to deliver the energy. The power supply must deliver around 25kW for this option to be feasible.

A third option combines elements of both systems described above, in that a charging bay with reduced power delivery (around 10kW) is required at the end of the circuit, but a second supply and buried track rated around 6kW is used to transfer additional power along the route in those areas with the steepest gradients (around 12%). In consequence the peak demands are removed from the battery, and supplied from the pickups directly. This allows the battery weight to be reduced further.

It was decided to use charging bays only, because the reduction in battery weight would not offset the additional cost of adding several track supplies. The potentially short duration of suitable charging opportunities at peak times (only three minutes might be available to deliver the required energy) requires some form of high-power-delivery mechanism incorporating fast charging and battery management [8]. To achieve this goal, specialised power pickups that are mounted underneath the vehicle had to be developed. The system had to ensure high power transfer over large air-gaps (typically 50 mm) [9].

The following sections discuss the design of the implemented system, from the development of the charging bays and supply, through to the design of the vehicle pickups, supervisory control and protection.

4 ICPT power supply design considerations

Two charging stations were installed to service the site. Each charging station consists of a single ICPT power supply and two charging bays. The ICPT power supply is a series resonant supply based on a standard industrial AC motor drive inverter, which has been extensively modified to drive the charging bays [10]. The original controller was reprogrammed to perform new functions: setting and controlling the timing of the bays, generating the reference current for each charging bay, and implementing the necessary overcurrent, overvoltage and overtemperature protection within the inverter. The gating signals to the power electronic switches are controlled from a second custom-designed ICPT controller board, designed to control the charging bay current in real time, at a switching frequency of 12.9kHz.

Each charging bay consists of 5 turns of Litz wire embedded in a protective protrusion in the middle of the path (Fig. 2). The vehicle must be positioned over the charging pad before charging can begin. The height of the pad must be limited so that there is sufficient clearance for a fully laden vehicle with flat tyres to pass over the top, while ensuring that the tolerances between primary winding of the coil and the pickup on the vehicle are kept to a minimum. The design objective is to deliver between 20-30kW over a significant air-gap (around 50mm) with large tolerances to horizontal misalignment (up to 50mm either way). To minimise the VA rating of the supply, however, it is necessary to compensate for the large leakage inductance in the primary coil [6,7].

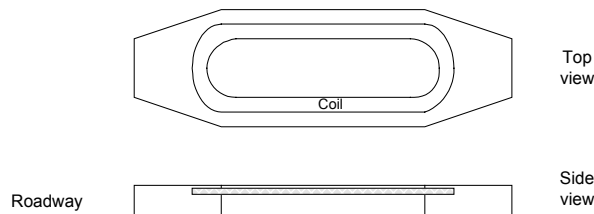


Fig. 2. Layout of a single charging bay.

The compensation capacitor is connected in series between one phase of the inverter output and the common contact of the charging bay coils as shown in Fig. 3. This capacitor compensates for some of the track/coil inductance and presents the inverter with a smaller inductive load to drive so that it can achieve the required charging currents.

Contactors are used to switch the charging unit between the two charging bays at three-minute intervals. During the period assigned to bay 1, bay 2 is inactive and vice versa. However the unit will not turn on and supply charge unless a vehicle requesting charge is detected via an infrared receiver.

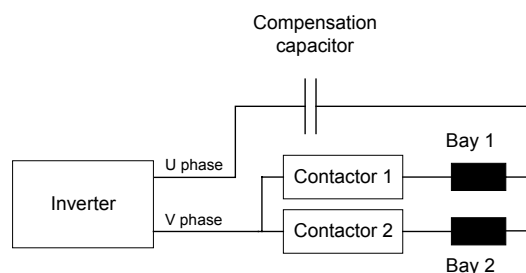


Fig. 3. Inverter, compensation capacitor and contactor configuration.

Aligning marks on the vehicle and the loading platform are used to indicate to the driver where the

vehicle should be parked for charging. Tolerance of misalignment is determined by the infrared link and is about 5cm forward or backward. If misalignment exceeds this, the infrared receiver will not detect the vehicle, and the charging unit will not switch on. Measured efficiencies for ICPT charging to the terminals of the battery from the mains supply are 90–91%, which compares with conventional plug-in chargers with efficiencies of 96–97%. However the battery efficiency with ICPT opportunity charging is significantly higher than a plug-in charger running at a lower average state of charge.

5 Vehicle control electronics

As shown in Fig. 4, each vehicle operates off a 120-volt DC system supplying a simple DC motor drive without any regenerative control. The motor drive and controller were sourced independently and therefore the on-board system had to be designed to work in with these components.

The battery bank was designed to have a capacity of between 5 and 7kWh. Peak discharge rates were anticipated to be around 15kW, although in practice they are closer to 25kW. The average rate is around 3kW. To meet these demands each vehicle uses 32 Hawker Genesis G12V38Ah10EP sealed-lead batteries. Thirty of these batteries are connected in a 10*3 matrix. The other two batteries are connected in parallel for the vehicle’s auxiliary 12VDC supply. This supply is used for the sound system, lights, and vehicle controller.

Each of the 10 pickups mounted underneath the vehicle are inherently isolated and able to individually charge one set of three batteries. As a result the battery string is balanced without additional circuitry. This process is monitored and controlled by the vehicle controller. Should any of the pickups or any of the batteries within a set fail only that set is affected. All other batteries will continue to be charged properly and it is only necessary to replace the one failed set of batteries or pickup.

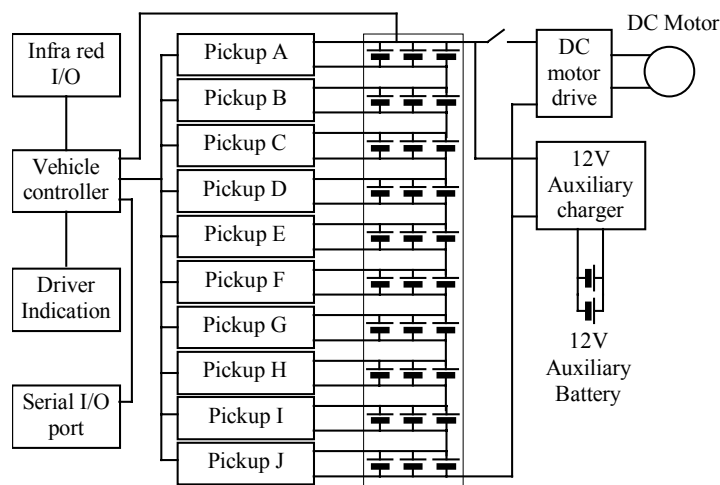


Fig. 4: On-board electronics and charging equipment.

The vehicle controller has three protection systems embedded in the normal charging process: pickup overtemperature protection, protection against battery overvoltage due to a pickup failure, and protection against undervoltage due to a broken sensing wire. If any of these conditions are detected the controller will deactivate the infrared transmitter, which effectively turns off the ICPT power supply. In addition, the DC motor drive and controller are isolated from the batteries during the charging process to ensure their voltage ratings are not exceeded.

6 Pickup design

6.1 A suitable roadway pickup

Each pickup (shown in Fig. 5) is controlled from the vehicle controller via an electrically isolated control signal to switch S. With this switch open, the pickup is compensated and can deliver full power. With this switch closed, the pickup is magnetically decoupled from the primary [1], and no power can flow. In this decoupled state, the pickup short-circuit current (nominally 14A) flows through the switch. A timing circuit ensures that each power switch is turned on only when the voltage across it is zero, which protects the device from accidentally shorting the compensation capacitor when it is storing charge.

The arrangement of each pickup is unique, in that it has two windings, a single-turn low-voltage power winding (physically constructed from two single-turn windings in parallel) and a high-voltage control and compensating winding.

A conventional pickup as described in [1] can be characterised in terms of its open circuit voltage and short circuit current (both of which are easily measured). The open circuit voltage induced in the pickup coil inductance L_2 is dependent on the track frequency (ω), and the mutual coupling (M) between the track and secondary (pickup), and is given by:

$$V_{oc} = j\omega MI_1 \quad (1)$$

The maximum output current is the short circuit current in the pickup, and is given by the open-circuit voltage in (1) limited by the reactance of the pickup coil. This can be expressed as:

$$I_{sc} = \frac{V_{oc}}{j\omega L_2} = \frac{M}{L_2} \cdot I_1 \quad (2)$$

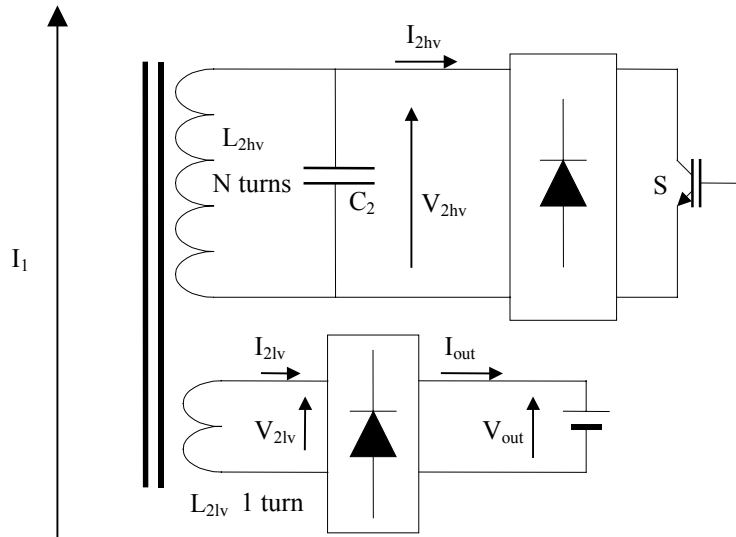


Fig. 5: Schematic of primary track current and secondary pickup coils.

In the battery charging system described in Section 5, it is desirable to supply a large amount of power into individual battery sets to charge the batteries as quickly as possible. As the battery voltage is constrained, large currents of approximately 200A are required. The primary current was limited by the cost and capacity of the supply. Consequently it was desirable to maximise the M/L_2 ratio. This ratio is complex and dependent on the physical dimensions of the pickup, and its position relative to the charging coil (primary track coil). Consequently the pickup design must be tolerant as to vehicle positioning. Given the complex arrangements this ratio was determined experimentally.

A simple magnetic arrangement consisting of 2 ferrite plates linked with a smaller ferrite plate was used to form the core of the pickup as shown in Fig. 6(a). These plates provide a low-

reluctance path for the magnetic flux generated by the track conductors placing particular emphasis on the horizontal component of the magnetic field. Due to the brittle nature of ferrite, the plates were constructed from smaller ferrite blocks (“fingers”) each of which is 118mm long, 35mm wide and 10mm high. These fingers were initially designed to have ground edges and to be held together using a spring-based mechanism, providing a structure that is able to withstand the shocks associated with being mounted on a moving vehicle. However, it was found during experimentation that small gaps between the ferrite “fingers” used to construct the pickup did not affect the results drastically. This eliminated the need for ground edges, and so the ferrite pieces were simply tightly packed with sponge rubber and sealed inside an ABS casing for rigidity.

A 10mm aluminium screen was placed over the pickup. This has little effect on the MAOP but substantially lowers the magnetic fields above the pickup, and provided the necessary shielding for the control electronics to operate, and heatsinking for the control electronics.

Whilst the magnetic structure of the pickup is designed to meet the physical tolerances and maximise the mutual coupling, electrically the secondary inductance was minimised by using a single-turn winding to improve the output (short circuit) current. However this also reduces the open circuit voltage, which is dependent on the number of turns. The maximum output power of such a pickup winding is the product of the open circuit voltage and short circuit current, and is normally insufficient to meet the requirements of the application. The available power can be improved by compensating the pickup winding using a tuning capacitor (C_2), which in this application is placed in parallel with the coil and output load, resulting in a parallel tuned circuit. The tuned coil voltage across this capacitor is given by:

$$V_2 = V_{oc} Q_2 \quad (3)$$

Here $Q_2 = \omega C_2 R_2$ is defined as the quality factor for a parallel compensated pickup with its output load represented by a resistance R_2 . The power capacity for this pickup is given by [1]:

$$P_2 = |V_2 I_{sc}| = \frac{\omega I_1^2 M^2 Q_2}{L_2} \quad (4)$$

The required capacitor compensation is normally chosen to completely tune out the inductance at the track frequency, and is therefore given by:

$$C_2 = \frac{1}{\omega^2 L_2} \quad (5)$$

Thus for a given track frequency, the tuning capacitance increases with decreasing secondary inductance. In practice, the very small inductance required by this application required large tuning capacitances, which are both costly and bulky.

Switch S is used to regulate the current into the battery and must be capable of sinking the short-circuit current of the tuned coil. Economical power switches are designed for high-voltage low-current applications. Power switches capable of switching large currents are too expensive for this project.

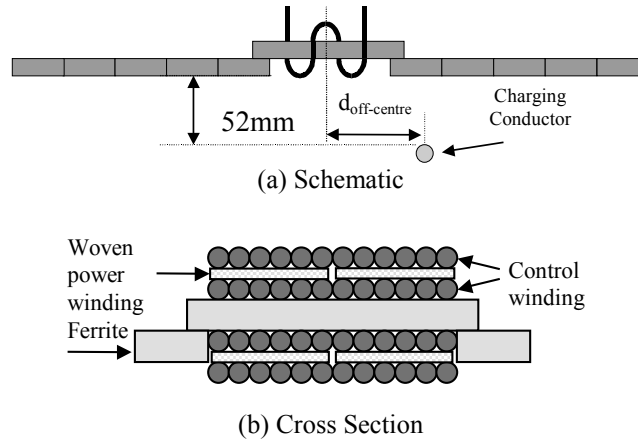


Fig. 6. Pickup construction

These problems were addressed by using two tightly coupled windings around the pickup core as shown in Fig. 6(b). The design of this high-current low-voltage (power) winding was especially difficult, requiring mechanical flexibility yet an electrically tight coupling to the control winding to achieve acceptable control. This power winding is constructed as a single turn made by hand-weaving Litz wire into a flat braid. In practice two flat windings are used to provide sufficient cross sectional area for the 200A output current at the desired voltage. Each winding is terminated using a bridge rectifier constructed using high speed Schottky diodes, and these two outputs are paralleled. At full output current, the loss across these devices is approximately 170W, therefore they must be heatsinked using the aluminium screen.

The second or ‘control’ winding has more turns of the Litz in order to increase the inductance and thereby reduce the necessary tuning capacitance. As shown in Fig. 6(b), the power winding is sandwiched between the control winding in order to achieve as the maximum possible between the two windings. A coupling coefficient (η) of 0.97 was measured, verifying this construction [11].

Because of the transformer coupling between the two secondary windings, the open-circuit voltage of the tuned coil is amplified by the turns ratio, while the short-circuit current is lowered by the turns ratio. Consequently, the current in the single-turn winding can be controlled by applying a short circuit to the control coil allowing the use of more cost effective high-voltage low-current switches. For example, if the single-turn winding had an output voltage of 17V at 200–300Arms, with a 22 turn control winding, the controlling switches would need to be rated at around 400V and 20A.

As the high-voltage winding with N turns is tuned, and coupled to the low voltage winding by the factor η , then the voltage across the low-voltage power winding is now given by [11]:

$$V_{2lv} = \frac{\eta V_{2hv}}{N} = \eta Q_2 V_{oclv} \quad (6)$$

where V_{oclv} is the open circuit voltage in the low-voltage power winding. Consequently the maximum available output power from (4) is now re-expressed as:

$$P_{2lv} = |V_{2lv} I_{sclv}| = \frac{\eta \omega I_1^2 M^2 Q_2}{L_{2lv}} \quad (7)$$

6.2 The electromagnetic pickup design

The pickup design was determined experimentally. A simple experimental rig rated to 1/80th of the power delivery of the final system was constructed as shown below in Fig. 7 to determine the effects of power transfer when the pickup was misaligned from the track inductor. In this

application the nominal height of the pickup from the track is well constrained since the vehicle height does not move significantly[?] between full and light load. This height was nominally $50\text{mm} \pm 5\text{mm}$, thus a nominal control height of 52mm was chosen. In contrast the horizontal positioning of the pickup relative to the track is dependent on the driver. Consequently this can vary by up to $\pm 100\text{mm}$. Therefore the pickup design focused primarily on determining the appropriate width of the ferrite section required to produce the output power. From a control perspective, a Q_2 of less than 5 is also desirable [1]. The parameters under which all initial measurements were taken are given below in table 1.

During initial tests the high-voltage winding remained uncompensated ($Q_2 = 1$). Open-circuit voltage and short-circuit currents were measured at various heights while deliberately increasing the horizontal misalignment from the track centre. The maximum available output power (MAOP) possible from this uncompensated pickup was calculated from (7). Fig. 8 shows one set of these measured results for varying pickup widths (l_a) as indicated in Fig. 7. Here the output is indicated in VA corresponding to a measured open-circuit voltage multiplied by a measured short-circuit current. The centre gap (l_g) required for the winding was held constant for all measurements.

These and other similar measurements enabled the final pickup magnetic structure to be fixed, which fixes the $\eta M^2/L_{2lv}$ ratio in (7).

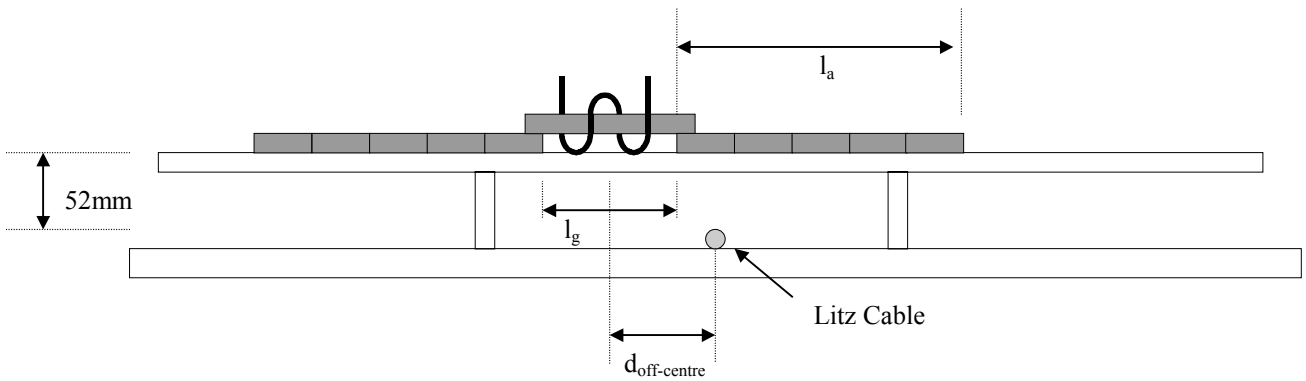


Fig. 7: The Experimental Rig

track inductance (L_1)	$43.6\mu\text{H}$
track frequency ($f=\omega/2\pi$)	10.04kHz
track voltage	$265 V_{\text{RMS}}$
track current (I_1)	$100A_{\text{RMS}}$
high voltage secondary coil turns (N).	24
length of the winding gap (l_g)	60mm

Table 1: Experimental system parameters

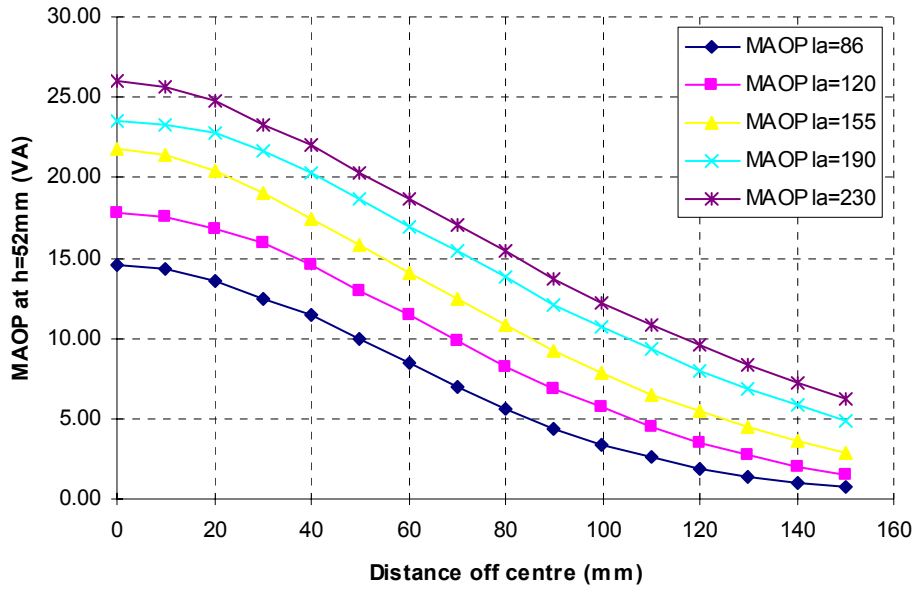


Fig. 8: Maximum Available Output Power (1/80 scale) against distance off centre for an uncompensated pickup with varying values of I_a .

The final pickup was constructed using 12 ferrite blocks, with I_a equal to 175mm (requiring 5 ferrite blocks on either side). During early experiments it was found that the control IGBTs could be protected from the large peak voltages that can occur during the short-circuit operation of switch S, by allowing the core to saturate during this time. This was deliberately achieved by limiting the amount of ferrite in the centre plate around which the coils were wound.

Measured results from Fig. 8 of this finalised pickup were scaled for an effective track current of 800 Arms (equivalent to 160A with 5 turns in the primary track) operating at 12.9kHz. The output current and power into the battery estimated from equation (7) are shown in Fig. 9 assuming perfect tuning, while table 2 summarises the key results. In practice these ideal conditions are very nearly met. As noted earlier, charging current variations with pickup height are not included here but by way of example, if the gap is reduced to zero the charging current rises from approximately 250A to 380A.

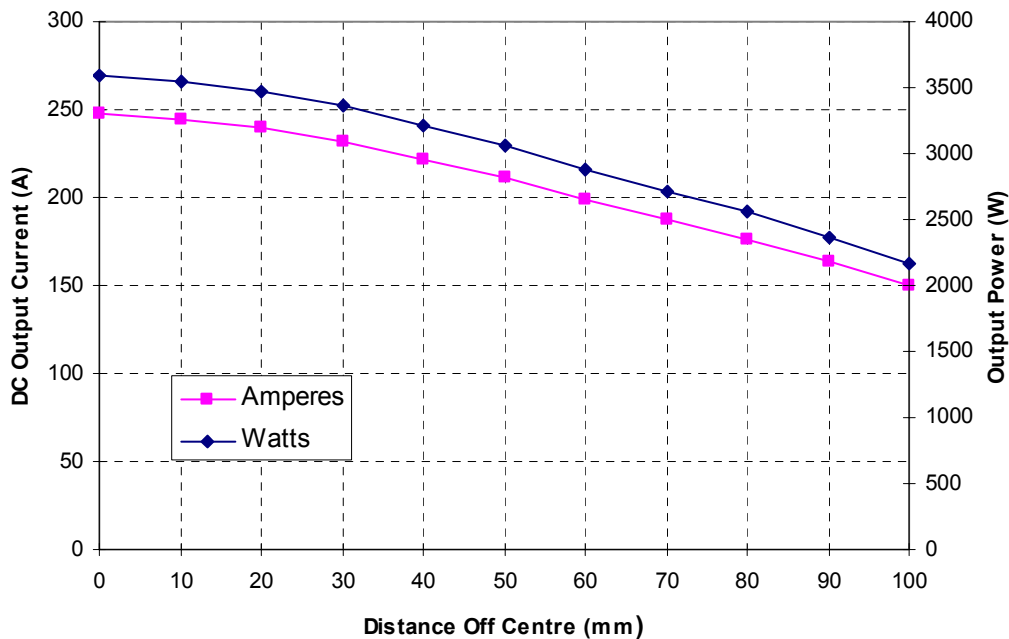


Fig. 9: Output current and power against distance off centre. ($I_a=175\text{mm}$, $I_1=800\text{A}_{\text{RMS}}$, $f=12.9\text{kHz}$)

Maximum output power	3592.8W
Output power @ $d_{\text{off-centre}} = 50\text{mm}$	3063.9W
Maximum output current	247.9A _{DC}
Output current @ $d_{\text{off-centre}} = 50\text{mm}$	211.4A _{DC}
Maximum Q ($I_T = 800\text{A}$)	2.12
Maximum flux density in the ferrite	0.24T

Table 2: Final Pickup Performance

6.3 A novel method of short-circuit current control

A novel method of short-circuit current control has been adopted to control the resonant energy in the pickup circuit and thereby control the current pulses to the battery. The circuit used on the high-voltage winding of Fig. 5 is shown simply in Fig. 10 and 11. Instead of a single power switch S rated for the DC short circuit current, two switches (S_a and S_b) are used on the AC side of the circuit. These switches are designed to collapse the resonant energy in the tuned coil using the following mechanism. Due to the AC resonance in the circuit, when V_a is positive, there is zero voltage across diode D_b (V_b) and zero current flowing through it. Thus if switch S_b is switched on some time during this period, no power is lost during switching and the timing is not exactly critical (providing it is on before the voltage V_b starts to rise). During the next half-cycle with rising V_b , switch S_b will start to conduct, collapsing the resonant energy within the circuit formed by $L_{2\text{hv}}$ and C_2 . During this same cycle V_a is zero and the current through D_a is zero, thus S_a can be switched on without loss and the resonance continues to collapse. This process is illustrated in Fig. 11. Note the switches in Fig. 10 will invariably fail to short-circuit. If either switch fails then the resonance will collapse and leave the circuit in a safe condition.

The main advantages of using this technique over the traditional technique of using one switch to short circuit the coil through a rectifier bridge are that the timing of the switching need not be exact and that there is minimal switching noise and higher efficiency from the zero-voltage zero-current switching. However, a drawback is that the switching devices must be able to handle the short-circuit currents multiplied by the quality factor of the circuit, but in a practical DC switching circuit a current-limiting inductor is also required so that the cost differences are minimal.

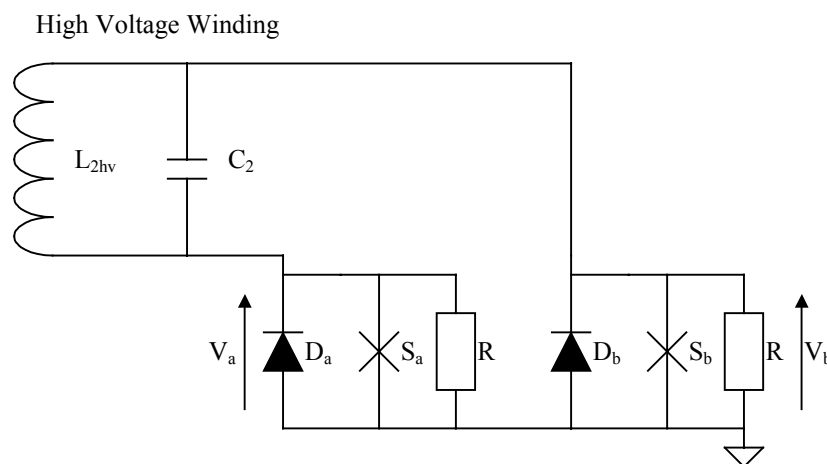


Fig. 10: Simplified Schematic of Short Circuit Mechanism.

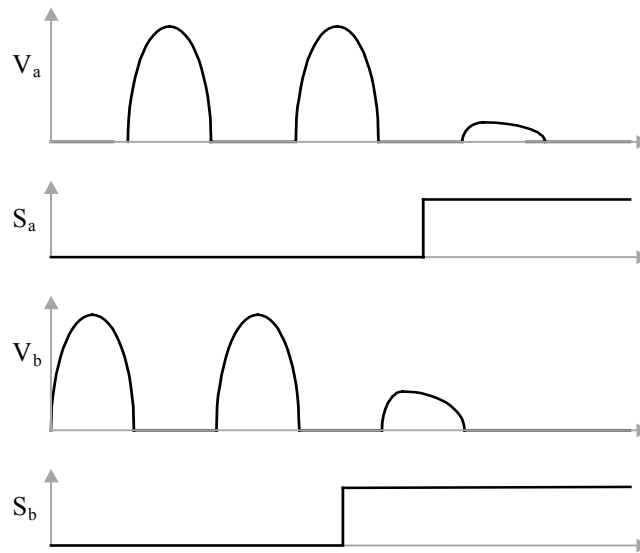


Fig. 11: Using the power switches to control the pickup energy

7 Battery charging

The algorithm used to charge the batteries uses a very simple pulse-charging strategy [8]. Current pulses of nominally 200A are injected into sets of three batteries in parallel by switching the pickups on and off. Each pickup is controlled independently, with the charging current controlled by varying the duty cycle of the pickups. Initially a short current pulse is applied to the battery. At the termination of this pulse, the temperature and voltage of the battery are measured. From these two parameters an approximation of the temperature-compensated resistance-free voltage can be made. If this is determined to be less than approximately 14.7 V the duty cycle is increased until either 14.7 V is exceeded or the maximum duty cycle is reached. In this particular application, the frequency of the charging pulses was chosen to be 2.5Hz, giving a delay between the start of these pulses (t_d) of 400ms. A maximum pulse width of 95% was chosen to ensure that a relaxed voltage could be measured even on full charge. The relaxed voltage is measured just before the beginning of the next charge pulse allowing the battery as much time as possible to reach a relaxed state. This is shown below in Fig. 12. As the battery's state of charge increases with charging, the duty cycle must be reduced to ensure that the resistance-free voltage does not rise above 14.7V. This is done in 10% increments. When the batteries are in a high state of charge (typically around 95%), t_d is increased in integer multiples of 400ms to a minimum charging rate of 1.25% (a 20ms pulse, $t_d = 1600$ ms) so that only intermittent charging will occur, allowing battery equalisation. To ensure good battery lifespan the batteries must be charged if one or more of the battery voltages is determined to be below 11.5V.

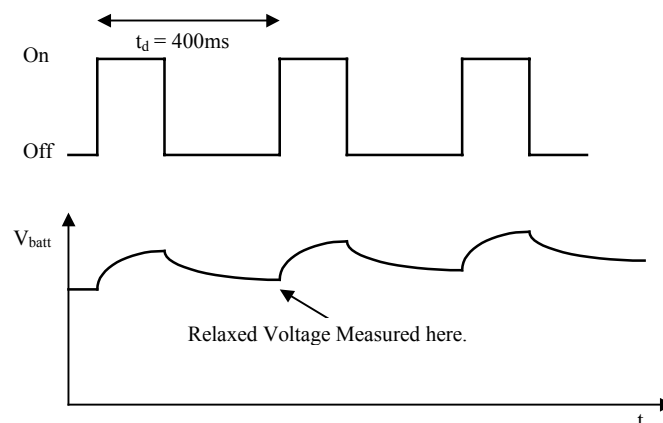


Fig. 12: Charging algorithm cycle.

8 Results

The charging unit energizes the charging coil and controls the coil current at 160A and a frequency of 12.9kHz when requested. The vehicle controller then manages the turning on of each pickup, enabling charge to be supplied to the batteries. Fig. 13 (a) & (b) shows typical measurements of the output current from a single pickup into a battery set. A typical current pulse is shown in Fig. 13(a). When the pickup is switched on the charging current takes about 800 μ s to reach its steady-state value. Here about 175A is being delivered into the battery set, which is less than the nominal 200A due to a 70mm lateral misalignment of the vehicle.

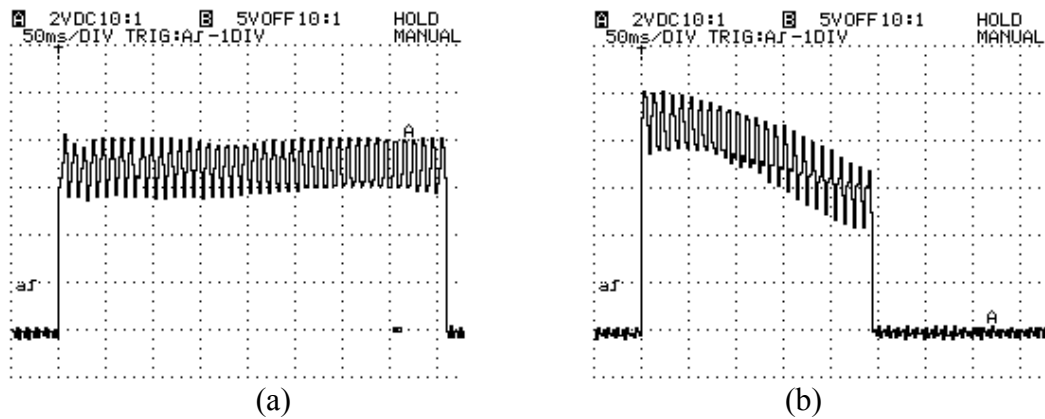


Fig. 13. Vertical scale: 50A/div, Time scale: 50ms/div.
(a) Charging current for one charging pulse.
(b) Battery charging current at the end of the charging cycle.

Fig. 13(b) shows the inherent voltage limiting property of the pickups. If the battery voltage exceeds 15V, which can happen when a large amplitude current pulse is applied to batteries with a high state of charge, the charging current automatically reduces. This reduction in current is due to saturation of the ferrite core in the pickup that protects the power electronic switches but also results in a reduced power transfer capability. At this point the controller reduces the charging current by reducing the duty cycle of the pickups. This prevents gassing in the battery, which if prolonged can lead to premature failure.

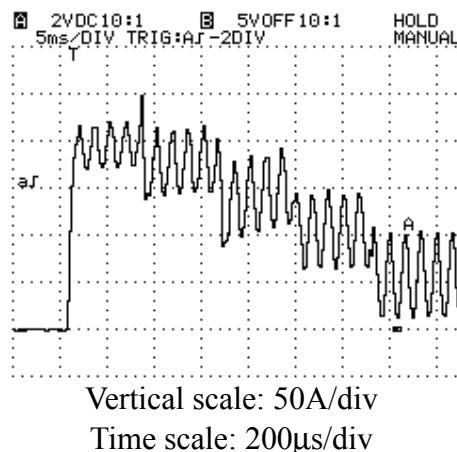


Fig. 14. Detuning effects of multiple pairs of pickups under commissioning

During commissioning, the power transfer was found to be less than desired when all 10 pickups requested full charging current. This is shown dramatically in Fig. 14; during initial trials as pairs of pickups were switched on to the supply the available power transfer dropped from the desired

30kW to less than 10kW. This loss in power transfer is principally due to the effects of multiple pickups and the mutual inductance between them reflecting back unwanted VARs on to the ICPT power supply [6,7]. Thus with each of the pickups demanding full power, the VA rating of the supply was exceeded because of this additional VAR contribution. Originally each pickup was to be individually screened to minimise this effect. However vehicle size constraints forced each of the pickups to be in close proximity to each other, without these additional screens, which exacerbated the above problem. In consequence, to improve the power transfer, only five pickups are switched on at any one time. This allows 17kW to be delivered during the charging process. After a 400ms period the vehicle controller switches across to the other five pickups. The consequence of this reduced power delivery is that the vehicle must be charged for seven minutes in order to replace the energy (approximately 2kW/hr) lost during one lap of the park. Because of the practical utilisation of the vehicles this is easily possible even during the busiest months of the year.

Currently the site is open every day, with peak demands in summer requiring approximately 20-25 trips per day. Normally four vehicles are available for operation on any one day (allowing one vehicle to be put aside for maintenance). In consequence during the summer months the vehicles operate at least 5 trips per day, while in the winter months this reduces to around 2 trips per day. Ideally all vehicles would have their batteries float charged overnight; however presently only two bays are used for security reasons. With current use, the battery's life is around 2.5 years, or around 2750 cycles if they experience 3 significant cycles per day.

9 Conclusions

This paper has described the application of an ICPT charging system to a continuously operating electric people-mover within a historic park. The non-contact nature of the ICPT power feed system significantly enhances the user-friendliness and appeal of such a system, while adding no restrictions on movement or access. The non-contact nature of the system also means that fixed charging stations or platforms are not necessary, and moderate vehicle alignment provisions are all that is required.

10 References

- [1] J. T. Boys, G. A. Covic and A. W. Green, "Stability and control of inductively coupled power transfer systems," IEE Proc.-Electr. Power Appl., Vol. 147, No. 1, January 2000, pp. 37-43.
- [2] Sakamoto, H. Harada, K. Washimiya, S. Takehara, K. Matsuo, Y. and Nakao. F. "Large air-gap coupler for inductive charger [for electric vehicles]." IEEE Transactions on Magnetics, Vol. 35, no. 5, Sept. 1999, pp 3526-3528.
- [3] Pedder, D.A.G. Brown. A.D. "A contactless electrical energy transmission system." IEEE Transactions on Industrial Electronics, Vol. 46, No. 1, February 1999, pp 23-30.
- [4] Abe, H. Sakamoto, H. Harada. K. "A noncontact charger using a resonant converter with parallel capacitor of the secondary coil." IEEE Transactions on Industry Applications, Vol. 36, no. 2, March/April 2000, pp 444-451
- [5] R. M. Green "Thermal Park People-mover System (Whakarewarewa, New Zealand) Analysis & Specification of IPT Equipment". Report to MACI, Auckland Uniservices, December 1996.
- [6] O. H. Stielau, G. A. Covic, "Design of loosely coupled inductive power transfer systems," IEEE-PES/IEE/CSEE International Conference on Power System Technology, POWERCON 2000, Perth Australia, December 4th -7th pp. 85-90.
- [7] C. Wang, O. H. Stielau, G. A. Covic, "Load models and their application in the design of loosely coupled inductive power transfer systems," IEEE-PES/IEE/CSEE International Conference on Power System Technology, POWERCON 2000, Perth Australia, December 4th - 7th, pp. 1053-1058.
- [8] J. J. A. Wilkinson and G.A. Covic. "A new pulse charging methodology for lead acid batteries" IPENZ Trans.25 no 1/EMCh, 1998, pp. 1-11

- [9] G.A.J. Elliott, J.T. Boys, A.W. Green. Magnetically coupled systems for power transfer to electric vehicles. Proceedings of the International Conf. on Pwr. Elect. & Drive Systems, PEDS'95, 1995, 2, pp 797-801.
- [10] O. H. Stielau, J.T. Boys, G. A. Covic, G. Elliott. "Battery charging using loosely coupled inductive power transfer." 8th European Conference on Power Electronics and Applications, EPE'99, 7-9 September 1999.
- [11] J.T. Boys, G. A. Covic, G.A.J. Elliott "A new pickup transformer for ICPT applications" IEE Electronics Letters, Vol 38, no 21, pp 1276-1278, 2002