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A concept of propulsion and power supply systems for PRT vehicles

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Abstract

An innovative propulsion and power supply topology for Personal Rapid Transit is presented. The concept is based on application of linear induction motor for propulsion and hybrid power supply using Contactless Energy Transfer supported by a supercapacitor energy storage. Proposed solution is based on the application of linear induction motor as a propulsion and inductive contactless energy transfer.

1. Introduction

One of the concepts of Personal Rapid Transit features usage of individual, autonomous vehicles, cable of dynamically selecting optimal route, in order to efficiently transfer passengers between one place and selected destination. Therefore, the vehicles carry highly complex systems for control and set of actuators, which allow vehicle to adjust its speed, acceleration and direction choice, at track junctions. Otherwise, PRT guide way is highly simplified and contains almost entirely passive elements, which provide mechanical support for the vehicles.

One of the most challenging problems for such PRT topology is energy delivery for the vehicle on-board systems like propulsion, control, lighting or passenger area air-conditioning control. One of the possible solutions can be application of contact wires or the on-board batteries.

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Contact wire or third rail technologies are well known and can provide simple and efficient energy transfer at very high power levels to the vehicle. Nevertheless, usage of energy transfer systems, which are based on physical contact in automated transit vehicles can make significant maintenance problems due to the presence of electrical arc and inherent contact wear. Live wires located in proximity of the vehicle can be a limitation, in emergency situations, when passengers should be evacuated from the vehicle. In difficult weather condition, due to rain, snow and refrozen snow, operation of a third rail system can deteriorate.

Battery technologies are widely used in electric cars and are being continuously improved. Nevertheless, the cost in case of application of modern fast rechargeable batteries is high. Moreover, apart from additional mass and space required on a vehicle, due to limited number of charge/discharge cycles, the batteries can lead to significant maintenance challenge, especially for PRT systems with large number of vehicles.

2. Propulsion and power supply system structure

In order to improve maintenance effort and system reliability, a power supply and propulsion systems for PRT vehicles are introduced.

Proposed topology directly reflects agreed concept of the PRT system developed, which assumes the use of autonomous vehicles, cable of individually selecting a route and control theirs movement. Thus, the guide way contains highly simplified, almost passive components of the power train. Conversely, the vehicle carries sophisticated control and power circuitry. A distinguishing feature, is an application of linear induction motor for the vehicle propulsion together with a hybrid power supply of the vehicle, which uses contactless energy transfer supported by a supercapacitor energy storage.

Figure 2.1 shows block diagram of the proposed power train for the PRT system developed. The system is divided into two parts: stationary located on the guide way and mobile located on the vehicle.

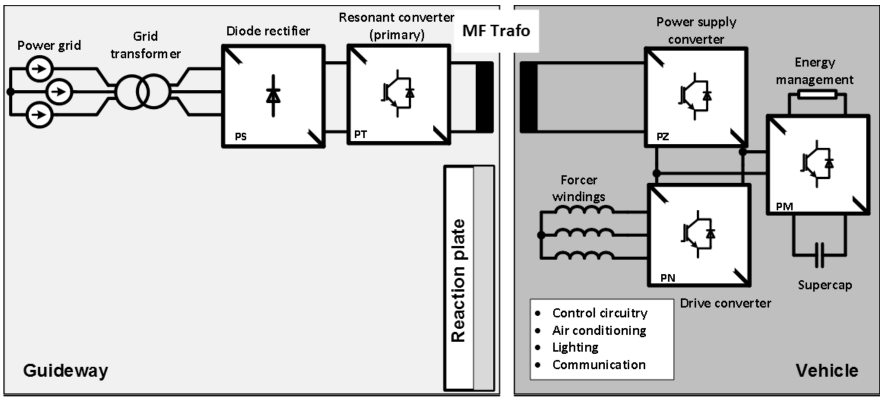

Fig. 2.1. Block diagram of the proposed propulsion and power supply system

Stationary part contains mainly elements of the power supply system, which are: power grid connector, matching transformer, diode rectifier and primary side of the contactless energy transfer system. The most complex element of the system is a resonant inverter, which supplies primary winding of CET transformer. A reaction plate of the linear induction motor, used for the vehicle propulsion is located on the guide way, additionally.

The vehicle carries forcer of the propulsion motor, secondary side of the contactless energy transfer system, super capacitor energy storage with management converter together with motor inverter.

3. Vehicle propulsion

It was decided to use flat type, single sided Linear Induction Motor (LIM) for the vehicle propulsion. Figure 3.1 shows a cross section of the construction used in the proposed PRT system concept.

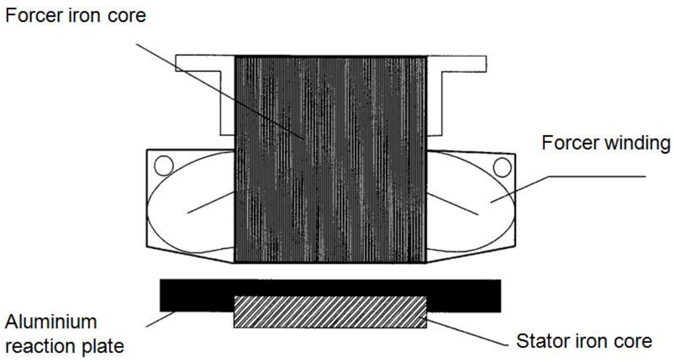

Fig. 3.1. Cross section of a Linear induction motor

The motor forcer is located at the bottom of the vehicle and contains copper windings wound on a laminated magnetic iron core. The motor’s secondary side in a form of a reaction plate, together with the stator core is located on the vehicle track. The reaction plate can be constructed with solid or ladder cut aluminium or copper. If a ladder type reaction plate is used instead of solid, performance and efficiency of the motor are improved at the increased cost of the secondary winding manufacturing.

Application of this type of the propulsion provides following benefits related to the use of conventional rotary motors with the PRT system:

- Direct source of thrust/breaking force - no gearbox
- Low sensitivity to the environmental conditions like icing/snow or rain
- Low maintenance cost
- Low noise
- Increased reliability

Unlike rotary type motors, linear induction motor features variable airgap and so called end effect [1,BOLDEA]. In the rotary motors the distance between a rotor and a stator is precisely kept constant by a set of bearings mounted on the machine shaft. Moreover, magnetic circuit of the rotary motor is symmetrical and closed. As a result magnetic flux in the machine airgap is evenly distributed under all operation conditions. Therefore, rotary machines can produce, speed independent, smooth torque.

The distance between primary and secondary sides of the linear motor in this vehicle propulsion application is very hard to be kept constant, due to vehicle suspension. Moreover, magnetic circuit of the linear motor is inherently open. At both ends of the forcer, the magnetic field is highly disturbed. Additionally, the disturbance is stronger with increasing mechanical speed. Therefore generation of a smooth thrust force can be a challenging problem.

One of the solutions investigated during the research is an application of high performance field oriented control methods, derived from the rotary motor control schemes [5,4]. These algorithms regulate machine airgap flux, together with a torque, based on the motor current, mechanical speed and DC inverter link voltage measurements. Since the torque and magnetic flux are difficult to measure, the quantities are estimated using numerical machine model calculated in the real time by the control scheme. Application of the control algorithms from the rotary to linear motors gives the best results, when variable airgap and the end effects are taken into account. The investigated system uses linear induction motor equivalent circuit developed in [3,4,5] for the machine flux estimation. The control scheme used is shown in figure 3.2

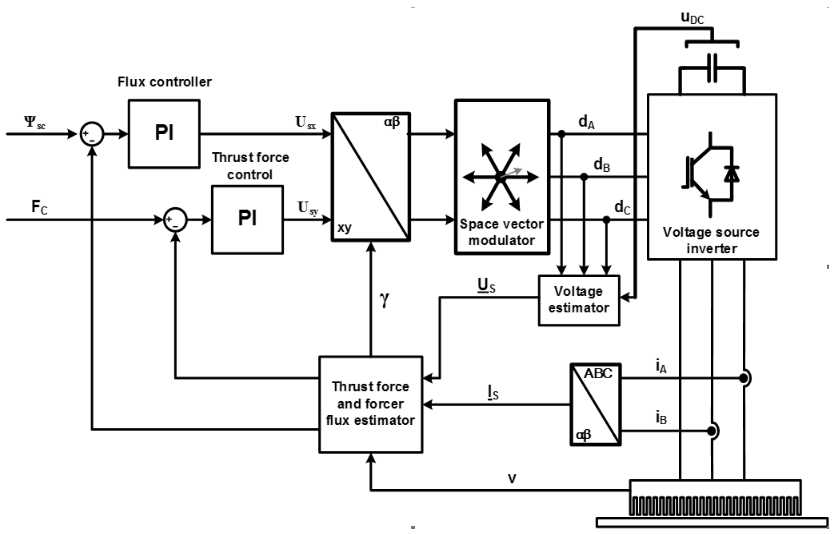

Fig. 3.2. Block diagram of the investigated linear induction motor control scheme

The motor is supplied by a three phase voltage source inverter, which is cable of precisely regulating electric currents flowing in the motor windings. According to the measurements of motor currents, dc-link voltage and vehicle speed, control algorithm, running on a microprocessor is cable of smoothly controlling generated thrust force and thus vehicle velocity.

In order to verify the proposed concept of the vehicle propulsion a scaled model of the system was constructed and is shown in figure 3.3.

Fig. 3.3. Photograph of the scaled down PRT vehicle propulsion and power supply module

The setup contains motor inverter, energy storage management converter and LiFePo4 battery backup for power electronics control circuitry. Apart from power electronics, a DSP based regulator provides bogie control together with the measurement data acquisition.

4. Power supply system

In case of the PRT topology discussed, especially for the wide spread system with a large number of vehicles, the power supply system should preferably be characterized by high reliability, low maintenance cost and high efficiency. Furthermore, it should provide high level of safety, especially in emergency situations. These features are ensured by the Contactless Energy Transfer (CET) system, which is based on Inductive Contactless Energy Transfer (ICET) transformer.

Figure [CET_TRAFO] shows concept of a ICET transformer [12,13], where primary winding, in a form of a loop, is distributed along PRT guide way. The E shaped core, with secondary winding, mounted on the center column creates energy pickup, which is located on the vehicle. Since the vehicle must cover guide way junctions or following sections of the primary winding, the core of the pickup must be left open, to enable safe operation in those areas.

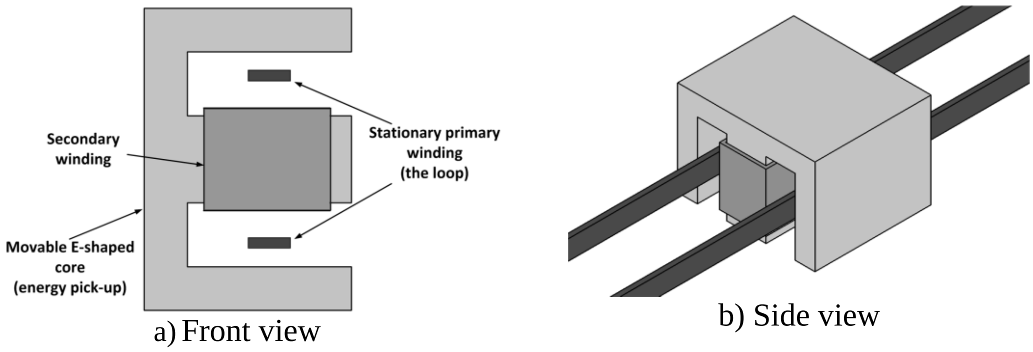

Fig. [CET_TRAFO] Concept of inductive contactless energy transfer system for PRT

Application of inductive contactless energy transfer provides significant benefits such as:

- Practically maintenance free system – no mechanical and electrical connection for the power transfer
- Reduced risk of electric shock to the users in emergency situations - completely insulated system elements
- No noise and pollution - the absence of the sliding elements and moving mechanical parts
- Increased resilience to weather conditions
- No electric arc

In order to reduce power required, and to simplify track side systems of the Contactless Energy Transfer System a hybrid solution was proposed, which utilizes energy storage located on the vehicle. The storage delivers peak power for the propulsion during acceleration and stores the energy recovered during regenerative breaking. As a result Contactless Energy Transfer power supply is designed to provide average power to the vehicle. In addition, it allows travel of the vehicle through track sections, where usage of contactless energy transfer is limited or impossible, like track junctions or hard turns.

4.1 Inductive contactless energy transfer

The inductive contactless energy transfer can be defined as a system in which energy is transferred from the primary to the secondary winding through a magnetic field [6, 7]. The basic elements of such system are two galvanically separated electrical circuits, which are located in a required proximity, in order to provide enough magnetic coupling. Therefore, the ICET system can be treated as a kind of transformer.

Typical transformers are used to provide galvanic isolation between primary and secondary side or to change voltage level. In these applications transformers operate at high magnetic coupling. Since the vehicle must cover guide way junctions or following sections of the primary winding, the core of the pickup must be left open, to allow primary winding to slide in and out of the pickup. The use of the open magnetic circuit results in a large air gap. Thus, there is much lower magnetic coupling factor, compared to the typical transformer. The ICET system equivalent circuit is shown at Figure [EQV_CETSCHEM].

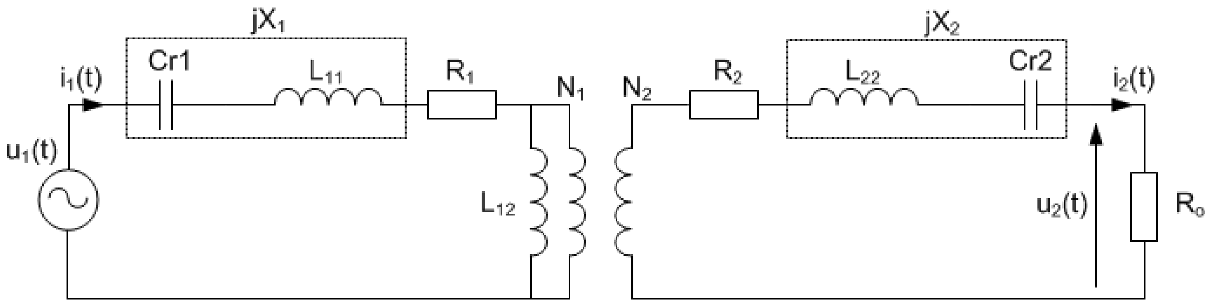

Fig. [EQV_CETSCHEM] Equivalent circuit of CET system for fundamental harmonic

Due to the presence of large air gap, magnetic circuit of the ICET transformer is characterized by a significant amount of a leakage inductance L_{11} and L_{22} and a small amount of main inductance L_{12}. As a result, in order to transfer required amount of active power from the primary to the secondary side, significant reactive power must be delivered to the magnetic circuit, at the same time. To minimize this effect, it is necessary to apply compensating capacitors on both sides of the ICET transformer. In this role a series-series compensation topology was used. The equations for reactance, shown in figure [EQV_CETSCHEM], can be presented as:

$$X_1 = \omega_s L_{11} - \frac{1}{\omega_s Cr1} \quad (1)$$

$$X_2 = \omega_s L_{22} - \frac{1}{\omega_s Cr2} \quad (2)$$

where $\omega_s = 2\pi f_s$ is converter switching pulsation,
L_{11} is a primary leakage inductance,
L_{22} is a secondary leakage inductance,
Cr1 is a capacitance of primary compensation network,
Cr2 is a capacitance of secondary compensation network.

When the converter switching frequency f_s is equal to the resonant frequency f_r, inductive reactance is equal to capacitive reactance, but has opposite sign. As a result, primary and secondary reactance (X_1 and X_2 respectively) are reduced nearly to zero. It means that, the leakage inductance of the primary and the secondary winding is compensated by putting capacitors in series on both sides [6, 8, 9, 11]. The capacitance of the network is selected to meet resonance criteria for the primary current frequency and for the output current. Since the resonance occurs, both sides are seen by the supplying source as nearly purely resistive. This means, that at both sides of the ICET transformer, voltage and current are in phase. Reactive power is exchanged between the capacitors and the leakage inductance of the transformer and does not need to be delivered by the supplying source.

Using equations that describe fundamental relationships in the transformer, transferred power in ICET system is expressed by:

$$P_{out} = \frac{\omega_r^2 \cdot k^2 \cdot L_{11} \cdot L_{22} \cdot I_1^2 \cdot R_0}{(R_2 + R_0)^2} \quad (2)$$

where $\omega_r = 2\,\pi\, f_r$ is the resonance pulsation,
k is a coupling factor,
L_{11} is a primary leakage inductance,
L_{22} is a secondary leakage inductance,
I_1 is a primary current
R_o is a load resistance,
R_2 is a secondary winding resistance.

Based on the equation (2), it can be seen that the output power depends mainly on the square of the loop current, the square of the resonant frequency and the square of the coupling factor k. Increasing the resonance frequency increases the cost of the supplying source and primary transformer winding. The coupling factor mainly depends on geometrical dimensions of the core, the size of the air gap and the geometrical arrangement of the pick-up in relation to the loop. Reducing of the air gap increases coupling factor. However, due to mechanical reasons, changes to this parameter are limited. Due to the imperfect surface of the track, and vehicle suspension the air gap makes it possible for the pick-up to move in a direction perpendicular to the loop, and guarantees safe operation of the pickup.

The increase in the value of the loop current, requires loop wires diameter increase. As a result cost of stationary part of ICET system is increased.

Input power can be described as:

$$P_{in} = I_1^2 \cdot \left(R_1 + \frac{\omega^2 \cdot k^2 \cdot L_{11} \cdot L_{22}}{R_2 + R_o}\right) \quad (3)$$

Based on the equation 2 and 3 efficiency of CET system can by described as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\omega_r^2 k^2 L_{11} L_{22} R_o}{(R_2 + R_0) \cdot (\omega_r^2 k^2 L_{11} L_{22} + R_1 R_2 + R_o R_1)} \quad (4)$$

The figure [POUT_CET] shows calculated, normalized output power and efficiency curves as a function of normalized load resistance. It can be seen, that if CET system delivers continuous power to the load – at specific load resistance, specific efficiency is achieved. Maximum output power of CET system is achieved at about 50% efficiency, which results from the equation 3.

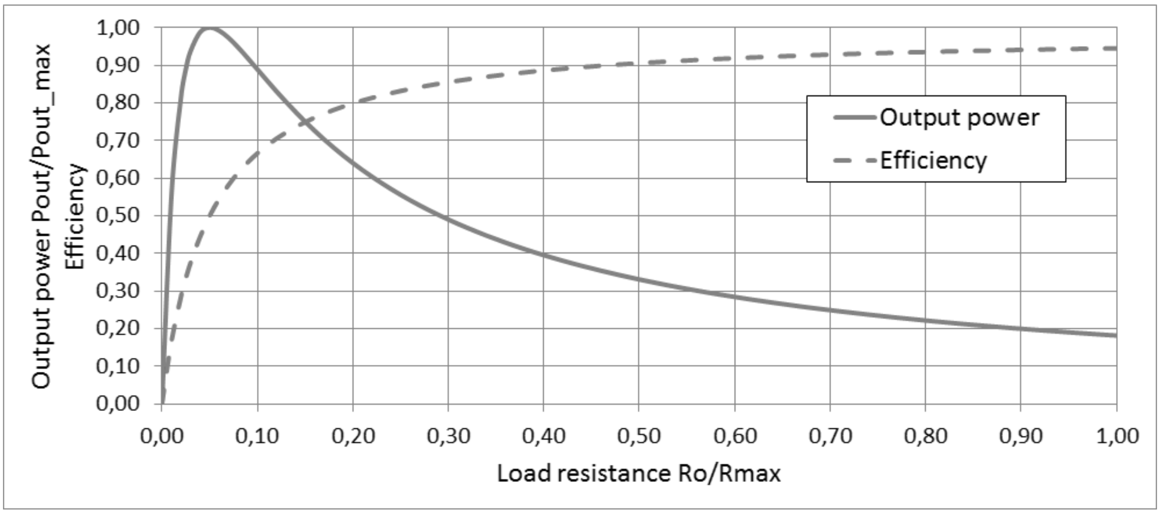

Fig. [POUT_CET] Output Power and Efficiency as a function of normalized load resistance

Required peak power to the propulsion should be delivered during acceleration of the vehicle. In this situation, the equivalent load resistance decreases. As a result, the energy transfer efficiency decreases as seen in the characteristics shown. In order to keep a constant level of efficiency it requires the use of energy storage that will provide peak power.

4.2. CET experimental results

The proposed CET system was investigated on 1 kW experimental laboratory setup. Figure [CET_LABSETUP] shows schematics of a scaled down laboratory model of the proposed CET system. Contactless Energy Transfer system required lower supplying voltage level than the grid voltage, thus matching transformer was used. It can be applied to the grid frequency (50 Hz) or at high frequency side. It could be noticed, that figure [CET_LABSETUP], shows a variant of the CET, where matching transformer is located at the high frequency side. As a result, the size and a cost of this element can be significantly reduced. The primary capacitor network was located on the input of the matching transformer. Thus, leakage inductance of both transformer and the loop is compensated. The stationary part of the system is powered by the resonant converter in such a way, that the current flowing in the loop has a sinusoidal shape. Assuming specific dimensions of the system components, in order to provide output power at a level of 1kW, the frequency of the current should range within the tens of kilohertz. Respectively, due to primary winding distribution, loop current amplitude should range within the tens of amperes. A single primary winding section has a length of 2m and was constructed using litz wire. The setup was supplied from a grid, through one-phase diode rectifier and step down chopper. Thus, smooth input voltage regulation for the resonant converter is possible, for the experimental purpose.

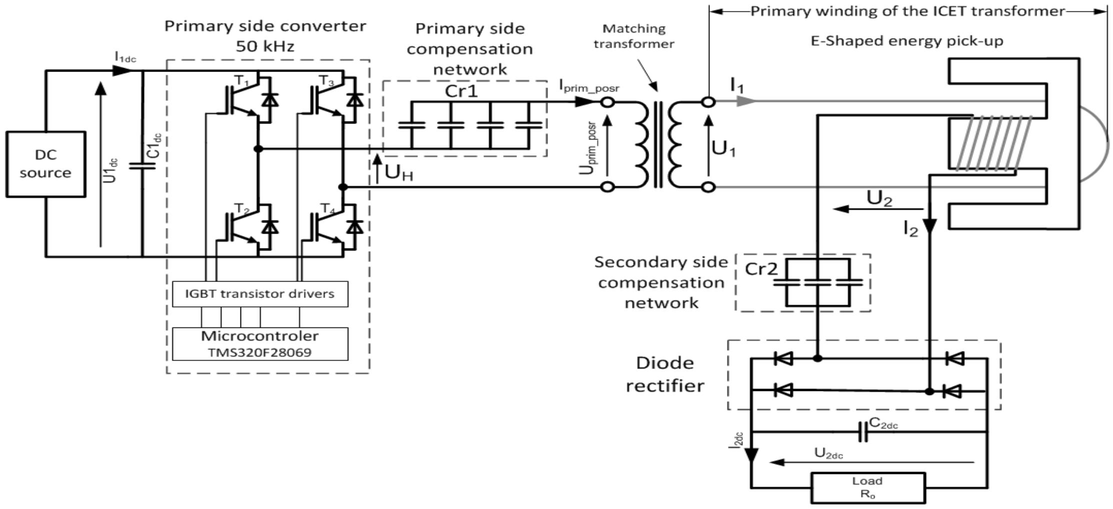

Fig. [CET_LABSETUP]. Diagram of the Contactless Energy Transfer System scaled down laboratory model

The E shaped pickup can be moved along and in the direction perpendicular to the axis of the loop. The output section of the system contains secondary side compensation capacitors connected in series together with diode rectifier and variable resistor load. The output circuit models a drive inverter. Moveable E-Shaped energy pickup simulates movement of the vehicle, which causes loop to move inside the pickup. Thus, magnetic circuit of the transformer will change, loosing resonance condition. As a result power transfer will be impeded. Such changes can be detected by the control circuit and loop current frequency can be adjusted to avoid this situation. The system is controlled by a real-time control scheme implemented DSP microprocessor. Main objective of the controller is to measure state of the circuit and adjust loop current frequency, so the resonance is always maintained. In addition, the controller provides a protective function for the system.

Figure [CET_TEST_SETUP] shows contactless energy transfer system installed in PRT test vehicle on the experimental laboratory setup.

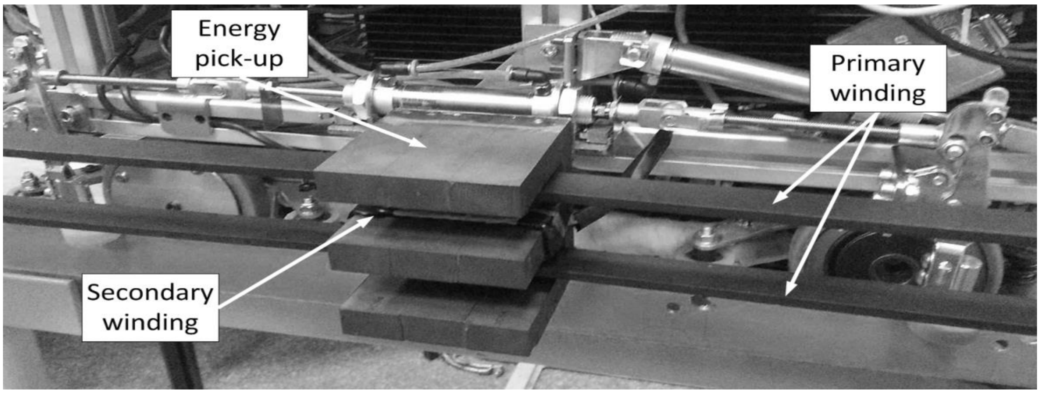

Fig. [CET_TEST_SETUP] PRT test scaled down vehicle with CET system

Figure [CET_POWER_TEST] shows the output power test results taken from the measurements of the scaled down laboratory setup. Presented waveforms show the operation of the CET system at resonance frequency. At the resonant frequency power transistors operate at zero current switching condition which result in a significant switching loses reduction. The resonant converter operates at about 50.5kHz, loop current amplitude is about 105 A_{RMS} and the transferred power is 1.0 kW at 92.6% efficiency.

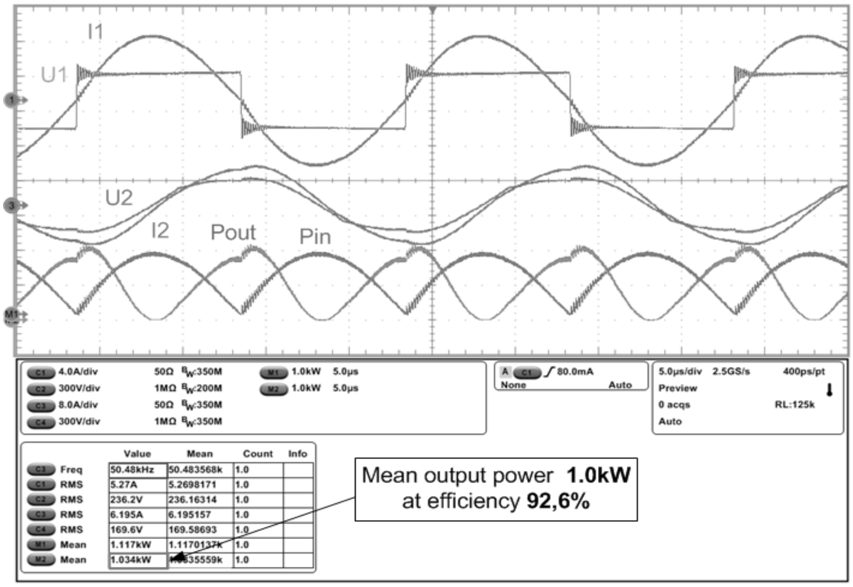

Fig. [CET_POWER_TEST]. Converter steady-state operation - maximum output power test of the scaled down laboratory setup

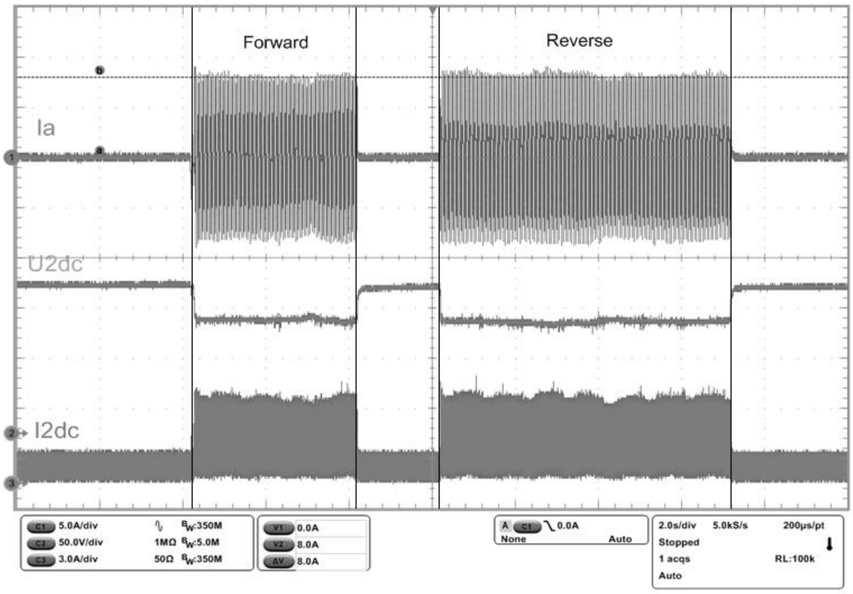

Fig. [MOVE_TEST]. Scaled down PRT vehicle test drive supplied by CET system

Figure [MOVE_TEST] shows the results taken from LIM and PRT vehicle part of the CET system when driving in the laboratory test.

It can be seen from the presented results that CET is cable of providing efficient power supply for PRT vehicle.

5. Conclusions

The paper presents propulsion and power supply topology for PRT vehicles. Proposed solution is based on the application of linear induction motor as a propulsion and inductive contactless energy transfer. The concept provides significant advantages, like low maintenance requirements. Some difficulties are associated with the linear motor application, which are: reduced efficiency, high attraction force between the forcer and the stator core, motor magnetic circuit end effect and variable airgap. High attraction force requires higher strength of the vehicle suspension, but can stabilize the vehicle during turns. The motor’s magnetic circuit end effect and variable airgap lead to the performance deterioration of the thrust force generation, but can be compensated by the control scheme. Finally, increased energy cost maybe compensated by reduced maintenance effort.

Acknowledgement

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