An Overview of a 50kW Inductive Charging System for Electric Buses

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Abstract – In order to be aligned with new emission standards for heavy duty transportation systems, there is a strong demand for alternative fuel buses. Pure electric buses are a possible solution; however, due to the average daily range requirement of 120-140 miles per day, the battery systems required for such vehicles significantly reduce its performance and increase its costs. One method to address this issue is to use opportunity charging on the vehicle while it is waiting at a fixed location (usually called recovery time). This helps to address the aforementioned issues while keeping capital infrastructure expenses relatively low. This paper explores the use of a 50kW inductive charging system as an opportunity charger for electric buses.

I. INTRODUCTION

There is a widespread increase in interest for inductive charging for electric vehicles [1]. Recently, inductive charging for electric buses has also gained widespread popularity [2]. From the transportation system standpoint, these can be generally classified into three different types of systems:

1. In-motion charging – This system uses extended sections of Inductive Power Transfer (IPT) couplers buried under the road to power buses as they move [3]. This technology can potentially provide the most significant battery size reduction on the vehicle; however, it also requires the largest capital investment.
2. Opportunity charging – This system uses the recovery time of buses to fast charge the on-board batteries using significant power levels. This technology can easily reduce the battery requirement on vehicles up to 50%, while requiring limited infrastructure installation, since it is a stationary charger.
3. Overnight charging – This system charges the electric bus overnight just like a conductive charger, but without a physical plug. The costs for these systems would have to be the lowest as they directly compete with the price of conductive chargers.

The average daily driving range for a typical bus is 120-140 miles per day. One of the major challenges with electric buses today is they require very large battery packs in the range of 200-350kWh to account for the driving range and also power hotel loads like heating, venting and air conditioning (HVAC) systems. These challenges with batteries are exacerbated by capacity fade during battery aging and operating in extreme temperatures (sub-zero Celsius or above 40C Celsius), consequently further needing a larger battery. As a result, pure electric buses are quite expensive and are also very heavy compared to their diesel counterparts. One way to reduce the need to package so many batteries onto the vehicle is to use in-motion or opportunity charging techniques to provide recharging throughout the day. High power opportunity chargers are probably the most popular today due to their reasonable costs [2]. There are many technologies that can support opportunity charging and two of the most well-known ones are conductive overhead charging and inductive charging below the vehicle. The advantages of inductive charging over traditional overhead catenary systems can be summarized as follows:

1. Maximization of charging power – the inductive charger requires minimal amount of time for the driver to park over the charging pad and begin charging. This is especially true with new solid state charging pads and also a wide range of misalignment tolerance that drivers are readily able to meet.
2. Weather proof – snow and heavy rain will not affect the inductive charger from operating, however, adverse weather can limit the operational availability (OA) for conductive chargers. This is especially true during overnight snow storms. Pretty significant snow/ice removal work is needed before the conductive overhead system is operational again, especially if the bus is not parked in doors.
3. Low risk of hazards – inductive chargers have no exposed high voltage contacts and the risk of electric shock is eliminated.
4. Aesthetics – inductive chargers can be installed under the road as compared to overhead systems. As a result, inductive chargers are more visually appealing than conductive overhead chargers. This may be especially important for population dense cities and municipalities. In addition, because inductive chargers are not easily visible, anti-vandalism protection comes naturally with such systems.
5. Lower maintenance cost – some of the newer inductive charging systems are complete solid state solutions and benefit from a much longer lifetime compared to the moving parts of a mechanically articulated system utilized for overhead chargers.

In this paper, a stationary 50kW inductive charger operating as an opportunity charging mode is outlined.

II. OUTLINE OF A 50KW INDUCTIVE CHARGING SYSTEM

A high level block diagram of the 50kW inductive charger is shown in Fig. 1. Power from the electricity grid is first

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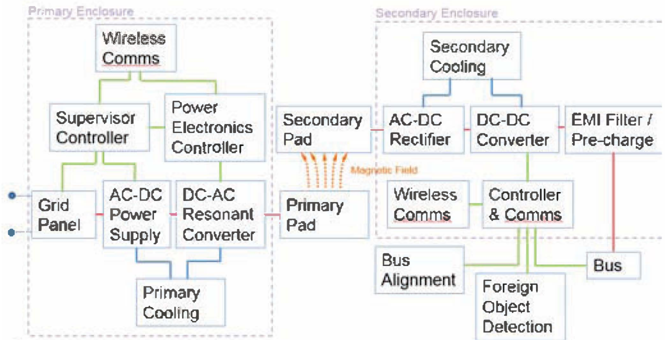

Fig. 1. Block diagram showing architecture of the 50kW inductive charging system

processed by an AC-DC power supply, and in this case it is a 480V 3-phase feed. A resonant converter generates a high frequency alternating current flowing in the primary pad. The secondary pad receives the coupled magnetic field and the power is processed through a rectifier back to DC. A DC-DC converter is used to further process the power and implement the necessary charging profile required for the battery management system (BMS). The charging mode includes a constant current and constant voltage mode for the lithium ion batteries. Due to the short duration of the opportunity charging system, cell balancing is only performed on the vehicle during overnight charging using a coventional plug-in conductive charger. The pre-charge stage helps the high voltage interface equalize in voltage during wireless charging as the inductive charging system is usually disengaged from the High Voltage (HV) propulsion system during vehicle operation. Digital controllers and low latency wireless communication is required for automated closed loop control in the power electronics system. Power regulation is achieved by both the primary and secondary sides to achieve improved efficiency against coupling variations [4]. A feedback loop also helps the system compensate against: coupling variations due to a varying height suspension as passengers board the vehicle, input grid voltage variations, the BMS disengaging from charging system (load shed) and system failure due to short circuits. It is also designed with a robust control concept to accept all resonant components variations up to 3%. A Dedicated Short Range Communication (DSRC) radio is utilized on both the primary and secondary to achieve low latency (<5ms) real-time closed loop control. The impact of occasional increases in the wireless delay and control loop gain that are accommodated during these events. Liquid cooling is used on both the primary and secondary systems. Finally, enclosures and cabinets are used to meet certain harsh outdoor temperature and environmental conditions. The primary pad is designed to handle H-20 loading condition by American Association of State Highway and Transportation Office (AASHTO) requirements which will be able to withstand normal passenger vehicles, semi-trailer trucks and the bus itself. It is also structurally enhanced to endure freeze/thaw cycling during harsh winters for a period of 12 years. Lastly, it is installed flush with the roadway so that the pad is snow plowable in winters and has no trip hazards. Other auxiliary systems like foreign objection detection (FOD) is used to detect metal debris on top of the primary pad. When the IR based technology detects a metal object (no more than 80C temperature), the charging system is automatically turned off and the driver is alerted. In addition, enhanced visual algorithms are adopted to sense for metal debris wrapped in a plastic or paper bag. A check to confirm that the bus is correctly parked within the misalignment range (4" at 7" air gap) is performed before a charging cycle begins.

A. *Inductive Charging System and Vehicle Integration*

The inductive charging performance is shown in Table 1. The charging system maintains a minimum of 50kW charging during the whole output voltage range of the BMS and coupling misalignment range. The DC-DC efficiency is measured from the DC input to the IPT system to the output to the BMS and varies depending on the output voltage and coupling conditions. The physical air gap is the minimum vehicle ground clearance and the magnetic distance between the coils is much larger. At 7" nominal, it is sufficient for most buses and no longer requires a mechanical articulation system to lower the secondary pad.

Vehicle integration is usually separated into four areas. The first is the high voltage interface where the bus has to allow both inductive charging and overnight plug-in charging. The second is the mechanical interface where the secondary enclosure and pad is mounted on the vehicle, and additional metal shielding is required in the flooring of the bus. The third is the thermal interface where the power electronics share the existing liquid cooling system on the vehicle. Last but not least is the software interface, where charging and control information is communicated between the inductive charging system and BMS. To help automate the charging system, other packets like vehicle gear and brake position is also provided.

A typical charging profile using the system was recorded and shown in Fig. 2. The y axis shows the power being delivered into the BMS, and x axis shows the time stamp. It can be seen that 50kW was guaranteed and in the particular example charging commenced for approximately 7 mins.

B. *EMC Safety*

Electromagnetic field safety is always a big concern especially given an inductive charging system at 50kW over a 7" air gap. This system uses a three tier interlock system to ensure the primary charging pad never starts charging until the bus is parked over the charging station and within alignment tolerances. During charging, the system needs to ensure the exposure of the magnetic field is low enough to the passengers. The two most common standards adopted today is the ICNIRP 2010 and ANSI 14117:2012 standards, for

Parameters	Values	Comments
Power Level	50kW	
Output Voltage	320-370V	BMS voltage range
DC-DC Efficiency	89-92%	
Operating Frequency	23.4kHz	
Air Gap	6.5-7.5"	Physical air gap between couplers
Misalignment	4" @ 7" gap	Up to 5" @ 6.5" air gap
Input Voltage	480V 3ph	

Table 1. Specification of inductive charging system

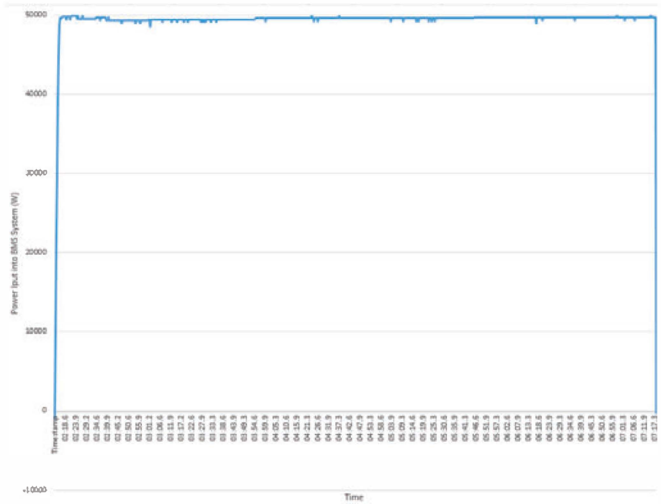

Fig. 2. A typical charging profile at 50kW

human tissue exposure and active implantable medical devices, respectively. At the operating frequency of 23.4kHz, the more conservative limit is set by ANSI 14117:2012 which is 15uT RMS for B field. Fig. 3 shows the 5 point measurements taken (A, B, C, D, E) at nominal alignment inside and outside the bus. The positions of measurement relative to the bus are shown in Fig. 4. B field at points 1-4 were measured for the misaligned condition. All other misalignment conditions were also measured. A NARDA ELT-400 measurement device was used. The highest B field point were measured outside the vehicle when the air gap is set to 6.5” with a misalignment of 5”. Point 1 shows the maximum field of 3.67uT (around D in Fig. 3). This point was also coincidentally the highest B field within the vehicle due to the small floor shielding and was 3.6uT (around E in Fig. 3). E fields for this low frequency system are negligible and not included here.

C. *Electric Bus Operation at University of Utah*

This system was deployed on a 1.6 mile route at the University of Utah and takes about 10 minutes to complete one loop. Normally wireless charging takes another 5 minutes. This cycle repeats operates about 12-16 hours a day.

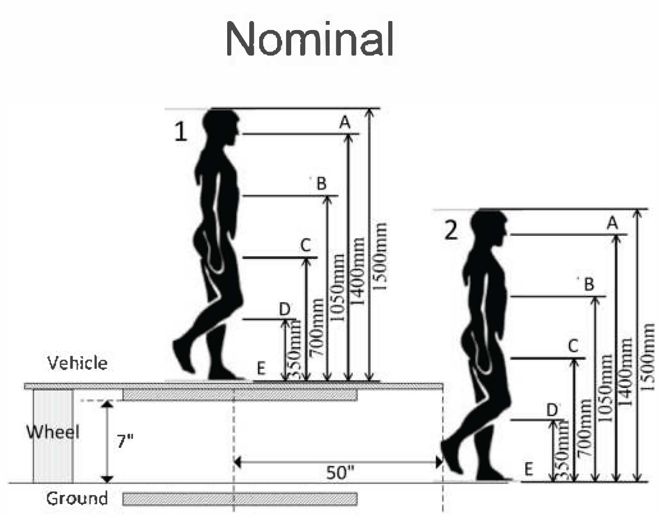

Fig. 3. Measurement diagram of B field.

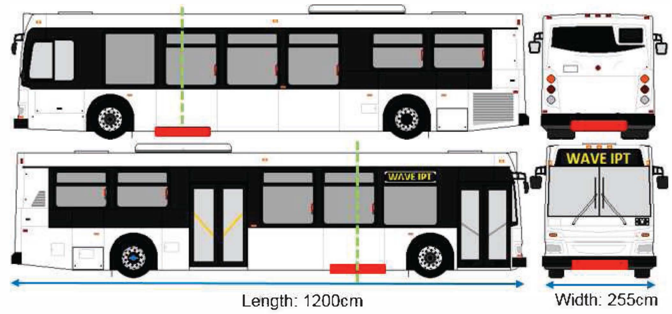

Fig. 4(a). Pad mounting relative to bus position.

Fig. 4(b). Showing measurement points for misalignment.

Fig. 5 shows the typical SoC vs time data for this system operated on this route with hotel loads. The inductive charging system does not charge the bus until the batteries can accept 50kW charging capability, hence the SoC is only replenished after it falls below 90%. As can be seen, charge neutrality can be maintained and the battery size on this bus can be further decreased for this particular route.

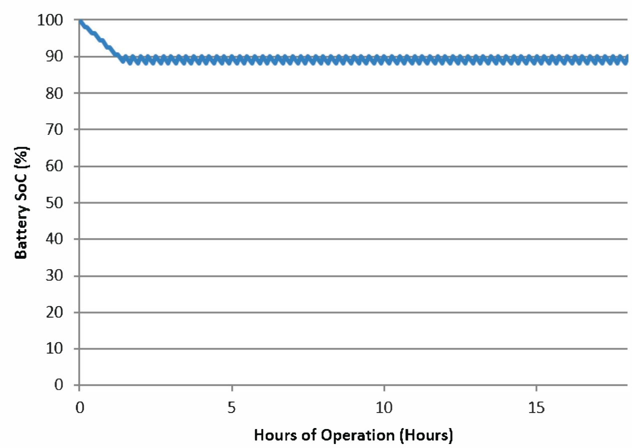

Fig. 5. SoC vs. time for 1.6mile route.

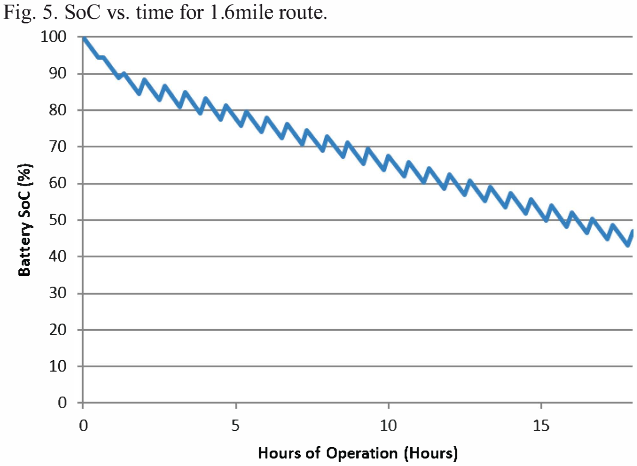

Fig. 6. SoC vs. time for 5mile route.

If this bus operated on a different route, with a 5 mile route and had 10 minute charges after each lap, then the SoC curve would look like Fig. 6. The bus would take longer for each lap and also needs slightly longer charging time to be able to complete the route for the day. It should be note for planning purposes the SoC should not fall below 40%. This is due to two reasons that are plaguing battery technology today. The first is that the batteries cannot fully discharge to 0% without causing a significant negative impact upon its lifetime and hence the batteries are usually limited to 100-20% SoC swing during operation. The second is capacity fade within the batteries over time, and can easily have 20% fade in capacity over 12 year operation. The bus should still be sized to operate the route at the end of 12 years including the capacity fade and limited SoC swing.

D. *Estimated Cost Reductions*

The last and probably the most important factor limiting adoption of inductive charging technology today is cost. Fortunately, the cost of operating an electric bus is much less than diesel and utilizing the system over its lifetime will allow the operator to recuperate the cost of the initial capital investment into the charging infrastructure. A proprietary cost model is developed to compare against other types of technology that can also be used in buses. Some key factors the model takes as input variables are:

1. Length of route
2. Laps per day
3. Number of buses on the route
4. Recovery time per lap
5. Electricity cost
6. Diesel cost

These factors have the strongest influence on cost comparisons. There are also well over 100 other variables that the model tracks but not included here for conciseness.

Two Original Equipment Manufactures (OEM's) making electric buses were also included in the cost model.

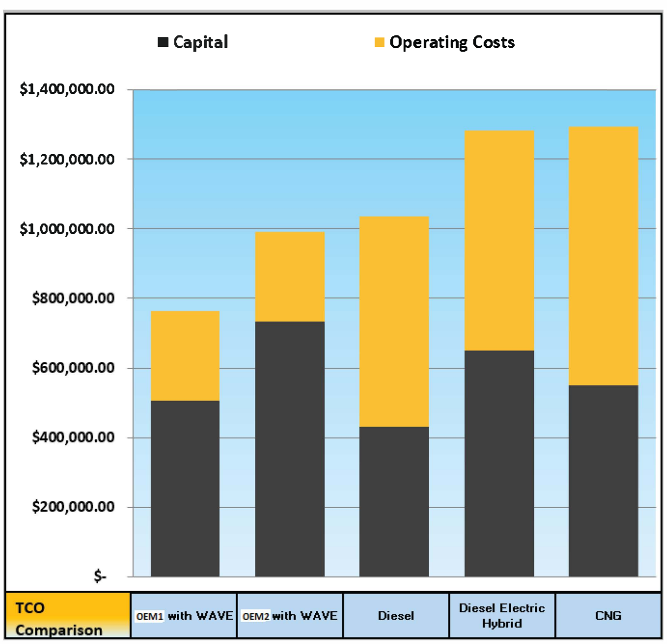

Fig. 7. Cost comparison for different technologies.

A very basic example using this model is shown in Fig. 7. The key inputs are:

1. Length of route = 5miles
2. Laps per day = 23
3. Number of buses on the route = 4
4. Recovery time per lap = 10mins
5. Using California data for electricity and diesel costs as of 2014

For this typical model, the battery size of an electric vehicle goes from 438kWh for pure electric to 97.3kWh for inductively charged buses. An staggering 78% reduction using opportunity charging alone. However, many OEM's already have a stand battery pack size and not sized to the minimum of 97.3kWh. It can still be seen that the cost of both inductive charging solutions beat diesel, hybrid diesel and CNG. Although the initial capital infrastructure is higher for inductive charging, the costs are recuperated during operation. In this example, the total cost of ownership is extremely favorable towards an inductive charger solution.

III. CONCLUSIONS

Green products are becoming an increasing requirement for mass transit applications. This is especially true for large cities where air quality is poor and zero tail pipe emission buses are desirable. Inductive charging operating in the opportunity charging model offers many advantages to electric buses. It may potentially pave the way forwards to a pure electric transportation system in the future.

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