A Fast Spotting Strategy of Optimal Frequency in Wireless Power Transfer

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***Abstract*—One of the most common questions in the Wireless Power Transfer (WPT) system is how to transfer much power over coils driven by the AC power source. This paper concerns how to determine the frequency of AC power source optimal to maximum WPT. Although it is theoretically possible to determine the optimal frequency by wide range frequency sweep, it is practically important to spot it in a few trials of frequency. This paper proposes a frequency spotting strategy using a square wave input power signal. The strategy avoids a long time-consuming sweeping process with knowledge of response by square wave input. The Automatic Multiscale-based Peak Detection (AMPD) algorithm is applied to select the initial peak finding on every data sample increment iteration to further analysis to find the set of peak patterns by calculating error parameters.**

***Index Terms*—Wireless power transfer, optimal frequency, square wave input, AMPD**

I. Introduction

WPT is one of the promising technology to provide a sustainable future since it could reduce the usage of batteries and cables on electronic appliances [1]. Started by the Tesla experiment [2], the WPT methods are classified into a radiative category (such as using a microwave) and non-radiative category that uses the inductive and capacitive power transfer [3]. The inductive power transfer method has gained popularity stimulated by the research [4] in 2007, where non-radiative inductive power transfer successfully transferred 60 watts within 2 meters range and get 40% of efficiency. Currently, the WPT has been implemented in many applications such as electric vehicles [5], consumer appliance [6], Internet of Things [7], and biomedical applications [8].

Improvement of power transfer efficiency to deliver much power over coils is a challenge in WPT. Several methods to improve efficiency have been review in [9], including impedance matching [10], parameter optimization [11], and selection of an optimal frequency [12]. Furthermore, to reach the required efficiency, several efficiency-tracking methods have been proposed, such as dynamic coupling coefficient estimation [13], phase shift [14], and adaptive frequency [15]. Therefore, the WPT overall system performance depends on several key parameters such as frequency, the shape of input power source signal, type and section of coils, the radius of coils, and transfer distance [16].

The power transfer efficiency requested can be found by knowing and giving a fixed parameter value. However, once the parameter changes, the efficiency of power transfer will decrease since the optimum parameters were only suitable for the previous condition. Optimum power transfer for the current situation was only able to be obtained by parameter recalculation and re-finding. In this meaning, the inverse problem of finding optimum parameters for a continuously changing situation is an open challenge in the WPT research field. Impedance and resonant frequency parameters (in the case of frequency) towards the coil distance variation is a situational example that can reduce the efficiency of a WPT system [15]. This problem can be avoided by always giving the correct frequency input to the WPT system by using frequency tracking and tuning. Frequency tracking and adjustment have been demonstrated in some research [12], [15], [17], [18]. However, tracking the optimal frequency without considering the number of frequency sweep is a time-consuming process. Therefore, by considering the number of frequency sweeping, a method improvement for tracking and validating optimal frequency needs to be conducted.

This paper concerns how to determine the frequency of AC power source optimal to maximum WPT. An optimal frequency can be found accurately by applying frequency sweep. However, the frequency sweeping takes a long time, and there is a high possibility that the parameters and situations might change during the process. This paper proposes a strategy to find and validate the optimal power transfer frequency in WPT with a square wave input signal. Compared to the sine wave, the square wave input signals can deliver higher power even if the input frequency restricted to a lower frequency than the resonant frequency [19], [20]. Furthermore, by using Fourier analysis of the response stimulated by the square wave input signals, the optimal power transfer can be validated, since the optimal frequency has a set of peak patterns between the frequency ranges.

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II. Methods

In the preliminary research and experiment, the WPT system received a 5 kHz to 100 kHz (with a 100 Hz interval) square wave input signal. We obtained 950 power data from the receiver with a 20 Ω load resistance and 35 mm distance between coils. Thus, based on the experiment result observation, a set of essential peaks (l) was found, including the optimum frequency that delivers the highest power to the receiver. Fig. 1 shows that obtained data include the optimal power transfer frequency 56.9 kHz (l_0), followed by other local peaks $\{l_1, l_2, l_3, l_4\}$, located at 18.2 kHz, 11 kHz, 7.8 kHz, and 5.9 kHz, respectively.

Furthermore, let $l=\{l_0, l_1, l_2, \cdots, l_n\}$, with respect to frequency, the pattern formula from a set of peaks was obtained and expressed as

$$l=\left\{l_0,\ \frac{1}{3}l_0,\ \frac{1}{5}l_0,\ \ldots,\ \frac{1}{2n+1}l_0\right\} \tag{1}$$

Moreover, since the square wave signal has 3rd, 5th, 7th, n^{th}-times frequencies in addition to the fundamental frequency, deciding an optimal frequency will be possible, by referring this knowledge to discover the set of peak patterns.

Our spotting method uses the AMPD algorithm [21] to find the initial peak since it is suitable for our WPT system that has a set of peak patterns with a multiscale periodic type of peaks [22], [23]. The AMPD algorithm will collect the initial peaks to further analyze by our spotting method. Afterward, our spotting method will determine the optimal frequency by validating its existence on each set of sample data. If the spotting method recognizes the set of peaks, the optimum power transfer value could be obtained. The generic process from the proposed method illustrates using the flowchart shown in Fig. 2.

By using (1) as a rule to validate the optimal frequency, the proposed spotting method is described as follows:

1. Retrieve a sample of data in 5-100 kHz starting from 10 kHz sampling interval (i). Collect a set of peaks by using the AMPD algorithm (p) in sample data by using several intervals.

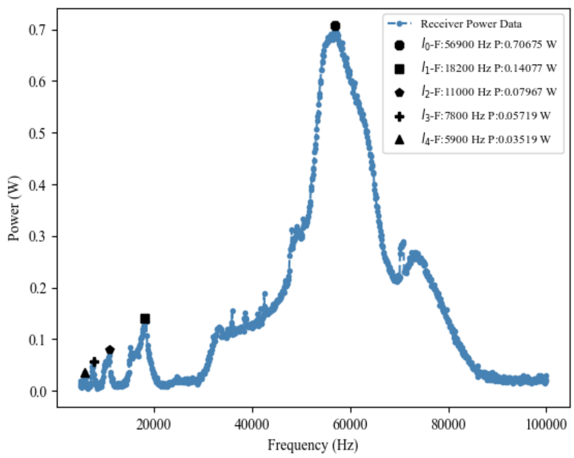

Fig. 1. Transferred power to 20 Ohm load depending on the driving frequency (experiment).

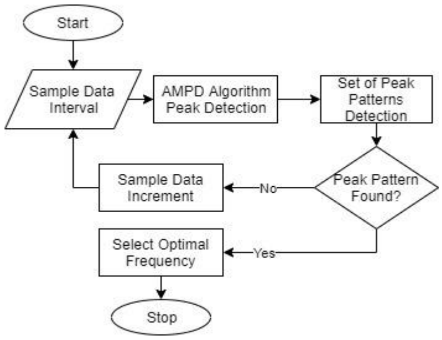

Fig. 2. Flowchart of the proposed method.

2. Increase the number of sample data until the number of p is higher or equal to the number of peak patterns to be found (n).
3. Afterward, the optimal frequency (l_0) assumption (g) is decided by finding the highest power in p. Next l_1, l_2, $\cdots$, l_n pattern approximation are found by computing a set of peak approximation frequency (a) by multiplying g with $1/(2n+1)$.
4. For each a, find the nearest frequency as a candidate peak (c) for each in p and measure the distance error (e_d) by averaging $|c_n-a_n|/9500$, where 95000 is the observed frequency width 5 kHz to100 kHz.
5. Measure the amplitude error by identifying whether the amplitude for each $c_n>c_{n+1}$ is satisfied using Boolean value, or not. If the result is false, then e_a=1 otherwise e_a=0.
6. Decide the optimal frequency validity by computing total error $e_{total}=(0.2e_d+0.8e_a)$, where 0.8 weight is given to e_a since the error is unacceptable. Therefore, if the result of e_{total} is higher than 0.8, the status of the optimal frequency will be considered invalid, and more data samplings are required.
7. Check whether all l_n have been found and e_{total} is less than 0.8. Increase the sample data if some l_n is missing or less then the desired n.

Increment of the sample data will include the previously gathered data appended with new sample data. The newly sampled data by reducing the initial interval of frequency (i) by a decrement variable (d) that decided by the experiment are shown in Fig. 3. The iteration process will continue until i=0.

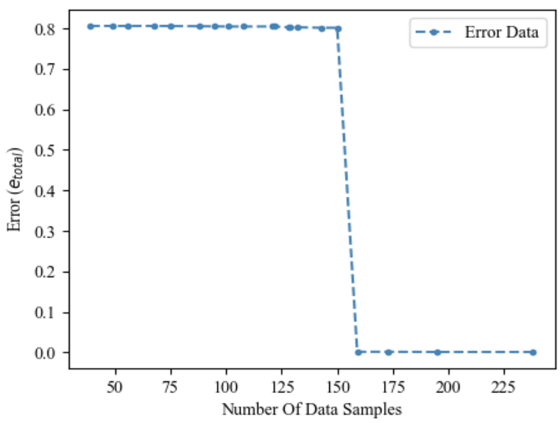

Fig. 3. The experiment conducted to collect e_{total} on each iteration with d=400. The data sample increment (i) starts with 10 kHz interval and find the e_{total} value from 5 kHz to 100 kHz.

TABLE I: SET OF PEAK CANDIDATE, ERROR COMPUTATION, OPTIMAL FREQUENCY DECISION, AND VALIDATION. OBTAINED DURING 159 DATA WITH TEN PEAKS FOUND BY THE AMPD ALGORITHM

Highest power frequency found by AMPD algorithm (p)		Set of peak candidate (c) (Hz)				Error		
Frequency c_0 (Hz)	Power (Watt)	c_1	c_2	c_3	c_4	e_d	e_a	e_{total}
57000 (l_0)	0.69452	18200 (l_1)	11000 (l_2)	7800 (l_3)	5000 (l_4)	0.005464	0	0.001093

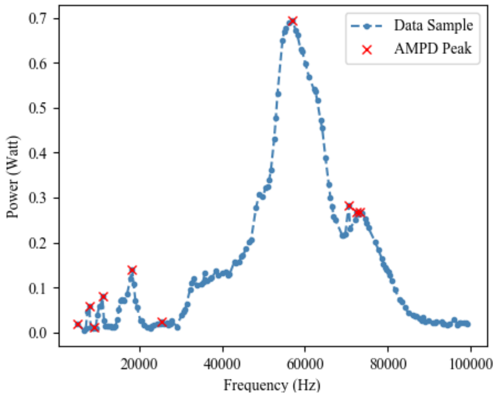

Fig. 4. The Experiment during the 159 data samples with 10 peaks found by the AMPD Algorithm.

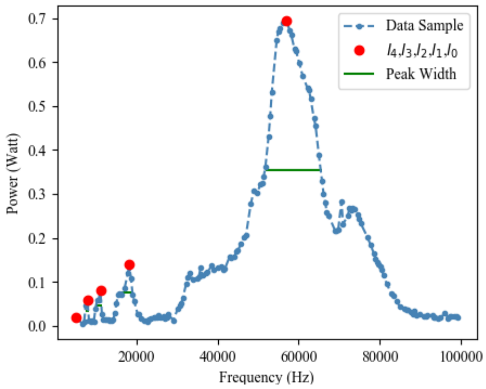

Fig. 5. The 159 data samples with set of peak (l=l_4, l_3, l_2, l_1, l_0) respectively from smallest to highest frequency alongside with the peak width, after being selected by the spotting strategies.

III. RESULT AND DISCUSSION

The spotting strategies are implemented using Python programming language and the experiment starts with finding the decrement interval variable. The experiment is conducted by collecting e_{total} on each iteration, as shown in Fig. 3. In the first iteration, 10 samples are obtained with 10 kHz interval. Since e_{total} is higher than 0.2, the optimal frequency is considered to be invalid, and it will continue to the next iteration. Sample data will be propagated (including the previously retrieved data) by subtracting i by 400. Therefore, on the next iteration, sample data will be appended every interval of 9.6 kHz.

The iteration will continue until i=0, and in the experiment, 238 data were sampled. Based on Fig. 3, the optimal frequency can be determined since the number of samples of data reaches 159. Therefore, by capturing e_{total} on each iteration, the optimal frequency can be decided whenever e_{total} value is less than 0.8 in some iterations. Fig. 4 shows the situation when the AMPD algorithm finds the peaks based on 159 data samples. The AMPD algorithm collects ten peaks for further analysis by the spotting method to find the correct set of peaks.

Table I shows the result when the iteration reaches a total of 159 data samples. e_d is a small value, which means that the approximation value (a) for each local peak is found in the peak collected by the AMPD algorithm. e_a is 0 since the condition of the power amplitude for $c_0 > c_1 > c_2 > c_3 > c_4$ is true. Afterward, e_{total} will be calculated and used to select a set of peak l=l_4, l_3, l_2, l_1, l_0, as shown in Fig. 5.

To validate the result obtained by the AMPD and the spotting method, we compare the set of peak l results from Table I with the real peak obtained from direct observation, as shown in Table II. This result shows that the optimal power transfer frequency obtained from the proposed algorithm has a 0.1757% error distance from the real optimum. Furthermore, this algorithm can continue to retrieve the data among the peak width if a more accurate result is required.

The second experiment is conducted to evaluate the spotting method works well in different experimental data. Fig. 6 shows additional data that have similar characteristics. These three data have a different optimal frequency, although the location of the peaks is close to each other.

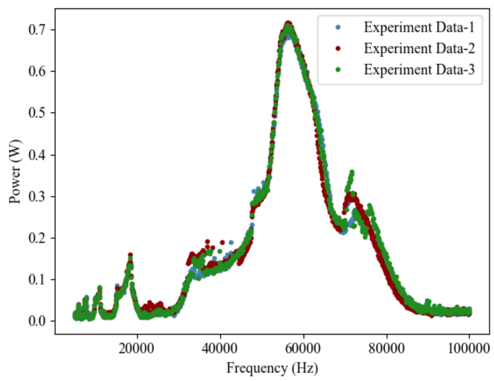

Fig. 6. Three experimental data consists of 950 power data, received from WPT system by 20 Ohm resistor using square wave input signal.

TABLE II: THE SET OF PEAK (L) COMPARISON BETWEEN THE SPOTTING METHOD RESULT AND CORRECT (L) SET OF PEAKS OBTAINED FROM DIRECT OBSERVATION

Set of peak pattern (l)	Peak detection with 205 data (Hz)	Power (Watt)	Peak width range (Hz)	Real peak frequency (Hz)	Power (Watt)	Error Distance (%)
l_0	57000	0.69452	51800-65800	56900	0.70675	0.1757
l_1	18200	0.008421	16200-19000	18200	0.14707	0
l_2	11000	0.07967	9800-11400	11000	0.07967	0
l_3	7800	0.05719	7400-8200	7800	0.05719	0
l_4	5000	0.01956	5000-5000	5900	0.03519	15.2542

TABLE III: ERROR DISTANCE COMPARISON BETWEEN THE SPOTTING STRATEGIES SET OF PEAKS WITH 159 SAMPLES WITH THE DIRECT OBSERVATION WITH 950 DATA

Data	AMPD Peak Find	Total Data	The spotting strategies error distance (%) compared to the real distance by direct observation					Optimal Power Difference (Watt)
			l_0	l_1	l_2	l_3	l_4	
1	10	159	0.1757	0	0	0	15.2542	0.01223
2	18	173	0	1.0869565	0	0	16.666667	0
3	5	150	0.1782531	1.0869565	0	0	16.666667	0.00636

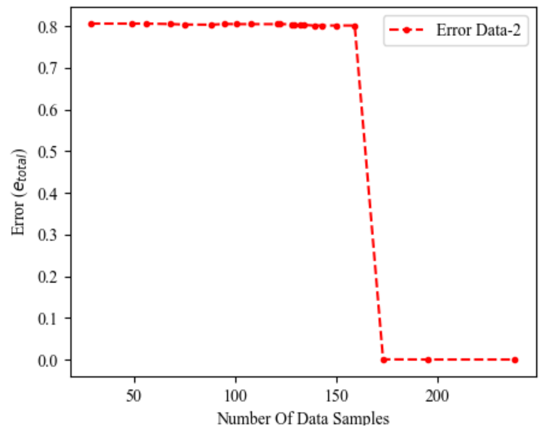

Fig. 7. The experiment conducted to collect e_{total} on each iteration with d=400 from a total 238 of data samples in Data-2 with $e_{total} < 0.8$ start at the 173 data samples.

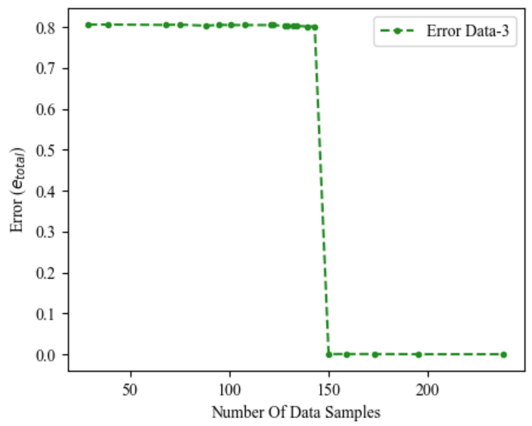

Fig. 8. The experiment conducted to collect e_{total} on each iteration with d=400 from a total 238 of data samples in. Data-3 with $e_{total} < 0.8$ start at the 150 data samples.

The same scenario is conducted, which is to check e_{total} plot on each iteration with the initial 10 kHz frequency (i) and the 400 Hz decrement variable (d). Afterward, check the plot result and find the first condition where e_{total}<0.8 on both data. In the last step, we compare the result with the peak obtained from the direct observation.

Fig. 3 shows e_{total} plot for data-1. While Fig. 7 and Fig. 8 display e_{total} plot for data-2, and data-3, respectively. Both figures show that the optimal frequency is discovered when the spotting method detects e_{total}<0.8 condition. The optimal frequency is validated after the iteration reaches 173 data samples on the data-2 and 150 data samples on the data-3. Thus, the proposed spotting method is successful in finding the optimal frequency without a time-consuming sweeping process.

Table III shows the error distance of the set of peaks found by the spotting method compared with the direct observation. The result shows that the accuracy of the proposed spotting method to find an optimal frequency (l_0) achieves a small error in frequency and a small difference in power. However, l_4 distance error is large since the peak shape in l_4 has short prominence proved with the peak width analysis in Table II. A frequency sweeping can be performed among the peak width on the discovered l_0 frequency to increase the accuracy to find the optimal frequency. Nevertheless, this process depends on the requirement, since on the experiment, the difference in power is small.

IV. CONCLUSIONS

Finding optimal driving frequency as fast and accurate as possible is essential in any WPT system to transfer much power over coils driven by the AC power source. This paper has proposed a spotting strategy to find the optimal frequency by the knowledge about how the WPT system responses if it is stimulated by a square wave input signal. The spotting method avoids a time-consuming sweeping process by using initial peak selections from the AMPD algorithm. From the experiment, our method finds and validates the optimal frequency using less than 180 sample data with 950 sampled data sweep from 5-100 kHz. The method has less than 1% error of the spotted optimal frequency compared with the correct optimal frequency. As further research, we are interested to enhance the spotting method performance by applying a robust pre-processing method and comparing it with different peak finding algorithms during the initial peak selections. Furthermore, the spotting method optimal frequency tracking and tuning could be implemented and evaluated with various conditions such as load, coil, and distance alteration in WPT.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The first author conducted paper writing, data acquisition, algorithm, and software implementation. The second author conducted data verification, formula derivation, algorithm improvement, paper verification, and validations. All authors had approved the final version.

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