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Inductively coupled modular battery system for electric vehicles

Karthik Kandasamy1, Don Mahinda Vilathgamuwa2, Udaya Kumara Madawala3, King-Jet Tseng4

Abstract: This study proposes two novel modularised battery systems capable of controlling the power of each module independently, and with inductive interface for convenient battery swapping. The proposed systems aid in overcoming the limitations such as unavailability of electric vehicle (EV) due to battery pack fault and lengthy battery recharging time which largely hampers the adoption of EVs for personal transportation. The proposed systems consist of a plurality of battery modules which are wirelessly coupled to the EV through inductive power transfer technology. The proposed systems are described in detail, and models are presented to analyse their steady-state behaviours. A design guideline for a 24 kWh 80 kW battery micro-pack system is discussed. Performances of the proposed topologies are investigated using simulations. To demonstrate the applicability, prototype systems of 1.5 kW are implemented and tested under various operating conditions. Results convincingly indicate that the proposed systems improve the vehicle’s availability under fault condition.

1 Introduction

The electrification of road transportation sector has been under investigation by various research organisations and automobile manufacturers for decades. There are various types of electric vehicles (EVs) such as battery EVs, fuel cell EVs, online EVs (OLEV) [1, 2] and photovoltaic EVs [3]. Amongst these various electrification methods, battery operated EVs have become predominant since the development of high-power and high-energy density lithium ion electrochemical cells. Having the open-circuit voltage of each lithium ion cell in the range of 3.7 to 4.2 V, high-power battery packs for EVs are constructed by connecting a number of electrochemical cells according to the design requirements. Although the electrochemical cells are of high quality, the reliability of the battery pack is compromised. The main inhibition in EV adoption is the reliability and availability of the vehicle. Any fault in the battery pack affects the vehicle availability, meaning that the vehicle cannot be operated further as battery pack is the only source of energy. A solution to increase the reliability of the system is to have modularity in the control of power extraction from the battery pack. This modular approach in designing the battery pack increases the availability of the vehicle, that is, increases the chances of operating the vehicle even in case of failure of one or more modules and hence increases the reliability of operating an EV.

The EV battery pack requires recharging to regain its depleted energy in order to run the vehicle again. It is analogous to refuelling a typical gasoline vehicle. Since the batteries employed in EVs are of high power and energy rating, recharging them requires a considerable amount of downtime for the EV. The term ‘downtime’ refers to the time taken for refuelling (or recharging) a vehicle during when the vehicle is inoperable. The conventional fossil fuel powered personal transportation vehicles usually have a downtime of <5 min for refuelling at the gas station. However, the electrochemical battery-based EVs would require a downtime in the order of hours. On the basis of the time taken to recharge an EV battery and the power levels of the chargers, the charging methods are categorised as Level 1 (or slow), Level 2 (or medium) and Level 3 (or fast). Society of Automotive Engineers and International Electro technical Commission are coming up with standards for the EV charging [4–6]. The EV charging can be broadly classified into conductive charging [7, 8] and wireless charging [9–12]. Conductive charging refers to charging the EV by connecting either to an external charger or power supply equipment (for the vehicles with on-board charger) through a charging cable. Wireless charging refers to charging the EV battery pack by means of any of the wireless power transfer methods such as inductive power transfer (IPT) with or without magnetic resonance. Wireless charging can be either stationary or dynamic. Stationary wireless charging requires the vehicle to be parked at the designated wireless charging bed, whereas the dynamic charging refers to the charging of EV battery back when the vehicle is in motion over a specially constructed road line. OLEVs are included in the dynamic wireless charging. A consolidated review of various EV charger topologies has been discussed in [13]. OLEVs can be considered having literally zero downtime if only the vehicle operation is considered and the power is transferred from the electrical roadbed to the drive directly. The disadvantages with OLEVs are the power transfer efficiency and it is not feasible to provide electrical roadbed at all places.

The battery swapping methods have been under investigation in order to achieve further reduction in downtime and are considered as ultrafast when compared with the other charging methods. The battery swapping system allows for the battery packs to be replaceable. The battery pack is detached from the vehicle when the energy is completely depleted and replaced with another fully charged battery pack. This battery swapping or replacement is done in designated stations. A battery exchange station holds certain number of charged battery packs. When an EV reaches the exchange station, the battery pack is replaced. An algorithm for such a kind of automated battery replacing is given in [14].
number of electrical and mechanical locking systems keep the battery pack attached with the vehicle chassis. These locking mechanisms are operated sequentially during the battery swapping process. Tesla motors demonstrated a successful battery swapping for its vehicle in which the whole battery pack is replaced in 90 s [15]. The replaced battery pack is recharged separately at external charging station. This external charging feature of battery swapping is the primary reason for the significant reduction in downtime. A good design of electrical interfaces prevents the creation and furtherance of hazards during swapping process. The mechanical vibration that is inherent in any vehicle motion may cause sparks between the electrical contacts. Therefore, it is desirable to develop an appropriate contactless electrical interface system. Hence, the use of IPT with modularised energy storage for a faster and more convenient battery swapping is investigated in this paper.

Applications of wireless power transfer are multi-field including hand phone battery charging, EV battery charging, OLEVs, industrial automation applications, medical applications, robotic applications etc [16–23]. Numerous topologies of IPT systems, control strategies and design techniques have been reported in the literature. Most of them were addressing the power transfer efficiency improvement through coil design [24], reactive power compensation [25], control strategy [26] etc. The IPT system can also be used for bi-directional power transfer and was demonstrated in [19]. This implies that the IPT systems are also suitable for auxiliary functions of EV such as vehicle-to-grid (V2G). Modular and redundant low-power IPT systems for high-power applications were studied in [27, 28]. In [27], the secondary coils of modular IPT systems were connected in parallel, whereas in [28] various modular low-power IPT systems were paralleled using intermediate LC network. This paper investigates two novel modular IPT systems for the intended application. The proposed systems are also highly suitable for smart charging where the EV batteries are charged with wide range of input power to meet the power system constraints based on certain optimisation algorithms [29]. The external charging of the proposed modular battery packs is not addressed in this paper. The operation of the proposed systems when the battery micro-packs are discharging is investigated in this paper.

The proposed modularised battery systems with inductive coupling are detailed in Section 2 and steady-state analysis and operation of the proposed systems are explained in Section 3. A design guideline and simulation results for a 24 kWh 80 kW battery micro-pack system with inductive coupling is discussed in Section 4. A laboratory prototype of 1.5 kW for each type of the proposed system is implemented to demonstrate the feasibility of the proposed concept. Details of the experimental setup and the results under different operating conditions are presented in Section 5.

## 2 Proposed systems

The modularised battery pack with independent power control is termed as modules or micro-packs in this paper. The number of modules or the micro-packs (N) depends on the vehicle design requirements. The conceptual representation of the proposed systems with inductive coupling is illustrated in Fig. 1. The proposed system would have hollow casings containing the IPT...
secondary side that are fixed to the EV. The battery micro-pack with the IPT primary side is designed to be in a container that fits into the hollow casing attached to the EV. First type of the proposed system depicted in Fig. 1a has one casing for each module. The output of each casing is cascaded to form the DC link of the three-phase motor drive inverter. Type 2 system (Fig. 1b) has one casing that accommodates all the modules. Hence, type 2 system employs less number of power switches when compared with Type 1. The output capacitor of the secondary forms the DC link of the three-phase inverter. The proposed application of the IPT system requires power to be transferred in both directions across the primary and secondary side inductors currents are given by

\[ I_{p,k} = -\frac{jV_{m,k}}{oL_{p,k}} \]  

Similarly, the secondary side inductor currents are given by

\[ I_{s,k} = -\frac{jV_{c,k}}{oL_{s,k}} \]

The input power from the battery module of the \( k \)th IPT system is given by

\[ P_{b,k} = \text{Re}\left[V_{m,k}I_{p,k}\right] = \frac{|V_{m,k}|V_{c,k}M_{c}\sin\theta_k}{oL_{m,k}I_{s,k}} \]

It can be concluded from (7) that the amount of power extracted from the primary side is controlled by either \( |V_{m,k}| \) or \( \theta_k \) which is the relative phase angle between \( V_{c,k} \) and \( V_{m,k} \). The magnitude of voltage \( V_{c,k} \) depends on the capacitor voltage \( V_{d,k} \) which in turn depends on the power extracted from the primary side and the load demand. In the proposed system, the power transferred from the battery should compensate for the power required by the three-phase motor drive inverter, power required by the DC link capacitor to maintain its voltage, and losses in the IPT system. A constant DC-link voltage is required for the three-phase inverter. Hence the system operation aims at maintaining a constant total DC-link voltage which is the sum of voltage outputs of each module-casing IPT system. In the proposed system, the converters at either side of the wireless interface are operated in the square wave mode. The power transferred between the primary and secondary coils is controlled by manipulating the relative phase angle \( \theta_k \) between the voltages \( V_{m,k} \) and \( V_{c,k} \). The maximum value of \( V_{c,k} \) varies with changes in the capacitor voltage \( V_{d,k} \). The \( V_{d,k} \) in turn depends on the relative phase angle which controls the amount

3 Steady-state analysis and system operation

3.1 Type 1: multiple module-casings

Electrical representation of the proposed Type 1 system is shown in Fig. 2. Averaged state-space model of Type 1 system and simulation results with feedback linearisation control for DC-link voltage regulation was discussed in [30]. However, the steady-state analysis and experimental verification of the Type 1 system are presented in this paper. The steady-state analysis of an IPT system was detailed in [19] and a brief of which is given in this section.

Following analysis is for the \( k \)th module-casing setup neglecting the resistive losses. All the LCL components of the system are designed at the angular resonant frequency given by \( o = 1/\sqrt{LC} \). \( V_{m,k} \) is generated by the primary side converter which causes the current \( I_{p,k} \) in the primary or module side coil. This primary current induces the voltage \( V_{c,k} \) in the secondary or casing side coil which is given by

\[ V_{c,k} = joM_{c}I_{p,k} \]

Similarly, the current \( I_{s,k} \) in the casing side coil induces voltage in the module side coil and is given by

\[ V_{m,k} = -joM_{c}I_{s,k} \]

where \( M_{c} \) is the mutual inductance between the module side and casing side coil. \( M_{c} \) is considered same for all the \( k \) IPT systems and is assumed to be constant as there is no movement required for the IPT coils in the proposed application.

By \( T-\pi \) equivalence analysis of the LCL circuit, the primary side inductor currents of the \( k \)th IPT system are given by

\[ I_{p,k} = \frac{jV_{m,k}}{oL_{p,k}} \]  

\[ I_{s,k} = -\frac{jV_{c,k}}{oL_{s,k}} \]
of power extracted from the primary side through the wireless interface. The power flow direction depends on the sign of the relative phase angle between $V_{m,k}$ and $V_{c,k}$. For motoring operation, power should be transferred from battery to motor for which the $V_{c,k}$ should lag $V_{m,k}$, whereas for regenerative braking operation, power should be transferred from motor to the battery for which the $V_{c,k}$ should lead $V_{m,k}$. Each module-casing is controlled independently to regulate its output voltage and hence the amount of power transferred. The voltage reference setting for each of the IPT system can be used to implement the control of power extraction from each battery micro-pack. This could be based on the state of charge reference or any fault detection-based algorithms.

### 3.2 Type 2: multiple module – single casing

Electrical representation of the proposed Type 2 system is shown in Fig. 3. As depicted, the casing side of this type has one converter which should be rated accordingly with the three-phase drive inverter. Each of the primary or module side coil is coupled with one casing side coil. With $N$ battery modules constituting the primary side of the IPT system, the LCL circuit of the $k$th IPT system is tuned to the frequency $\omega$ which is given by

$$\omega^2 = \frac{1}{L_{m,k}C_{p,k}} = \frac{1}{L_{p,k}C_{p,k}} = \frac{1}{L_{s}C_{s}} = \frac{1}{L_{c}C_{c}}$$

(8)

The reflected voltage in the primary coils depends on the currents in the secondary coil as well as the current in the other primary coils. Thus the induced voltages in the respective coils of this type of IPT system because of the coupling through mutual inductance are given by

$$V_{m,k} = \sum_{k=1}^{N} ioM_{c,k} I_{p,k}$$

(9)

$$V_{m,k} = -jioM_{c,k} I_{s} + \sum_{k=1}^{N-1} ioM_{c,k} I_{p,k}$$

(10)

where $M_{c,k}$ is the mutual inductance between module side coil and casing side coil of the $k$th IPT system and $M_{c}$ is the mutual inductance between primary side coils of $k$th and $l$th IPT systems.

The primary side inductor currents of the $k$th IPT system are given by

$$I_{m,k} = \frac{V_{m,k}}{\omega L_{m,k}}$$

(11)

$$I_{p,k} = -\frac{V_{m,k}}{\omega L_{p,k}}$$

(12)

The secondary side inductor currents are given by

$$I_{s} = \frac{V_{s}}{\omega L_{s}}$$

(13)

$$I_{c} = -\frac{V_{c}}{\omega L_{c}}$$

(14)

Neglecting the switching and conduction losses of the H-bridge inverter interfacing the battery module and the primary side of the IPT system, the input power from the $k$th battery module is given by

$$P_{m,k} = \text{Re}(V_{m,k} I_{m,k}^*)$$

Using (10) and (11)

$$I_{m,k} = -\sum_{l=1}^{N} \frac{L_{c,k} I_{s} + \sum_{l=1}^{N-1} L_{c,l} I_{p,l}}{\omega L_{m,k}}$$

(15)

Therefore

$$P_{b,k} = \left| V_{m,k} \right| \frac{V_{m,k}^*/L_{s}}{\sin \theta_{k}} - \sum_{l=1}^{N-1} \frac{L_{c,k} I_{s} + \sum_{l=1}^{N-1} L_{c,l} I_{p,l}}{\omega L_{m,k}} \sin \theta_{l}$$

(16)

where $\theta_{j}$ is the relative phase angle between $V_{m,k}$ and $V_{m,j}$ of $k$th and $j$th modules and $\theta_{k}$ is the relative phase angle between $V_{m,k}$ of the $k$th module and $V_{c}$ of casing side. Thus the power extracted from the battery module contains two terms: the first term represents the power transferred to the secondary coil or casing represented as $P_{(b-c),k}$, and the second term is the power transferred to the rest of the module side coils represented as $P_{(b-b),kl}$. The power exchange between the battery modules in the primary side is undesirable

![Fig. 3 Electric circuit representation of Type 2 system: multiple modules in single casing](image-url)
during motoring operation. Therefore, to nullify the circulating power amongst battery modules in the primary side, the relative phase angle $\theta_{ij}$ should be zero. Meaning that $V_{m,k}$ for all $k=1$ to $N$ should be in same phase. Moreover, to maximise the power transferred from primary side to secondary side of the wireless interface $\theta_{k}$ for all $k=1$ to $N$ should be 90°.

The output power of the IPT system at the secondary side can be derived in the similar manner and is given by

$$P_{o} = \text{Re}\{V_{o}I_{o}^{*}\} = \frac{V_{m}}{\omega L} \sum_{i=1}^{n} V_{m,i} \sin \theta_{i}$$

$$= \sum_{i=c} P_{m-c,i}$$

Thus output power is the sum of input power from all the battery micro-packs (if losses are not considered) at the primary side, provided $V_{m,k}$ are all in phase.

The three-phase inverter operation requires a constant DC-link voltage across the capacitor $C_i$ at the output of the casing side converter. The voltage at the input of the casing side converter, that is, $V_{c}$ determines the maximum output voltage of the converter. From (17), it is clear that $V_{c}$ is dependent on $P_{o}$, which in turn depends on $P_{m-c,k}$ and hence on $V_{m,k}$. Hence for Type 2 system, the power transferred is controlled by manipulating the required voltage $V_{m,k}$. The H-bridge inverter at primary side is controlled using phase shift modulation and hence the average output is controlled by varying the phase shift $\alpha_{p,k}$ between the two legs of the H-bridge converter. The DC-link voltage is controlled by varying the power transferred from each input module which is achieved by manipulating the phase shift $\alpha_{p,k}$. The casing side converter is operated as full bridge rectifier for motoring operation. Each module side converter is controlled independently according to the power reference. The power reference setting for each IPT system can be used to implement the control of power extraction from each battery micro-pack. This could be based on the state of charge reference or any fault detection-based algorithms. The real-time implementation of this system requires wireless communication on either side of the inductive interface which is not addressed in this paper.

4 Design and simulation results of 80 kW systems

The basic design parameters of the EV battery pack are maximum acceleration and driving range requirement. Maximum acceleration for a given vehicle weight and the driving range requirement determines maximum power required and maximum energy capacity of the battery pack, respectively. Terminal voltage of the battery pack should be in accordance with the rated line-line voltage of the drive motor. To compare with the conventional battery pack design, a commercially available EV is taken into consideration. Nissan Leaf battery pack (with rated power of 80 kW, capacity of 24 kWh and nominal voltage of 360 V) has 192 lithium ion cells of 33 Ah [31]. The battery micro-packs of the proposed systems should provide similar performance such as the Nissan Leaf. To achieve this with at least two micro-packs in operation, $P_{max}$ of each inductive interface should be at least 40 kW. Therefore for this design, $P_{max}$ is taken as 50 kW considering the losses in the inductive interface. Operating frequency of 10 kHz, coupling coefficient of 0.6, $P_{max}$ to be 50 kW (for $N=3$) and $V_o$ to be 240 V are taken as the desired parameters. For Type 1 system with multiple module-casings, the total DC-link voltage at the three-phase inverter input is the sum of output voltages of each module-casing. Hence, $V_{dc}$ should be 120 V for $N=3$ and $V_{dc}$ to be 360 V. For the design of inductive interface, $V_{dc}$ is considered as 180 V for Type 1 system, so that $V_{dc}$ of 360 V could be achieved with one module is not in operation. Therefore for Type 1 system, $L$ and $C$ are calculated to be 8.25 $\mu$H and 30.7 $\mu$F, respectively. For Type 2 system with one casing, $V_{dc}$ should be same as $V_{dc}=360$ V. Therefore for Type 2 system, $L$ and $C$ are calculated to be 16.5 $\mu$H and 15.35 $\mu$F, respectively. It has to be noted that even when the battery micro-pack is supplying 40 kW, the discharge is about five C-rate which is still under the limiting the design. The design guidelines explained earlier shows that the proposed systems are technically feasible and hence are applicable to EVs. However, the mechanical design and thermal management of the battery micro-packs in the proposed systems would be challenging. Particularly, the conventional methods of liquid cooling of the battery cells become difficult with the proposed system. This is a main disadvantage of the proposed contactless battery system.

Simulation models for Type 1 and Type 2 systems of 80 kW were developed in Simulink and PLECS. Both topologies of the proposed systems act as a power source to the three-phase inverter. The primary objective in these systems is to maintain a constant DC-link voltage. This is achieved by supplying enough amounts of power to meet the load demand and the power required by the DC-link capacitor. This simulation was conducted to verify that the power extracted from each battery micro-pack is independently and simultaneously controllable along with the primary objective of maintaining a constant DC-link voltage. The simulations were carried out for three scenarios: equal amount of power extracted from each of the battery micro-pack, unequal amount of power extracted and one faulty micro-pack unable to contribute to the load demand.

The capacitor voltages at the DC link of three-phase inverter and the corresponding input powers from each battery micro-pack for Type 1 is given in Figs. 4a and b, respectively. For 0 ≤ $t$ ≤ 1 s, three battery packs contribute equally to the load demand of 78 kW while maintaining the DC-link voltage of 360 V with 120 V at the output of each IPT. For 1 s ≤ $t$ ≤ 2 s, 78 kW is supplied with 28.5 kW from first module, 26.4 kW from second module and 24.3 kW from third module. For 2 s ≤ $t$ ≤ 3 s, the second module is considered faulty and removed from operation and the remaining two battery packs contribute 39.5 kW each to the load demand of 78 kW. The difference between the sum of input
powers from the battery micro-packs and the input power to the three-phase inverter is due to losses in IPT system.

The DC-link voltage at the input of three-phase inverter and the input powers from each battery micro-pack for Type 2 is given in Figs. 4c and d, respectively. For $0 \leq t \leq 1$ s, the second module is considered faulty and removed from operation and the remaining two battery packs contribute 40.5 kW each to the load demand of 80 kW. For $1 < t < 2$ s, 80 kW load demand is supplied with 31.4 kW from first module and third module each and 18.2 kW from second module. For $2 \leq t \leq 3$ s, three battery packs contribute equally to the load demand of 80 kW while maintaining the DC-link voltage of 360 V. The difference between the sum of input powers from the battery micro-packs and the input power to the three-phase inverter is due to losses in IPT system.

5 Experimental setup of 1.5 kW systems

A laboratory prototype for both Type 1 and Type 2 systems with $N = 2$ was constructed to demonstrate the concept. The proposed application requires transferring power over a shorter distance of $10 - 20$ mm. There are two types of coils that are suitable for the proposed application: planar coils and coils with cores. A detailed analysis of various types of pads with planar coils was given in [32]. An E-shaped ferrite core-based power transfer coils was built and used for the demonstration. The E80/38/20 3c90 from ‘Ferroxcube’ was used for this paper. For Type 1 system, both primary and secondary cores were built by stacking four E cores. For Type 2 system, the primary side cores were made by stacking three E cores and the secondary core was made by stacking seven E cores. ‘Type 2’ Litz wire was used for the coil windings. Further investigations on the IPT coil design for high power, mechanical design of the battery micro-packs with IPT system and the design of thermal management would be required for real-time implementation. The difficulties associated with high-power IPT systems could be avoided by increasing the number of modules $N$ so that power of each module is lesser which would then require finding the optimum value for $N$. The parameters of the coils built are given in Table 1. A snap shot of the IPT coils with the built prototypes for the demonstration of the proposed systems is shown in Fig. 5.

The converters for IPT systems were built with metal–oxide–semiconductor field-effect transistors and gate signals were generated using digital signal processor (DSP) controller. Insulated gate bipolar transistor-based three-phase inverter was controlled using dSPACE controller and a three-phase RL load was employed as load. Laboratory DC power supplies were used in place of battery modules. The parameters of the experimental setup are given in Table 2.

The experimental verification of the operation of the proposed systems were carried out for three scenarios: case 1 – equal amount of power extracted from both the inputs, case 2 – unequal amount of power extracted from the inputs and case 3 – one faulty module unable to contribute to the load demand. The desired DC-link voltage for the three-phase inverter was chosen to be 50 V. The capacitor voltages at the DC link of three-phase inverter and the corresponding input powers for Type 1 and Type 2 are given in Figs 6a–d, respectively. In Fig. 6, $t < t_1$ denotes case 1,
\( t_1 < t < t_2 \) denotes case 2 and \( t > t_3 \) denotes case 3. It can be observed from Fig. 6 that the proposed systems are capable of maintaining the total DC-link voltage at 50 V and hence meeting the load demand irrespective of the differences in the input power. As explained in Section 3, the difference in amount of power extraction is achieved by manipulating the required \( V_{d,k} \) for Type 1 system and \( V_{m,k} \) for Type 2 system. It has to be noted that the total input power of Type 1 and Type 2 are different even though the loads to both the systems are same. It is because of the difference in the losses in the respective system.

The voltage and currents of the IPT components of Type 1 system for case 1 are shown in Fig. 7, in which left plots are from the experimental setup and right plots are using simulation. To extract

**Table 2** Setup parameters

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<th>Parameters</th>
<th>1.5 kW system (prototype)</th>
<th>80 kW system (simulation)</th>
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<tr>
<td>( V_{b,k} )</td>
<td>50 V</td>
<td>240 V</td>
</tr>
<tr>
<td>( L_{m,k} ), ( L_{c,k} )</td>
<td>30 ( \mu )H</td>
<td>8.25 ( \mu )H (type 1) and 16.5 ( \mu )H (type 2)</td>
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<td>( C_{p,k} ), ( C_{s,k} )</td>
<td>2.2 ( \mu )F</td>
<td>30.7 ( \mu )F (type 1) and 15.35 ( \mu )F (type 2)</td>
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<td>( C_{v_1} ), ( C_{d} )</td>
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<td>6600 ( \mu )F</td>
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<td>Operating frequency ( f(IPT) )</td>
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<td>10 kHz</td>
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<tr>
<td>Coupling coefficient ( k_c )</td>
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**Fig. 6** Experimental waveforms of

a) DC-link voltages of Type 1 system

b) Battery micro-pack power and input power to three-phase inverter of Type 1 system

c) DC-link voltages of Type 2 system

d) Battery micro-pack power and input power to three-phase inverter of Type 2 system

\( t_1 < t < t_2 \) : case 1 – equal power extraction; \( t_1 < t < t_2 \) : case 2 – unequal power extraction; \( t_1 < t < t_2 \) : case 3 – one faulty module.
equal amount of power from each of the input modules, the voltage references for each of the IPT system were set at 25 V so that the total DC-link voltage could be 50 V. Both the primary side converters were operated in square wave mode at the IPT resonant frequency of 19.6 kHz. The relative phase angle of $V_{c,k}$ with respect to $V_{m,k}$ was controlled so that output voltages $V_{d,k}$ were regulated at 25 V. It can be observed from Fig. 7a that the relative phase angles ($\theta_1$ and $\theta_2$) of two IPT systems are equal. The maximum value of $V_{c,k}$ indicates that the output of both the IPT system are 25 V.

Similarly, the voltage and current waveforms of the IPT system of Type 2 under case 1 are presented in Fig. 8a. Both primary side converters were operated to ensure that the power extracted was equal and the DC-link voltage was regulated at 50 V as it can be observed from the maximum voltage of $V_{c}$. In Type 2, this is achieved by manipulating the phase shift $\alpha_{p,k}$ between the two legs of the H-bridge converter at the primary side of the IPT.

The voltage and currents of the IPT components of Type 1 for case 2 are presented in Fig. 7b, in which left plots are from the experimental setup and right plots are using simulation. This scenario was carried out to emulate the condition of unequal power extraction from the battery micro-packs. The difference in the amount of power extracted from the micro-packs was obtained by setting different voltage references to the IPT system, with total desired DC-link voltage set as 50 V. For this case, $V'_{d,1}$ was set as 21 V and $V'_{d,2}$ was set as 29 V. It can be observed from Fig. 7b that the relative phase angles ($\theta_1$ and $\theta_2$) of two IPT systems are not equal. The maximum value of $V_{c,k}$ indicates that the output of both the IPT systems are 21 and 29 V each. Similarly, the voltage and current waveforms of the IPT system of Type 2 under case 2 are presented in Fig. 8b. One of the primary sides was controlled to supply more power and other one to supply lesser power.

The voltage and currents of the IPT components of Type 1 for case 3 are presented in Fig. 7c, in which left plots are from the experimental setup and right plots are using simulation. This scenario was carried out to emulate the condition of one faulty module and to verify the efficacy of the proposed system for its redundancy. For this case, $V'_{d,1}$ was set as 50 V and $V'_{d,2}$ was set as 0 V. The second IPT system was completely turned off by keeping all the switches of the power converters open. The voltages and currents of the inactive IPT system are all zero and hence not shown here. The load demand was entirely supported by one IPT module by regulating the DC-link voltage at 50 V. During this operation, the load current passes through the anti-parallel diodes of the secondary H-bridge converter of the inactive IPT system. Similarly, the voltage and current waveforms of the IPT system of Type 2 under case 3 are presented in Fig. 8c. For this case, $V'_{m,2}$ was set as 0 V. The entire load demand was supported using one input module with the DC-link voltage regulated at 50 V. Even though the second input was commanded to be zero, there was an induced current in the primary coil of the inactive module