A Non-Contact Method for Fair and Accurate Metering of Wireless Power Transfer in Electric Vehicles

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Motivation

- Wireless power transfer is emerging as the pre-eminent way to charge electric vehicles, but there appears to be no fair way to measure power transfer.
- Electrical terminal power measurement which is currently available cannot provide disaggregated efficiency between transmitter and receiver.
- In this paper, transfer-power measurement (TPM) is introduced. TPM employs non-contact sensing elements to measure magnetic field from wireless power transfer and calculate the real power propagating through space. TPM provides fair metering because individual losses from the transmitter and receiver are disaggregated. Signal and data processing as well as a calibration method are discussed. Experimental results demonstrate a fair method of metering the real transfer power with low estimation error.

Fig. 1. US Weights and Measures Program qualifies secured gas pump metering(left) with a seal (right). [Photo (left): Peter Casolino/New Haven Register "Connecticut gas station inspections show some pumps may be inaccurate."].

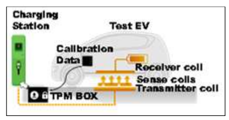

Fig.2. Conceptual diagram of calibration of WPT with a test EVs by transfer-power measurement (TPM).

Transfer-Power Measurement Theory

1. Magnetically-Coupled Circuit with Two Sense Coils

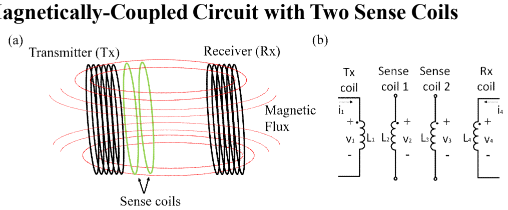

Fig. 3 Sense coils in the transfer-field to measure the real power: (a) Conceptual diagram, (b) Circuit diagram..

$$
\begin{aligned}
I_2 &= I_3 = 0\\
V_1 &= j\omega L_1 I_1 + j\omega M_{14} I_4\\
V_2 &= j\omega M_{12} I_1 + j\omega M_{24} I_4\\
V_3 &= j\omega M_{13} I_1 + j\omega M_{34} I_4\\
V_4 &= j\omega M_{14} I_1 + j\omega L_4 I_4
\end{aligned}
\longrightarrow
$$

$$
\begin{pmatrix} V_4 \\ I_4 \end{pmatrix} = \begin{pmatrix} \frac{\sqrt{L_4}}{\sqrt{L_2}}\left(\frac{k_{13}-k_{14}k_{34}}{k_{13}k_{24}-k_{12}k_{34}}\right) & \frac{\sqrt{L_4}}{\sqrt{L_3}}\left(\frac{k_{14}k_{24}-k_{12}}{k_{13}k_{24}-k_{12}k_{34}}\right) \\ \frac{1}{j\omega}\frac{k_{13}}{\sqrt{L_2L_4}(k_{13}k_{24}-k_{12}k_{34})} & \frac{-1}{j\omega}\frac{k_{12}}{\sqrt{L_3L_4}(k_{13}k_{24}-k_{12}k_{34})} \end{pmatrix} \begin{pmatrix} V_2 \\ V_3 \end{pmatrix} = \begin{pmatrix} A & B \\ \frac{1}{j\omega}C & \frac{-1}{j\omega}D \end{pmatrix} \begin{pmatrix} V_2 \\ V_3 \end{pmatrix}
$$

2. Signal Processing in the Frequency Domain

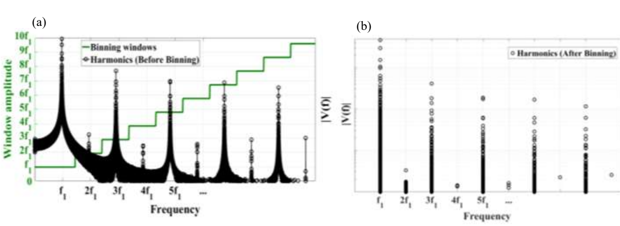

Fig.3. An example of binning with respect to binning frequency windows:

(a) Harmonics before binning (b) Harmonics after binning

3. Calibration

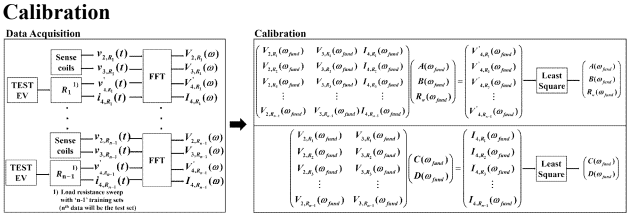

Fig.4. Calibration strategy

Results and Discussion

1. EV-sized Proof-of-Principle Experiments

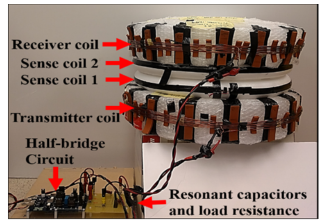

Fig.5. Proof-of-concept experiment.

TABLE 1. Specifications of Experiments

Parameters	Value	Parameters	Value
Transmitter coil Self-inductance,	146 μH	Tx and Rx coil Number of turns	11-turn
Receiver coil Self-inductance,	145 μH	Sense coil Number of turns	1-turn
Sense coil #1 Self-inductance,	2.6 μH	Transmitter coil Radius,	25 cm
Sesse coil #2 Self-inductance,	2.6 μH	Receiver coil Radius,	25 cm
Resonant Capcitance,	10 nF	Sense coil Radius,	24 cm
Resonant Capcitance,	30 nF	Tx-Rx coil Distance,	21 cm
Operating (Switching) Frequency	96 kHz	Vdc	50V

2. Experimental Results

- Power from terminal measurements deviate a lot from TPM.
- Transmitter and Receiver had disaggregated efficiency through TPM
- Experimental results within target standards (Metering Accuracy)

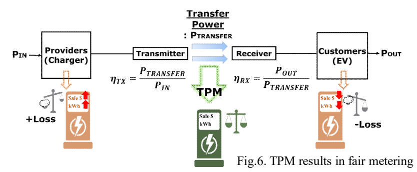

Fig.6. TPM results in fair metering

TABLE 2. Experimental Comparison of TPM with Terminal Power Measurements.

Load Resistance (R_L)	P_{IN}: Terminal Power Measurement at Tx (W)	$P_{TRANSFER}$: Transfer Power (W)	P_{OUT}: Terminal Power Measurement at Rx (W)
5 Ω	163.74	103.99	85.89
10 Ω	133.24	97.15	86.98
25 Ω	77.04	60.56	57.81
33 Ω	62.84	48.83	47.12
50 Ω	46.00	34.56	33.77

- TPM with rectifier loads are comparable

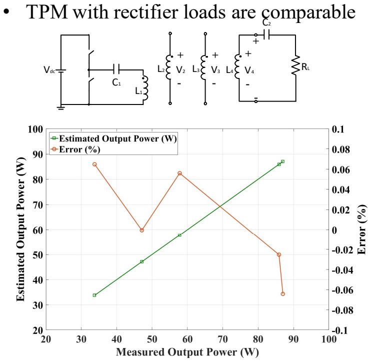

Fig.7. Experimental results: Estimated powers and their errors were plotted at each validation set

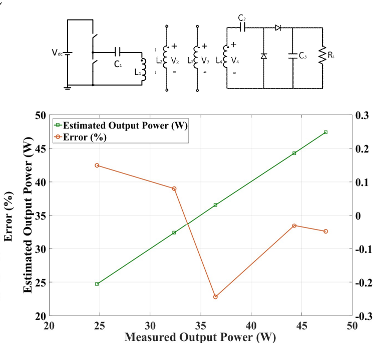

Fig.8. Experimental results: Estimated powers and their errors were plotted at each validation set for rectifier loads

3. Misalignment and Power Estimation Error

- Calibration is performed when Tx and Rx are perfectly aligned.
- Subsequent misalignment from vehicles results in errors in TPM
- TPM error due to misalignment only depends on the coupling coefficients.

$$
\varepsilon_{MIS} = 1 - \frac{P_{EST,MIS}(\omega)}{P_{TRUE,MIS}(\omega)} = 1 - \frac{k_{14,0}}{k_{14}}\frac{(k_{13}k_{24}-k_{12}k_{34})}{(k_{13,0}k_{24,0}-k_{12,0}k_{34,0})}
$$

- Sense coil's proper position and size can reduce misalignment error significantly.

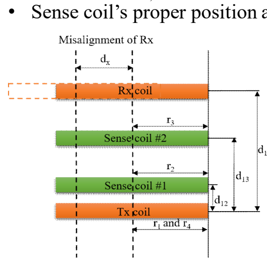

Fig.9. Configurations of Tx, Rx, and sense coils for misalignment analysis.

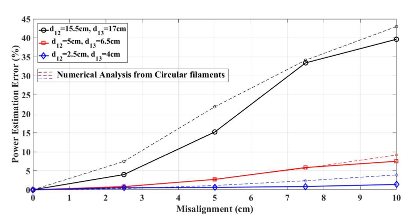

Fig.10. Experimental results of power estimation error over misalignment with different sense coil positions.

Conclusion

Transfer-power measurement (TPM) was introduced and theoretically analyzed. Two non contact sense coils were employed to estimate the real transfer power. Signal processing in the frequency domain and a calibration strategy at the fundamental harmonic for accurate power estimation were addressed and verified by proof-of-principle experiments which showed TPM's strong capability to be an accurate and reliable method. Errors from misalignment were analyzed with respect to the size and position of the sense coils to improve the sensitivity of TPM.

S. Y. Chu and A. T. Avestruz, "Transfer-power measurement: A non-contact method for fair and accurate metering of wireless power transfer in electric vehicles," *2017 IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Stanford, CA, 2017, pp. 1-8.COMPEL.