An Enhanced Performance IPT Based Battery Charger for Electric Vehicles Application

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Abstract— **World-wide scientists/engineers were motivated to research in the area of renewable energy resources and to reduce the consumption of fossil fuels. Hence, electric and hybrid vehicles have won the attention of many researchers and vehicles manufacturers. Electric vehicle requires a charging system having a high degree of reliability and robustness and to run maintenance-free. This brings the inductive power transfer (IPT) systems to play a significant role in electric vehicle battery chargers applications. IPT system has proved its capability to be a safe, convenient, and efficient electric vehicle battery charger through its features, such as operating in a harsh environment, high efficiency at reasonable power levels, and decreasing equipment maintenance through operating without any mechanical contacts. This paper presents an enhanced performance IPT system, which is particularly suitable for electric vehicle battery charging application. The proposed system is slightly affected by the small tolerance between sender (track coil) and receiver (pickup coil). Relation between application, transformer configuration selection, and power converter controller is discussed in details. The proposed system effectiveness is investigated, in addition to simulation, by an experimental set-up.**

***Keywords*— IPT applications, wireless energy transfer, electric vehicle**

I. INTRODUCTION

Electric vehicles (EVs) help in reducing the dependence on fossil fuel, greenhouse effect, and emission of pollutants. With presently used contact-based connection systems, opportunistic charging creates a major inconvenience for EV owners since the vehicle needs to be physically plugged in at the end of every short journey. In addition, charging can be done outdoors where exposed contacts present a safety hazard. Inductive power transfer charging system introduces an imperative solution for the safety hazard and inconvenience problems, through transferring the charging energy over a weakly magnetic coupler [1]–[3].

IPT charging system is based on Ampere's and Faraday's laws, by using a varying magnetic field to couple a track coil (TC) as an energy sender and pickup coil (PC) as an energy receiver. Among the several inherent advantages, the components are electrically isolated and operation in wet environments presents no safety risks as such conditions do not affect the IPT systems performance.

Loosely coupling between TC and PC makes the IPT charger face various challenges. To transfer the charging energy through that weak coupler, a high-frequency primary-current should be utilized in the TC to deliver a reasonable power level at realistic efficiency. So, a power converter should match the grid-frequency to the TC current-frequency by rectifying the grid voltage and store the rectified energy into L or LC filter then carryout an inversion on the stored energy into the TC current-frequency [4]–[6].

The very low coupling factor leads to a high magnetizing current which means storing a large value of energy in the IPT transformer's air gap. This leads to efficiently deliver the required power level. IPT transformer requires a relatively large VA to perform the power delivery. It is neither efficient, nor economic to utilize all the VA rating required by the IPT transformer from the power converter alone. Hence, a compensation network is commonly installed at the power converter output to utilize the reactive component of that VA rating required. Consequently, the power converter ratings are reduced and its utilization factor is improved [7, 8].

The current delivered to the battery side through the PC has the same frequency of the TC current. Therefore, another power converter should be installed at the battery side to control the charging power flow. Charging controller should meet the requirements of the battery charging, deal with TC output-current frequency and utilize the grid interfacing options like bidirectional power flow in V2G applications [9].

In this paper an enhanced performance IPT electric vehicle battery charger is proposed. The proposed system depends on series compensation in track and pickup networks to minimize the effect of coupling factor and load variations on the compensation tunning and system operating conditions. A constant dc voltage through un-controlled rectifier and C filter is applied to single phase series resonant inverter to generate the TC-current. Delivered power is supplied through a series compensated pickup tank circuit to a high frequency rectifier. Output voltage of the high frequency rectifier is filtered to adequately supply the battery charging current.

The presented paper is organized as follows, section I illustrates a brief introduction to IPT system and demonstrates its advantages as electric vehicle battery charger. IPT technology overview and analysis are discussed in section II. IPT electric vehicle battery charger design considerations and simulation results are illustrated in section III. Practical verification and experimental setup details are shown section IV. Finally, conclusion is given in section V.

II. IPT SYSTEM ANALYSIS

A. IPT Transformer

IPT system transformer-configuration selection is subjected mainly to application geometry, so there is no specific configuration for the IPT transformer. However, it is possible that there could be more than one configuration appropriate for implementation for the same application.

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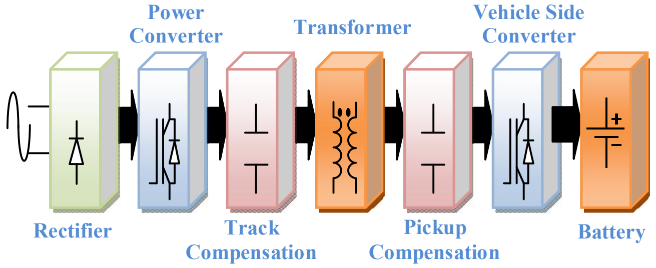

Fig. 1 – IPT system block diagram

The most common used configurations in the electric vehicle battery charging systems are the flat spiral configuration which is preferred in single vehicle charging systems [11, 15].The long track coil (TC) and flat pickup coil (PC) configurations are applicable in the multiple pickups applications, like in public charging stations [3, 10]. IPT transformer analysis is based on IPT transformer parameters which are determined using finite element analysis programs like MAXWELL or JMAG. IPT transformer parameters can be summarized in track self-inductance L_t, track AC resistance R_t, pickup self-inductance L_p, pickup AC resistance R_p, and the coupling factor k which determines the transformer magnetizing inductance M. The IPT transformer equivalent circuit is shown in Fig. 2. Fundamental electrical parameters of the IPT PC are the open circuit voltage V_{oc}, which can be obtained when the load impedance tends to infinity, and the short circuit current I_{sc}, which can be obtained when load impedance tends to zero. Open circuit voltage and short circuit current are given by (1) and (2) [7, 10, 14].

$$V_{oc} = j\omega M I_t \tag{1}$$

$$I_{sc} = \frac{M I_t}{L_p} \tag{2}$$

From (1) and (2) the theoretical uncompensated VA product (S_{uc}), which could be obtained from the IPT transformer is given by (3).

$$S_{uc} = V_{oc} I_{sc} = \frac{\omega M^2 {I_t}^2}{L_p} \tag{3}$$

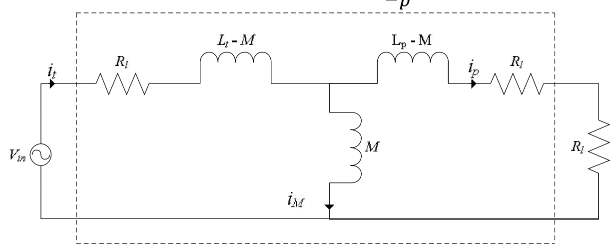

Fig. 2 – IPT transformer equivalent circuit

While S_{uc} cannot be achieved in an uncompensated system (the maximum power output achievable with no compensation is ($S_{uc}/2$)). Practically, applied S_{uc} becomes obvious when the pickup is tuned through the addition of a capacitor, either in series or in parallel. If the pickup operates at a tuned quality factor of Q then the output power into the load is given by (4) [7, 10].

$$P = QS_{uc} = Q(V_{oc} I_{sc}) = Q\omega \frac{M^2}{L_p} {I_t}^2 \tag{4}$$

B. Compensation Networks

As shown in *A* Section, IPT system depends on a weak coupled transformer to deliver the power from track network to the pickup network with a coupling factor of IPT transformer typically less than 0.5 [16].

Utilizing the total VA required from the power converter couldn't be efficient, reliable, or cost effective. So IPT system should have another element utilizing the stored energy in the IPT transformer.

Compensation network is used as a reactive energy source for the IPT transformer. Compensation network is composed of capacitor(s) connected in series, parallel, or a combination with the track and pickup networks [16]-[18]. Basic compensation topologies are shown in Fig. 3.

Selecting the compensation topology is strongly related to application and selected power converter topology.

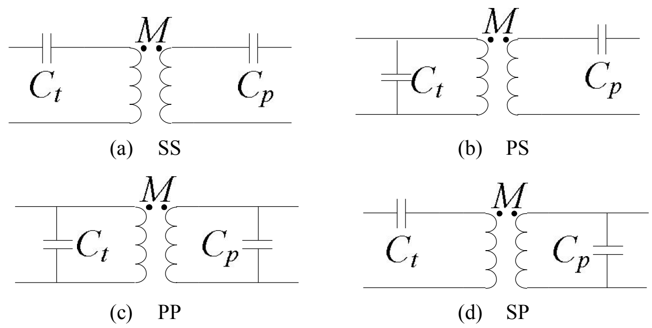

Fig 3. Basic compensation topologies. (a) series-series (SS) compensation topology, (b) parallel-series (PS) compensation topology, (c) parallel – parallel (PP) compensation topology and (d) series-parallel (SP) topology

Analysis of a compensation network is accomplished by finding the equivalent impedance of the overall IPT system at the tuned point of the operating frequency.

Equivalent circuit of the IPT system with SS compensation topology is shown in Fig. 4. Pickup side equivalent impedance Z_1 is given by (5)

$$Z_1 = j\omega\left(L_p - M - \frac{1}{\omega^2 C_p}\right) + R_l \tag{5}$$

If the operating frequency is tuned to be $\omega = \frac{1}{\sqrt{L_p C_p}} = \frac{1}{\sqrt{L_t C_t}}$, then the pickup side equivalent impedance is

$$Z_{1n} = -j\omega M + R_l \tag{6}$$

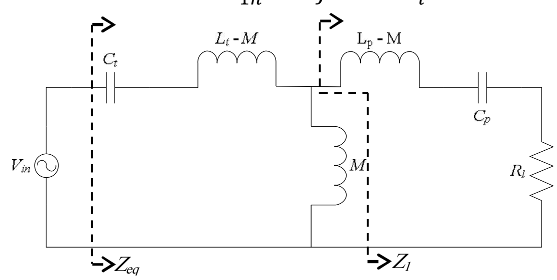

Fig. 4 – IPT system with SS compensation topology equivalent circuit

Similarly the total equivalent impedance of the SS IPT system could be given by (7)

$$Z_{eq} = \frac{(\omega M)^2}{R_l} \tag{7}$$

C. Power Converter

Power converter in IPT system has a very significant role in matching the grid power frequency with the track current frequency and controlling the power delivered to the pickup side through controlling the track current level.

Due to the essential high operating frequency, using any hard switching converter will be inefficient, not cost effective and inapplicable in size. So power converter with soft switching technique is commonly utilized.

Because of the need to use the compensation network and the requirement of using soft switching technique in the power converter, the resonant converter could be a reasonable choice as an IPT system power supply [19]-[22]. Selecting of resonant converter topology is strongly related to the application and the selected compensation topology. For example, in the long track single pickup application (like in monorails) the system requires a very large track current and it has a very low coupling factor less than 0.05 in most cases [6, 7]. Using of parallel compensation in the track system reduces the current rating of the power converter, consequently the system overall cost. Using the current source resonant converter could be reliable, because the current source topology already requires a shunt capacitor at the converter output and track current could be easily controlled by controlling the dc-link current [6, 23, 24].

In a single vehicle wireless battery charger application, a flat spiral transformer configuration is commonly used. Therefore, the system has a low coupling factor (typically between 0.2 and 0.4) but larger than the long track single pickup application and the system is sensitive to horizontal tolerance between track and pickup coils. Consequently, the compensation system shouldn't be affected by the variation in coupling factor. One of the very common converter topologies used in this application is the voltage source series resonance converter [25-29].

LCL configuration is one of the most common topologies in bidirectional system, because of the appropriateness in grid interfacing. Also it introduces a high current gain which reduces converter current ratings.

Analysis of these resonant converters is mathematically complex and requires a numerical solution to a large number of simultaneous transcendental equations. An alternate methodology is the fundamental-mode approximation (FMA) analysis, which provides a much simpler and more intuitive approach to the analysis of resonant converters by modeling the resonant circuit in terms of the fundamental mode or first harmonic of the circuit waveforms. FMA simplifies the converter analysis by assuming all the energy is supplied through the fundamental component of the output signal of the converter. Then, the circuit could be analyzed as any simple AC electrical circuit.

III. ELECTRIC VEHICLE IPT CHARGER DESIGN

The system topology under investigation is shown in Fig. 5. For modeling, vehicle side converter and battery is replaced with a resistance equivalent to the power and voltage levels required by the vehicle battery charging system. Switching action of the converter shown in Fig. 5 generates pulsating voltage across the inverter output terminals as shown in Fig. 6

Converter output voltage RMS value is given by (8)

$$V_{inv(fund.)} = \frac{2\sqrt{2}}{\pi} E \tag{8}$$

Steady-state equivalent FMA model of the converter, shown in Fig. 7, can be easily obtained.

The IPT system design is based on finding the equivalent impedance of the circuit shown in Fig. 7.

$$Z_1 = R_l + j\left[\omega\left(L_p - M\right) - \frac{1}{\omega C_p}\right] \tag{9}$$

The converter operating frequency is equal to the resonant frequency of the track and pickup tank circuits so (9) tends to (10)

$$Z_1 = R_l - j\omega M \tag{10}$$

$$Z_2 = \frac{(\omega M)^2}{R_l} + j\omega M \tag{11}$$

$$Z = \frac{(\omega M)^2}{R_l} \tag{12}$$

From (8), the required DC link voltage could be easily calculated

$$E = \frac{\pi \omega M}{2}\sqrt{\frac{P}{2R_l}} \tag{13}$$

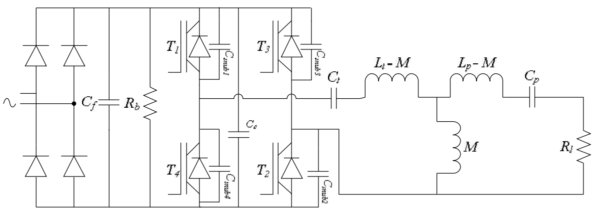

Fig. 5 – System under investigation topology

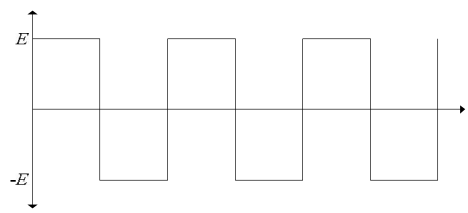

Fig. 6 – Voltage source converter output voltage

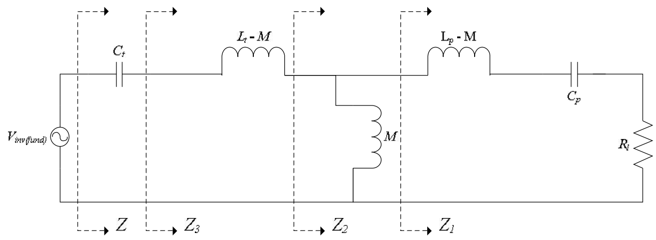

Fig. 7 – FMA model of the IPT charger

A. Simulation Results

To verify the proposed analysis of the flat circular spiral transformer based IPT electric vehicle battery charger system, a SIMULINK model of the system shown in Fig. 8 has been built with the parameters shown in table I. IPT system simulation results are shown in Fig. 9 to Fig. 16. The IPT inverter, working at resonant frequency of 75 kHz, outputs square-wave voltage as shown in Fig. 10.

Table I. Simulation model parameters

DC-link voltage	E	$50V$
Operating frequency	f	$75kHz$
Track coil inductance	L_t	$97\mu H$
Pickup coil inductance	L_p	$97\mu H$
Coupling factor	K	0.5
Battery nominal voltage	V_B	$12V$
Battery capacity	C_B	$7AH$
Charging current	I_B	$1.7A$
Track compensation capacitor	C_t	$47nF$
Pickup compensation capacitor	C_p	$47nF$
Output filter capacitance	C_f	$9400\mu F$

The track and pick-up voltage and current waveforms are illustrated in Fig. 12 and Fig. 13 respectively. Proper resonant operation leads to sinusoidal current waveform output from the pick-up compensation network as shown in Fig. 15. The final stage performs a rectification and smoothing to charge the battery load as illustrated in Fig. 16.

IV. Practical Verification

To verify the simulation result, a test rig shown in Fig. 17 has been built with the parameters shown in table I

Practical results are shown from Fig. 18 to Fig. 25. The experimental results show matching between the simulation and practical setup.

V. Conclusion

An IPT battery charger for electric vehicles has been presented in this paper. The paper investigates the IPT battery charger from analysis, design and simulation. The proposed IPT system utilizes flat spiral topology for tolerance benefits. In addition, resonant converter is suggested with series-series compensation networks for efficiency considerations. An experimental setup is implemented to verify the presented technique effectiveness.

VI. Acknowledgment

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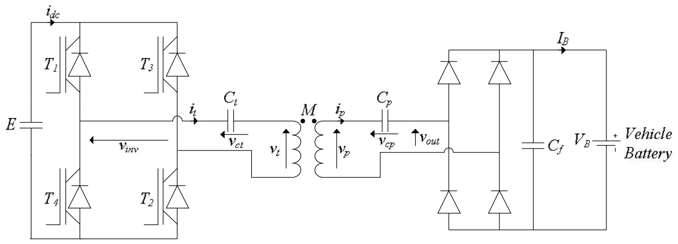

Fig. 8 – Simulated system

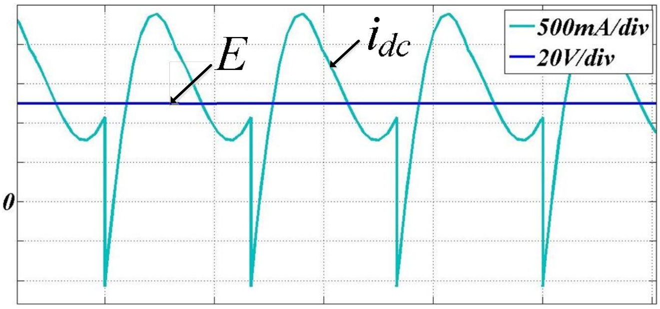

Fig. 9 – DC-link voltage (E) and current (i_{dc})

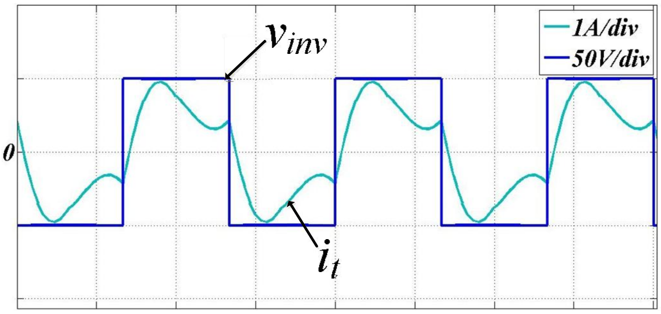

Fig. 10 – Inverter output voltage (v_{inv}) and current (i_t)

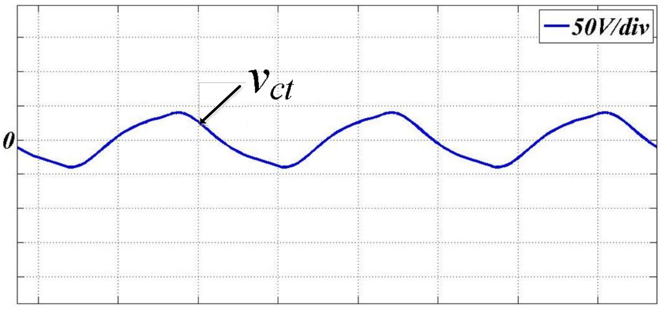

Fig. 11 – Track capacitor voltage (v_{ct})

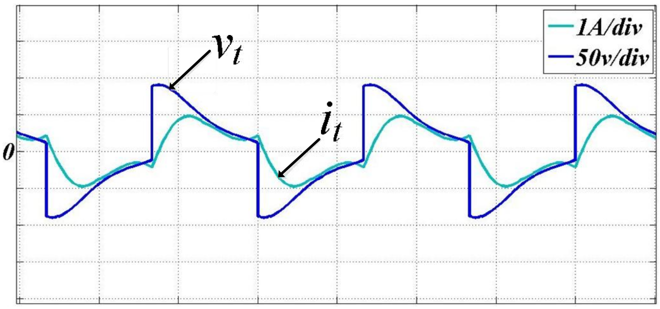

Fig. 12 – Track voltage (v_t) and current (i_t)

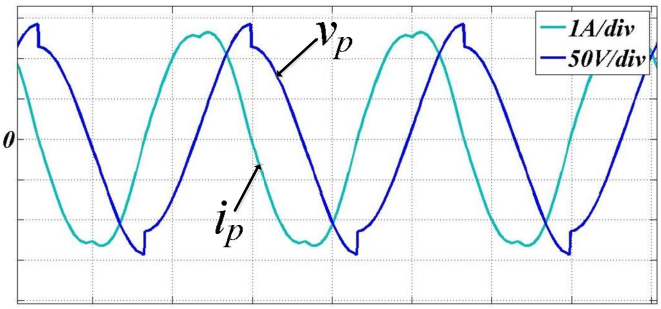

Fig. 13 – Pickup voltage (V_p) and current (i_p)

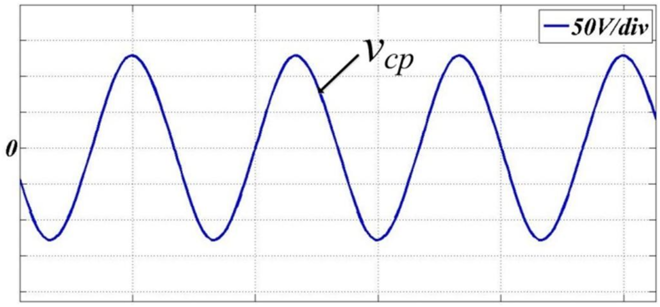

Fig. 14 – Pickup capacitor voltage (v_{cp})

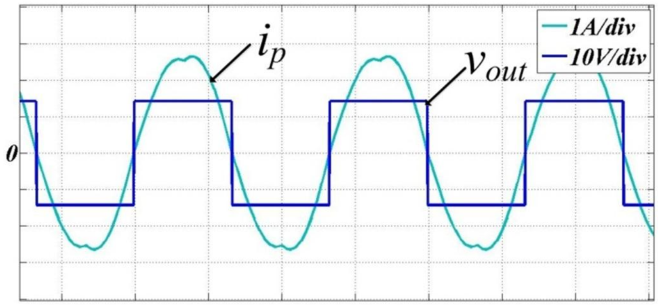

Fig. 15 – Load rectifier input voltage (V_{out}) and current (i_p)

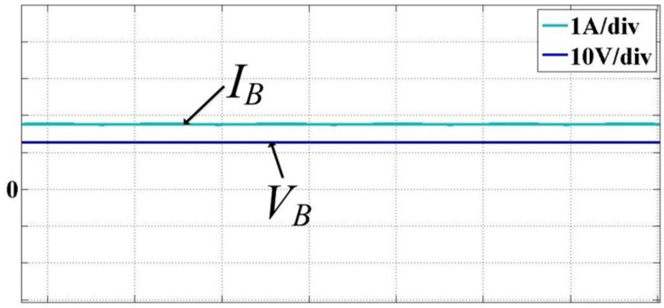

Fig. 16 – Battery voltage (V_B), current (I_B)

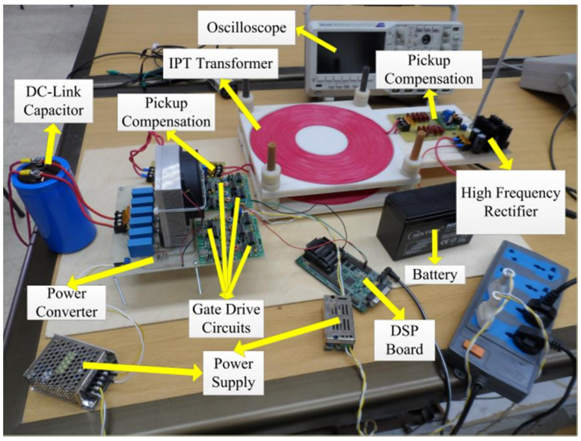

Fig. 17 – IPT charger test rig

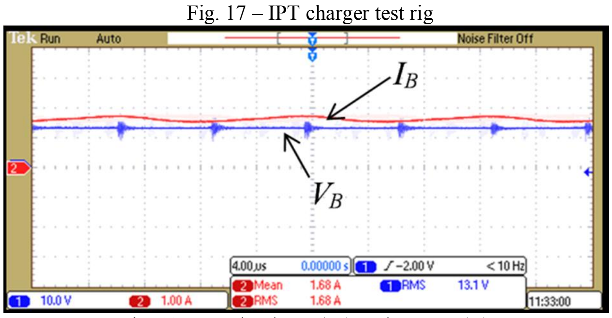

Fig. 18 – Load voltage (V_B) and current (I_B)

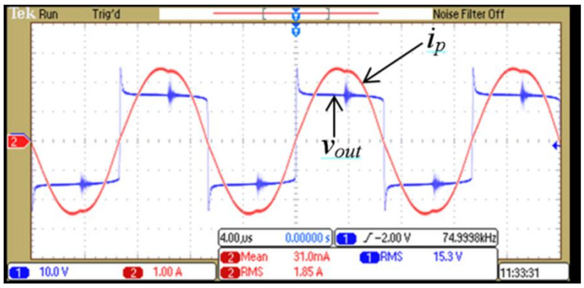

Fig. 19 – Load side rectifier voltage (V_{out}) and current (i_p)

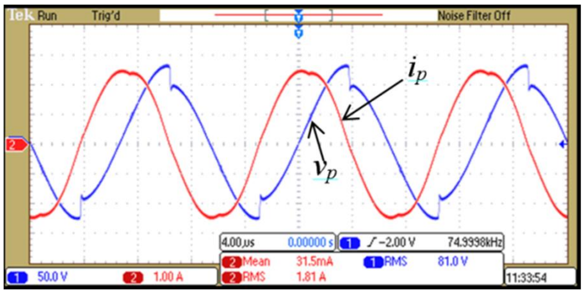

Fig. 20 – Pickup output voltage (V_p) and current (i_p)

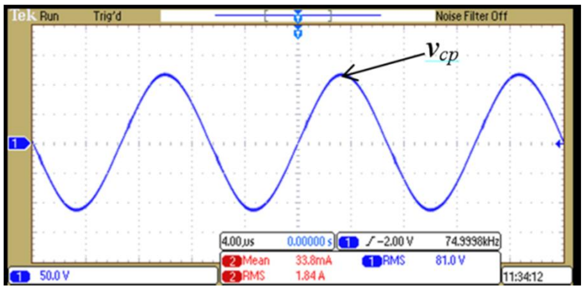

Fig. 21 – Pickup compensation capacitor voltage (v_{cp})

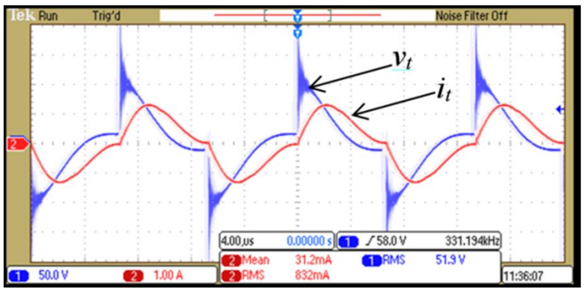

Fig. 22 – Track input voltage (v_t) and current (i_t)

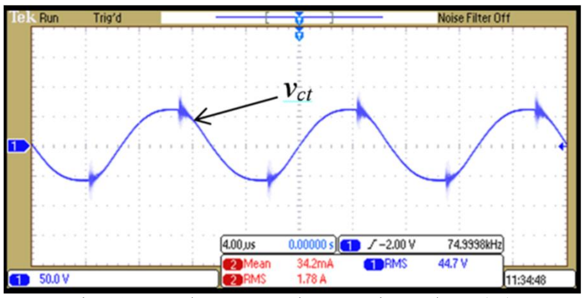

Fig. 23 – Track compensation capacitor voltage (v_{ct})

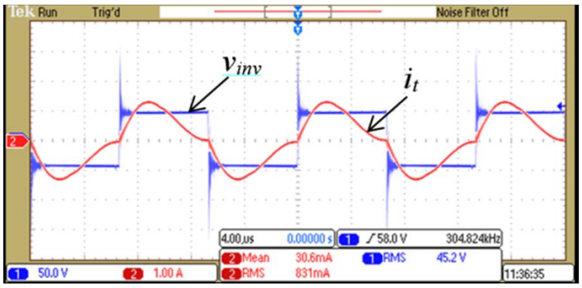

Fig. 24 – Inverter output voltage (v_{inv})/current (i_t)

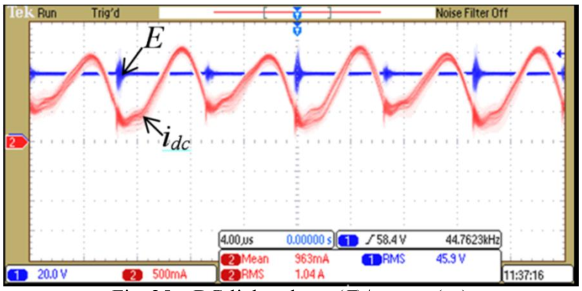

Fig. 25 – DC-link voltage (E)/current (i_{dc})

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