Energy Conversion
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A Novel Target Detection Algorithm for Capacitive Power Transfer Systems

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***Abstract*—To mitigate standby power and safety issues, wireless power transfer system requires an algorithm to determine the presence of the target object. Even though various foreign object detection schemes have been investigated so far, such a study is still not so active for capacitive power transfer system. In this paper, we propose a method to detect the presence of the target object by monitoring the capacitance in the transmitter-side electrodes without adding additional distance or pressure sensors. This capacitance increases when the target object is completely aligned as compared with when separated. Therefore, the proposed method identifies the presence or absence of the target object by measuring the change in capacitance of transmitter-side electrodes using step pulse injection of micro controller unit. Verification has been made in two step processes. At first, performance of capacitance measurement has been compared with LCR meter. The performance of target receiver detection algorithm has been tested in a 5 W capacitive power transfer hardware. In our experimental set-ups, the inter-electrode capacitance increased 6 times when the target object was fully aligned and thus the proposed scheme successfully detected the presence of the target object.**

***Keywords*—Receiver detection method; capacitive wireless power transfer; capacitance measurement;**

I. Introduction

In wireless power transfer system, operation of the transmitter power circuit in the absence of receiver is a waste of standby power, and in the case of the capacitive power transfer (CPT), it can be dangerous because a voltage may exist between the transmitter electrodes. Particularly, as the scale of the system increases as in the e-vehicle charging, the waste of standby power and the risk become larger. Therefore, an algorithm should be implemented so that the transmitter circuit is turned on only when the receiver is located on a specific surface with the transmitter.

Several target detecting techniques have been presented in the literature [1]-[5]. Among them, analog ping in Qi standard is the most popular method usable only for the inductive power transfer (IPT) technology. It periodically injects a few cycles of sinusoidal current waveforms at a specific frequency into the primary coil to sense the receiver. Because the specific frequency is tuned to the resonant frequency of the primary network with no receiver coil, the resonant point of the transmitter resonant circuit shifts as the receiver coil approaches, which causes the magnitude of the primary current to become smaller, thereby detecting the receiver [1]. As this resonance shift technique requires the entire power stage to be energized regularly to detect the target object, the standby power is relatively high and may generate a periodic ticking sound. To resolve this issue, literature [2] proposed impulse injection method, where it senses the decay time in the transient waveforms of the injected current to detect the receiver. Other methods in [3]-[5], they use both the voltage and current information of the transmitter to determine the power transfer state or calculate the mutual inductance in real time. However, they all require auxiliary circuitry for current measurement, and sometimes increased computation burden is requested as in [4], [5].

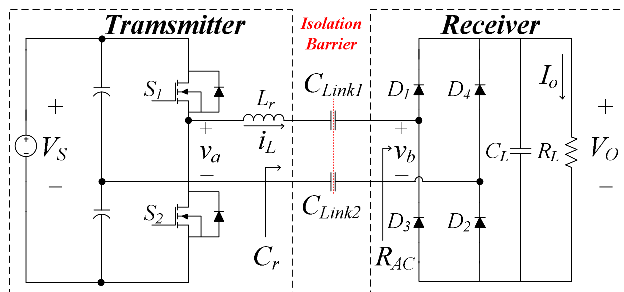


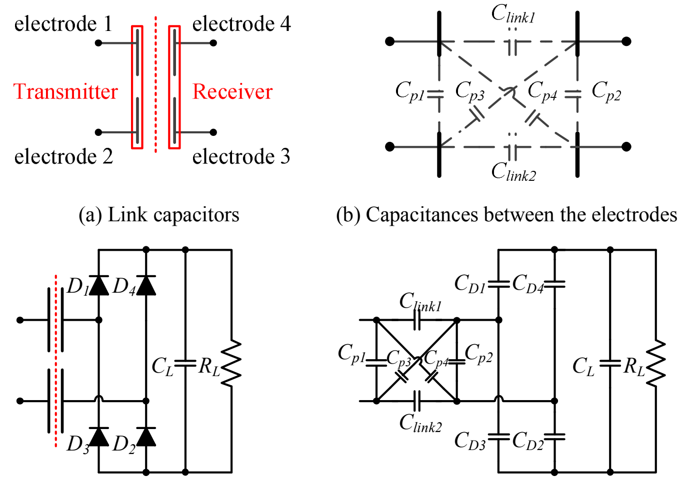
Fig. 1. A typical CPT system converter

As mentioned above, it is clear that even though various foreign object detection schemes have been investigated so far in IPT system, such a study is still not so active for capacitive power transfer (CPT) system. Therefore, this paper presents an effective target object detecting algorithm for detecting the receiver by monitoring the change in the capacitance between the transmitter-side electrodes in the CPT system.

II. Principle of Receiver Detection

A. Capacitive Wireless Power Transfer

CPT system contains electrodes in both a transmitter and a receiver, and performs wireless power transfer using the displacement current through the link capacitors [6]. Fig. 1 shows a half-bridge series resonant converter, one of the basic CPT system structures. Since the DC voltage cannot be passed through the link capacitors, the transmitter circuit converts the DC input voltage to the AC voltage through the switching of



(a) Link capacitors (b) Capacitances between the electrodes

(c) Link capacitors with receiver (d) Equivalent circuit of (c)

Fig. 2. Detailed circuit modeling of CPT link capacitors

the MOSFETs S_1 and S_2 and transfers the power through the link capacitors. In the receiving part, the DC voltage is recovered from the AC voltage through the full wave rectifying diodes D_1 to D_4.

B. Alteration of equivalent capacitance due to load presence

The CPT system forms two equivalent link capacitors by using four electrodes in the transmitter and the receiver, and transfers power through two opposing electrodes as shown in Fig. 2(a). These energy link structures are modeled by six different capacitors (C_{link1}, C_{link2}, C_{p1}, C_{p2}, C_{p3} and C_{p4}) including the cross coupling as shown in Fig. 2(b) [7], [8]. When the receiver is separated from the transmitter, the equivalent capacitance C_{eq} of the two electrodes 1 and 2 is equal to C_{p1} as shown in (1).

$$C_{eq(separated)} = C_{p1} \tag{1}$$

But if the receiver is fully aligned to the transmitter as shown in Fig. 2(c), the equivalent circuit seen from the transmitter is like Fig. 2(d), where C_{D1} to C_{D4} are the equivalent capacitances of the rectifying diodes, D_1 to D_4. In other words, the capacitors of the four electrodes ($C_{link1, 2}$ and C_{p1} to C_{p4}), the equivalent capacitors of the rectifying diodes (C_{D1} to C_{D4}), the output filter (C_L), and the load (R_L) are visible through the two electrodes of the transmitting part. Through measuring the equivalent capacitance seen from the transmitter electrodes, system can detect the presence of the receiver.

As will be described in the following paragraphs, if the step (pulse) voltage test is conducted to detect the receiver, the output filter C_L can be regarded as a short circuit because the output filter capacitance is much larger than the equivalent capacitances C_{D1} to C_{D4} of the rectifying diodes. Furthermore, in fully aligned condition, C_{link1} and C_{link2} is dominant, and thus C_{p3} and C_{p4} are negligible. Assuming that C_{D1} to C_{D4} are identical as C_D, and C_{link1} and C_{link2} have the same value as C_{link} , the equivalent capacitance C_{eq} seen from electrodes 1 and 2 is given by the series-parallel combination of C_{link}, $C_{p1,2}$ and C_D and thus is represented as (2). In this equation, the parallel symbol represents the calculation of the series capacitance, where || denotes a parallel resistance operator.

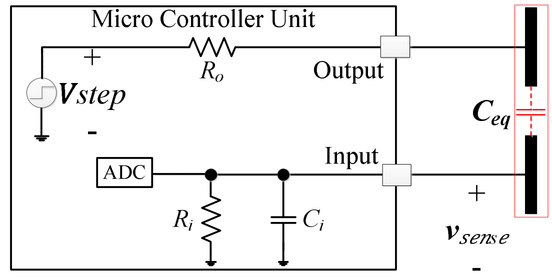


Fig. 3. Capacitance measuring circuit

$$C_{eq(aligned)} = C_{p1} + \frac{C_{link}}{2} \,||\, (C_{p2} + C_D) \tag{2}$$

C. Capacitance measurement by MCU

Fig. 3 shows the circuit in which the micro controller unit (MCU) measures the capacitance of transmitter electrodes. The output and the input port of the transmitter MCU are connected to the two electrodes, respectively. In the proposed method, MCU injects a step voltage (V_{step}) into the output node and read the v_{sense} value using analog to digital converter (ADC) of the input port. Because the MCU output and input port have the internal resistances and capacitances, the step response of v_{sense} shows the exponential decaying behavior with R-C time constant and is derived as (3) using the transfer function analysis. R_o is the internal resistance in the output port, R_i and C_i are the internal resistance and capacitance in the input ADC port of the general MCU. Generally, in the MCU, R_o is very small compared to R_i and can be omitted.

$$v_{sense}(t) = V_{step}\frac{C_{eq}}{C_{eq}+C_i}e^{-\frac{t}{R_i(C_{eq}+C_i)}} \tag{3}$$

Since the v_{sense} is read from the input port immediately after outputting V_{step}, the scaling coefficient of the exponential function in (3) is directly measured as the time axis value of the exponential function portion is taken as $t = 0^+$. By rearranging (3), the capacitance C_{eq} between the transmitter-side electrodes is obtained by (4). In (3) and (4), V_{step} is the height of the step excitation.

$$C_{eq} = C_i\frac{V_{sense}(0^+)}{V_{step} - V_{sense}(0^+)} \tag{4}$$

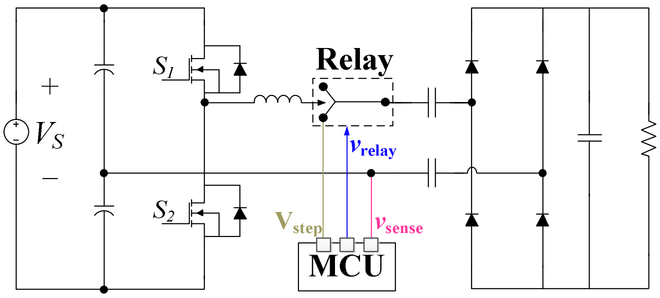


Fig. 4. CPT circuit with relay switch

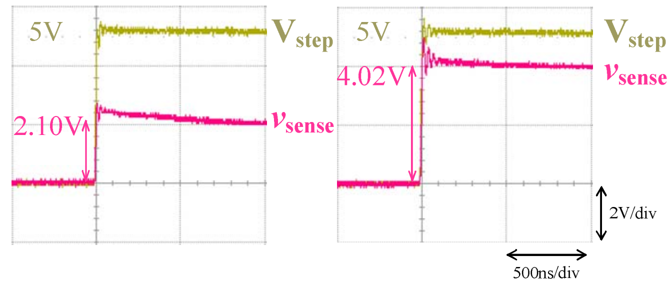


Fig. 5. Capacitance measurement waveforms by MCU v_{sense} in separation (left) and fully alignment (right).

To apply the proposed capacitance measurement circuit to the CPT system, the MCU must be disconnected from the transmitter electrodes when the power transfer circuit is in operation. Fig. 4 shows how the proposed capacitance measurement method is applied to existing CPT circuits connecting the MCU to the front of the transmitter electrodes using the relay switch.

III. VERIFICATION WITH PROTOTYPE HARDWARE

A. Comparison of measurement results between MCU and LCR meter

In order to study the feasibility of the proposed detection method, variation in the equivalent capacitance value according to the receiver position has been cross-checked by MCU method and LCR meter. The lateral dimension of the transmitter electrodes 1, 2 and receiver electrodes 3, 4 used for hardware verification is 13 cm x 9.5 cm and 13 cm x 9.0 cm, respectively. In the experiment, glass (dielectric constant $\varepsilon_r = 3$, separation distance of 1.60 mm) was inserted between the electrodes as an energy link medium to increase the link capacitance.

Using LCR meter (Agilent, 4263B), the capacitance of C_{p1} and C_{p2} were measured as 10 pF and 5 pF, respectively, and the C_{link} was calculated as 274 pF by measured $C_{link1,\,2}$. C_D was obtained 550 pF through the Schottky diode (STMicroelectronics, STPS5L40) datasheet. [9] This junction capacitance, C_D was obtained assuming that the reverse voltage of the diode was zero. Resultingly, $C_{eq(separated)}$ and $C_{eq(aligned)}$ have been calculated to be 10 pF and 120 pF by (1) and (2), and measured to be 10 pF and 110 pF respectively.

To verify the proposed MCU capacitance measurement method, the capacitance of C_{eq} was measured using an MCU by (4). The MCU used in the hardware implementation is ATMega328P, and the equivalent circuit parameters in Fig. 3 of this MCU are $R_o = 50\ \Omega$, $R_i = 100\text{M}\ \Omega$ and $C_i = 24$ pF [10]. Calculated capacitances by MCU are 17 pF and 98 pF, respectively, when the receiver is separated and fully aligned. Fig. 5 shows the measured waveforms of V_{step} and v_{sense}. The capacitances of 17 pF and 96 pF were calculated by the measured $v_{sense}(0+)$ of 2.10 V and 4.02 V, respectively.

B. Receiver detection flow chart

According to the above observation, the MCU can determine the presence or absence of the receiver by the alteration of the v_{sense}. In the standby state, the two electrodes of the transmitter are connected to the MCU, not the power transfer circuit by the relay switch in Fig. 4, and the MCU continues to measure the capacitance. When the v_{sense} is above the threshold voltage due to the capacitance increase in the presence of the receiver, the relay is operated to stop the measurement and start power transfer. The threshold voltage is determined by the degree of misalignment at which the CPT system can be driven.

Figure 6 is an algorithm flowchart of the receiver detection procedure of the MCU. The algorithm begins by outputting V_{step} to one of transmitter electrode. To utilize (4), $v_{sense}(0+)$ is measured immediately from the other transmitter electrode, and the output port is reset to 0 V after the measurement process. C_{eq} can be calculated through the measured $v_{sense}(0+)$ and (4). If C_{eq} is lower than $C_{threshold}$, the measurement procedure will restart after a ping interval, T_{ping}. The threshold level, $C_{threshold}$ is determined by threshold voltage, as mentioned in the above paragraph. If C_{eq} is larger than $C_{threshold}$, the algorithm confirms the receiver is aligned enough to transfer power and determines that power transfer is ready. Then, the transmitter power circuit is operated and relay switch disconnects the connection between the MCU I/O ports and the transmitter electrodes. After performing the power transfer for a refresh period, T_{on}, the transmitter power circuit is briefly turned off , go back to the beginning of the algorithm and repeat the process. to detect again the receiver status.

C. Hardware test result

For hardware verification, a 5 W wireless power system has been built. The operating frequency of the half-bridge inverter is 429 kHz. Fig. 7(a) and (b) are experiment waveforms when the receiver is separated and when it is fully aligned, respectively. In Fig. 7(a), the receiver is detected every ping interval, where the experimental hardware programmed T_{ping} to 100 msec. The shorter this time is, the faster the receiver will be detected, but the standby power consumption will increase. The v_{relay} waveform which shows power stage turn on status is kept at low (off) as it is in the separated condition. Fig. 7(b) shows waveforms in which the MCU repeatedly detects the receiver when the receiver is fully aligned. After every predetermined time (T_{on}), the transmitter suspends the power transfer, and then detects the receiver availability again. Stopping power transfer for a short period of time to detect the receiver may be a problem without a filter or a battery, but is not a big problem if it is not.

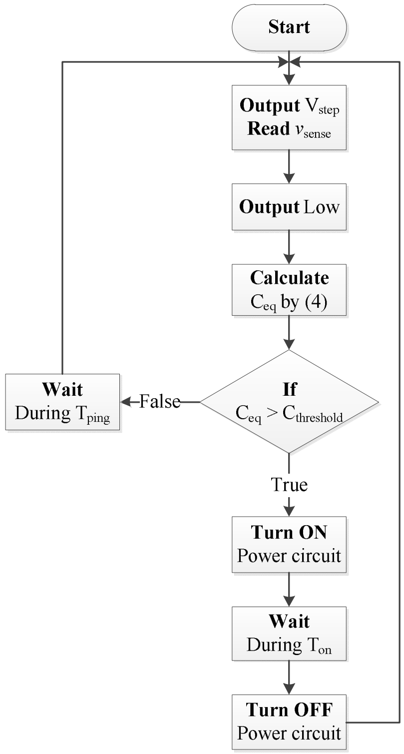


Fig. 6. Receiver detection flowchart

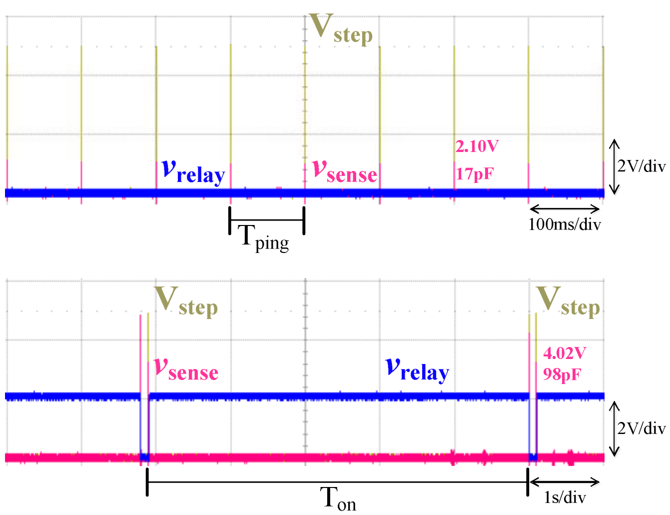


Fig. 7. System operation waveforms

in separation (upper) and fully alignment (under)

IV. CONCLUSION

In this paper, an algorithm to detect the presence of the receiver has been presented for CPT system. It injects a step voltage into the transmitter-side electrode to monitor the changes in inter-capacitance. As the proposed method can be easily integrated into the digital PWM controller with A/D converter existing in the transmitter and does not require auxiliary sensing circuit, it is simple to implement and thus can be a low cost alternative of the conventional method with current sensors or position sensing circuitry. This method is especially useful for wake-up process with minimized stand-by power and also for monitoring the degree of partial alignment of the energy link structures, which will be essential for advanced power flow control in CPT system.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant founded by the Korea government (MSIP) (No. 2017R1A2B4005488). The authors have patented this scheme in [11].

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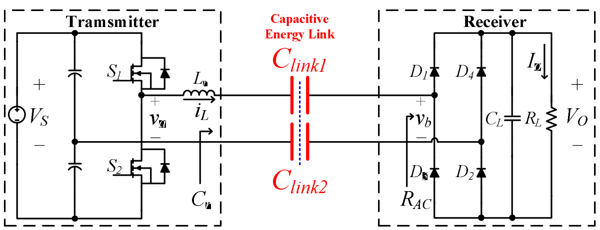
I. Research Motivation

- In wireless power transfer (**WPT**) system, it is waste of standby power to drive the transmitter when there is no receiver.
- Especially in the case of capacitive power transfer (CPT), it can be dangerous because there is a voltage between the transmitting electrodes when the transmitter is turned on.
- In case of the scale of the system increases, the waste of standby power and the risk become large.
  - ➢ An algorithm should be implemented so that **the transmitter circuit is turned on only when the receiver is placed on a transmitter.**



II. Conventional and Proposed Methods

❖ Conventional Methods

① Qi standard: In inductive power transfer, it periodically injects a few cycles of sinusoidal current waveforms at a specific frequency. Since the resonant frequency of the transmitter shifts when the receiver coil is present, the injected current is lowered and the receiver is detected by sensing the current.

② Impulse injection method: It senses the decay time in the transient waveforms of the injected current to detect the receiver. (Ref. [2] in the paper)

③ Power flow estimation: To determine the power transfer state or to calculate the mutual inductance it senses both voltage and current. (Ref. [3] – [5] in the paper)

❖ Proposed Method

- The conventional methods require auxiliary circuitry for current measurement. And power flow estimation method increase computation only for receiver detection.
  - ➢ **The proposed method detects the receiver through the capacitance alteration between two electrodes of the transmitter.**
  - ➢ It measures capacitance through voltage sensing and it is simple and low cost because only existing the voltage I/O terminal and the ADC are used.

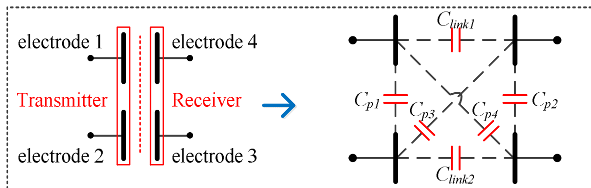
III. Principle of Receiver Detection

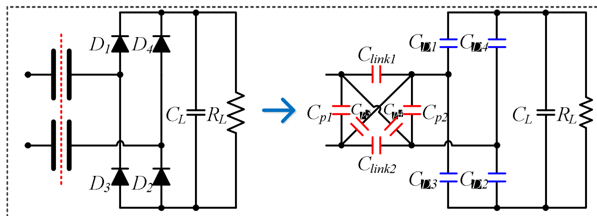
❖ Capacitive Wireless Power Transfer

- CPT system performs wireless power transfer using the displacement current through the link capacitors.
  - ➢ **The receiver is detected by the circuit structure of CPT.**

❖ Alteration of Equivalent Capacitance due to Receiver Presence

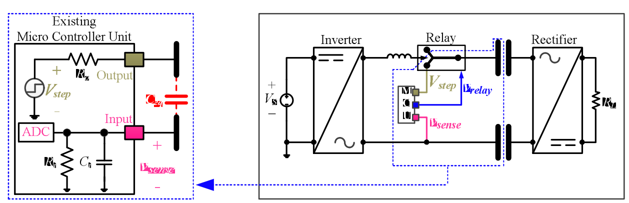
- Link capacitors are modeled as shown in the following figures.





- ➢ When the receiver is separated, the equivalent capacitance seen by the transmitter electrodes is $C_{eq(separated)} = C_{p1}$.
- ➢ In the case of aligned, $C_{eq(aligned)} = C_{p1} + (C_{link}/2) \parallel (C_{p2} + C_D)$.

❖ Capacitance Measurement by MCU



- The output and input ports are connected to two electrodes.
  - ➢ **In the MCU, V_{step} is applied and v_{sense} is read by the ADC immediately to measure the capacitance.**

$$v_{sense}(t) = V_{step}\frac{C_{eq}}{C_{eq}+C_i}e^{-\frac{t}{R_i(C_{eq}+C_i)}} \longrightarrow C_{eq} = C_i\frac{V_{sense}(0^+)}{V_{step}-V_{sense}(0^+)}$$

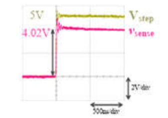
- ➢ When the power transfer circuit is operating, the MCU must be disconnected from the transmitter electrodes.

IV. Verification with Prototype Hardware

❖ Comparison of Capacitance Measurement Results between MCU and LCR Meter

- Size of transmitter (receiver) electrodes : 13cm x 9.5 (9.0)cm.
- Measurement results of LCR meter and MCU.

	LCR Meter	MCU
C_{eq} (separated)	10pF	17pF
C_{eq} (aligned)	110pF	98pF



Measurement waveforms of MCU

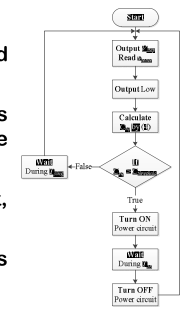
❖ Receiver Detection Flow Chart

① Algorithm begins with output V_{step} and immediately reads v_{sense}.

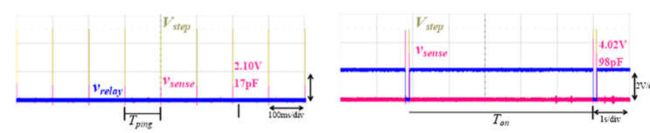
② MCU calculates capacitance of electrodes (C_{eq}) and determines the presence of the receiver by comparing with $C_{threshold}$.

③ If present, drive the power transfer circuit, otherwise re-measure capacitance again.

④ During power transfer, the capacitance is remeasured at preset time (T_{on}) intervals.



❖ Hardware Test Results



(a) in case of separation (b) in case of alignment

V. Conclusion

- **An algorithm to detect the presence of the receiver has been proposed for CPT system.**
- **The presence of the receiver is detected by the capacitance alteration of the transmitter electrodes** caused by the CPT's link capacitors.
- It uses only basic functions such as general MCU input and output to detect the receiver and does not require auxiliary current sensing, additional sensors or complex operations.
- This method is useful for wake-up process with minimized stand-by power and also for monitoring the degree of partial alignment of the energy link capacitors, which will be essential for advanced power flow control in CPT system.