The Development of Wireless Power Transfer Technologies for Low Power Applications: An Acoustic Based Approach

S. Saat, N. F. Mokhtar, T. Zaid, Z. A. Ghani, A. A. Isa, A. M. Darsono, Y. Yusop, F. K. A. Rahman, S. H. Husin, M. S. M. Isa, M. S. I. M. Zin
Faculty of Electronic and Computer Engineering (FKEKK)
Universiti Teknikal Malaysia Melaka (UTeM), Malaysia
shakir@utem.edu.my

***Abstract*—Wireless power transfer (WPT) is the transmission of electrical power across a medium without the use of electrical conductors. This paper aims to transfer low power wirelessly by using acoustic based method. The feasibility of transmitting electric power through some specific surface or material by propagating acoustic waves using piezoelectric transducers was analyzed here. The efficiency of power transmission for Acoustic power transfer (APT) has been briefly examined for different transmission medium. For this paper, the air and metal block were chosen as the transfer medium and the efficiency performance of these medium have successfully been analyzed. At the end, a prototype of APT system was developed which was capable of transferring voltage through air at the maximum distance of 10cm at 0.96V. The prototype of APT system with metal medium had also been completed but it failed to transmit the power due to unsuitability of transducer used.**

***Index Terms*— Acoustic Power Transfer (APT), Class E Converter, Air medium, Low power applications, Metal medium, Piezoelectric.**

I. INTRODUCTION

Nowadays, the wireless power transfer (WPT) systems are widely developed and attracted so many attentions from researchers in the field [1]. The purpose of WPT is to supply mobile devices with electrical energy due wirelessly and therefore it will eliminate the use of cables, connectors and/or slips-rings. This will increase reliability and maintenance-free operation of such a critical system such as in biomedical, aerospace, multisensory and robotic application [1]. The most popular use technique in WPT for power transfers are inductive power transfer (IPT), capacitive based power transfer (CPT) and lastly acoustics based power transfer (APT). These techniques are divided according to the method used to transmit the power from transmitter to receiver. There are some other techniques beside the IPT, CPT and APT which are light-based power transfer, optical coupling, and far-field electromagnetic (EM) coupling [2], [3].

The main issue of IPT is it cannot be possible to be used in metal environment because its working principle is based on the electromagnetism. Hence, metal environment will definitely degrade performance of IPT. But, CPT, on the other hand, can overcome the problem efficiently because the power is transmitted in the form of electrical energy. However, the main limitation of CPT is the performance is degraded significantly when the distance is increased. This leads to unsuitability of applying the method for applications that require a larger distance of transmitter and receiver (load). Therefore, this paper focuses on the APT as its ability to overcome all those previous mentioned problems that were experienced by IPT and CPT. The acoustic power transfer technique uses sound waves to propagate power without relying on the electrical contact. A transmitting transducer converts electrical energy into a pressure wave that propagates through a medium, i. e air and metal. A receiving transducer is positioned at a point along the path of the sound wave for the inverse process of converting the motion caused by the sound wave into electrical energy. The medium can be anything ranging from air to human tissue or a solid wall; in principle, any material that will propagate a pressure wave will do [2],[3]. The basic structure of an APT system is shown in Figure 1.

In this paper, the main objective is to analyze APT system at the two different medium which are through air and through metal wall. In this work, the paper is structured as follows; Section II consists of methodology for developing APT system. Section III describes experimental results of developed APT system. Lastly, section IV provides the conclusion of this work.

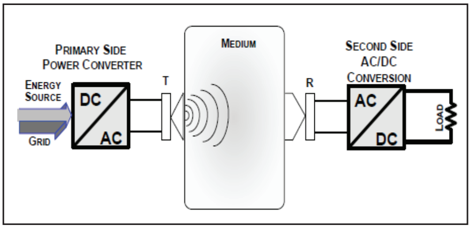

Figure 1: The basic principle of APT system

A. *Acoustic Power Transfer (APT) System.*

The APT system has it owns features and advantages in comparison to the IPT and the CPT. First, any given dimensions of the transmitter and receiver, the frequency used in the APT system can be a factor indicating the propagation speed of EM and acoustic waves in air, respectively smaller than that of IPT for the same directionality. Consequently, the losses in the power electronic converter can be lower [2]. Secondly, the APT system can be used where the EM fields are not allowed [2],[3]. Thirdly, the APT system have smaller system dimenstion when high directionally is required. Lastly, the efficiency of the APT system is less than IPT ones, but, when the distance between the transmitter and receiver is much larger than their radii, the efficiency of the APT system can be much more higher [1-3].

Acoustic energy in its purest form is used in various applications, such as ultrasonic cleaning, medical ultrasonography, nondestructive testing, distance measurement. Example like sonar, therapeutic ultrasound, and ultrasonic welding. These applications are different from APT system in that they directly use the acoustic energy to achieve a specific goal, without converting it back to electrical energy [3].

The APT system are somehow related to the piezoelectric energy harvesting and piezoelectric transformers. Energy harvesters make use of available (vibrational) energy to generate electricity and could be considered to be a nondriven APT system. Piezoelectric transformers convert electric energy into vibrations, with the inverse process taking place at the secondary side and this is the essence of APT system itself. However, it lacks the spatial separation of the transmitter and receiver that is desired for a WPT system [2],[3], [11-15].

B. APT System through Air Medium.

The advantages of APT in comparison to IPT based on the EM field can be found in the much lower propagation speed of acoustic waves in air Cair with respect to the electromagnetic propagation velocity Cem [3].

As the result in previous studied, the frequencies used by the APT are a factor of Cem or Cair are less significant for a particular wave length. So, the losses in the driving power electronics can be maintained much lower. The design of the electronics can be kept considerably simpler. The APT has obviously also leave gaps that are to be filled in, such as application of APT for air medium as well as the accompanying constraints posed by the medium, analytical derivation of an upper limit on the attainable efficiency, near field calculations, parameter optimization, greater distances (meters, instead of centimeters), higher power (tens to hundreds of Watts, instead of mill watts), beam steering and focusing, and others [4].

The APT uses a radiative field for transferring power. The power transfer has to be collected at the surface of receiver transducer. Any part of the sound wave that is not captured radiates out into space and thus can be considered as a form of loss. Of course, the power transfer will be in optimal if the sound waves are focused into a narrow beam. However, diffraction at the edges of objects, such as the piston itself prevents a truly perfect focus [4]. All of these elements will definitely lower the efficiency of such APT system.

C. APT System Through A Metal Wall.

There actually are situations whereby one would want to transfer energy wirelessly via a metal wall, i. e. sensors in nuclear waste containers, gas cylinders, vacuum chambers, pipelines, etc. The metal wall of such type of an enclosure contains a shielding or protection effect that limits the coupling of WPT system, and eddy currents in the wall cause high losses [3].

High output power levels and also efficiencies are more convenient to obtain with AET through a metal wall than through air or tissue, due to the similarity in acoustic impedance between the wall and piezoceramic material (approximately 45 Mrayl for steel and 30 Mrayl for Piezoelectric transducer). An effective match in impedance indicates little reflection and optimal power throughput (identical to the situation that occurs in transmission lines with different characteristic impedances). In [9], a through-wall APT system is described and capable to transfer power of 50Watt with 51% efficiency. Bao et al. [8] even managed to transfer more than 1 kW at efficiency of 84% by using a pre-stressed piezo actuator.

D. Power Converter of APT System.

The power converter in this work is used to convert from DC voltage or current to AC voltage or current. To ensure the effectiveness of the power transmission, the frequency of converted AC source needs to be high enough [16]. In this paper, two types of converter will be discussed; 1. Push-pull converter, and 2. Class-E converter. The working principles of each converter are highlighted respectively. Both converters use a power MOSFET as a switch in the circuit. The MOSFET is a voltage-controlled device. The MOSFET has two state; first, when the MOSFET is “ON” and secondly when the MOSFET is “OFF”. When the MOSFET is “ON” state at the gate-source voltage (V_{gs}), the appropriate magnitude is being supplied continuously to gate. While the MOSFET is in “OFF” state, the MOSFET is relatively as a closed switch when the gate source voltage is lower than the threshold voltage [16]. It does not have any gate current flows, except throughout the transition swapping from “on” to “off” or other way round, which the gate capacitance is being charged or discharged. On top of that, the switching times are quite short which can reduce the switching losses in the converter circuits

II. METHODOLOGY

A. Push-Pull Power Converter Circuit

The Push-Pull converter is designed using 555 Timer IC and simulated by using Multisim software. Simple circuit design for Push-Pull inverter is as shown in Figure 2. Here, IFR7404 as the P-channel while IRF540 as the N-channel MOSFET. The complete push-pull circuit is simulated.

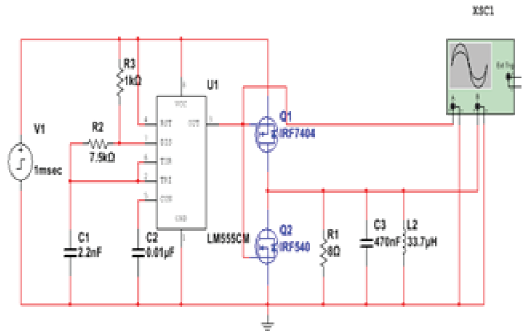

Figure 2: Push-Pull converter design circuit

In order to achieve the frequency, f of 40 kHz (the operating frequency of the system), the following equations are used with VGS is ±20V and required load resistance, value RDS is 44 mΩ [13].

$$f = \frac{1.44}{(R1+2R2)C} \quad (1)$$

$$f = \frac{1}{T} \quad (2)$$

To find the respected value of 50% duty cycle, the following formula is used [13].

$$\text{Duty cycle} = \frac{R2}{R1+2R2} \text{ x } 100\% \quad (3)$$

B. *Class E Resonant Power Converter Circuit*

The Class-E converter is designed and also simulated by using Multisim software. Simple circuit design of Class-E converter is shown in Figure 3. An IRC530 is used in designing class-E.

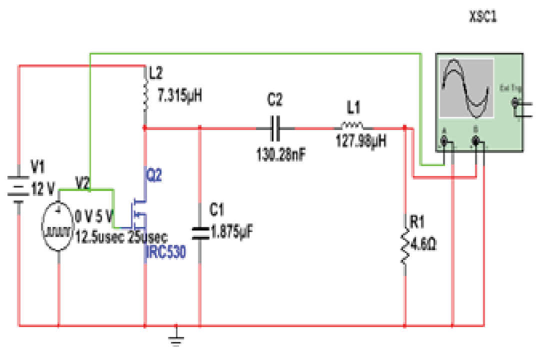

Figure 3: Class-E converter design circuit

This Class-E Converter circuit is designed to obtain frequency of 40 kHz. The Class-E Converter circuit as shown in Figure 3 is designed based on the following specification; the input voltage, V_{in} ± 9V, the maximum output power, Po is assumed to be 3W, duty cycle is 50% and the operating frequency, f_0 is 40 kHz. The analysis is then carried out as follows (The details are omitted here because it can be found in [6]). To find frequency at the ON state of gate, we use

$$f_{o1} = \frac{1}{2\pi\sqrt{LC}} \quad (4)$$

To find frequency at the OFF state gate, the equation is given as follows:

$$f_{o2} = \frac{1}{2\pi\sqrt{LC_{eq}}} \quad (5)$$

Furthermore, the equivalent capacitance is calculated as follows:

$$C_{eq} = \frac{C \times CS}{C+CS} \quad (6)$$

For frequency to remain the same at both gate states,

$$f = f_{o1} = f_{o2} \quad (7)$$

Therefore,

$$C = C_{eq} \text{ , } C >> CS \quad (8)$$

By using optimum design formula, the components value of the frequency used in class-E Converter, choke inductor, shunt capacitor, load resistance, series inductor and series capacitor can be determined by using the formula as given in [6], where, resistance, R1 can be determined as:

$$R1 = \frac{0.5514\, Vin^2}{Po} \quad (9)$$

Next, the shunt capacitor, C_{shunt} value that is connected in parallel with the switch can be determined as follows:

$$C_{shunt} = \frac{0.1971}{\omega R1} \quad (10)$$

where ω is resonance frequency. At the same time, the series resonant inductor, L_{series}, series capacitor, C_{series} and choke inductor can be determined, as follows:

$$L_{series} = \frac{QR}{\omega S} \quad (11)$$

$$C_{series} = \frac{1}{2\pi f\ (QR - 0.3533R)} \quad (12)$$

$$L_{choke} = \frac{0.4001R}{2\pi f} \quad (13)$$

where Q is a quality factor and must be greater than 7 to achieve an optimum result. Therefore the value of capacitance are equally are same as equivalent capacitor,

$$C = C_{eq} \text{ , } C >> CS \quad (14)$$

C. Rectifier Circuit

At the transducer receiver, the parameter obtained is the power received in AC voltage form. These powers received require to be rectifying from an AC to DC voltage to ensure that it could be supplied to the load. The schematic diagram is shown in Figure 4.

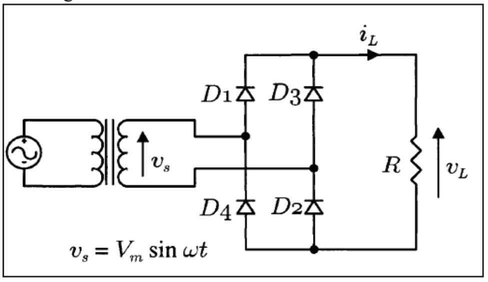

Figure 4: Schematic diagrams of Rectifier circuit design [13]

III. EXPERIMENTAL RESULTS

A. Experimental Result of Push-Pull Power Converter

The experimental result for push-pull converter is shown in Figure 5.

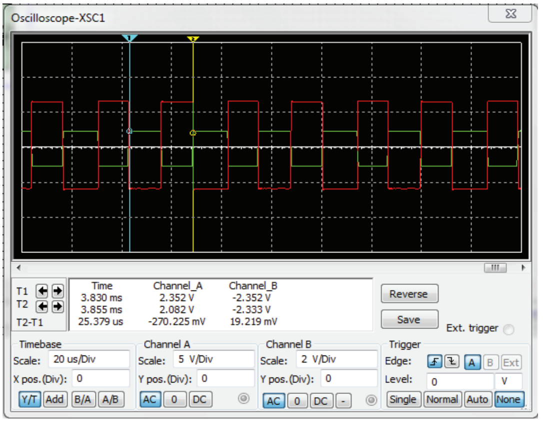

Figure 5: Oscilloscope output at f = 40 kHz (Ch. A – VGS, Ch. B – Output)

From the figure it is obvious that the zero voltage switching is successful achieved and the duty is around 46.88% which is much closed to the calculation value.

B. Experimental Result of Class-E Power Converter

From the optimum design formula that is discussed in Section II and by assuming the value of output power value is 3 watt and Q factor is more or equal to 7, the following parameters are obtained and will be used for designing Class E converter.

Table 1
Circuit Parameters of Class E Resonant Power Converter Circuit

Design Specification	Calculated
Supply voltage, V	5v
Operating Frequency, f_0	40kHz
Resistance, R1	4.6Ω
Shunt Capacitor, C_{shunt}	1.875 μF
Series Capacitor, C_{series}	130.28 μF
Choke inductance, L_{choke}	7.315 μH
Series Inductance, L_{series} $\mathbf{L_{series}}$	127.98H

The output voltage is shown in Figure 6. In comparison with result shown in Figure 5, the Class E result is better in term of power losses because it only uses one MOSFET instead of two and therefore the ZVS is easier to be obtained. Due to this, the Class E converter will be used in our design here to develop APT system.

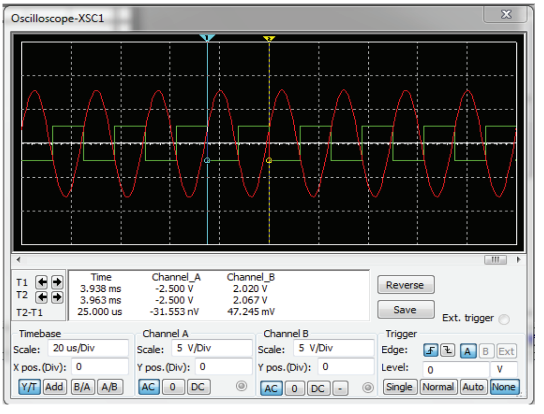

Figure 6: Oscilloscope output at f = 40 kHz (Ch. A – VGS, Ch. B – Output)

C. Result of Zero Voltage Switching (ZVS)

This section is now only focuses on the Class E circuit as the push-pull does not provide efficient solution. In the Class-E circuit, an oscillator is needed to generate pulse and feed it to the gate of the MOSFET. To be able to drive the MOSFET, the output from the oscillator must be at the minimum value of the current and voltage to enable MOSFET to operate. After the MOSFET is triggered, the results of the ZVS condition and the output of the resonant tank are determined and recorded, respectively.

The ZVS requirement is absolutely needed in Class-E convertor in order to ensure the switching losses are minimized and therefore ensuring a better efficiency of overall APT system. Generally, if the components in the resonant circuit are selected effectively, the switch (MOSFET) would switch at the zero voltage. To determine the ZVS result, the PIC 16F877A circuit is used to trigger the MOSFET of Class-E circuit. This is shown in Figure 7.

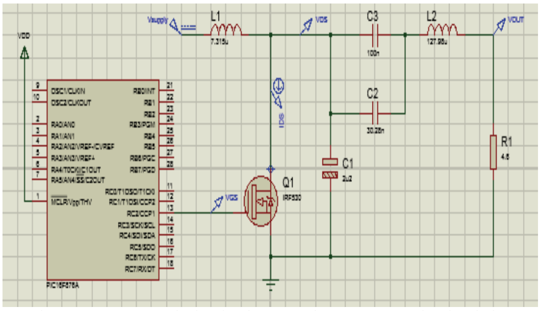

Figure 7: Constructed Circuit Class-E and PIC 16F877A in Simulation

From the resulted signal waveform, the ZVS is achieved with the calculated value of the component of the Class-E power converter. In the Figure 8, the green waveform represents the voltage gate-to-source (V_{GS}), the red waveform represents the voltage drain source at the MOSFET (V_{DS}), the blue waveform represents the voltage output (V_{out}) and the turquoise waveform represents the current at the drain source at the MOSFET (I_{DS}). The value simulated of the VDS, V_{out}, IDS and VGS are shown in Table 2.

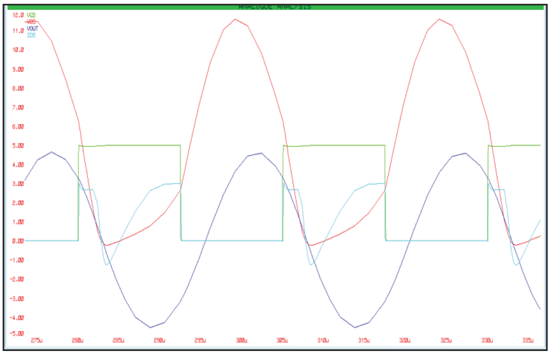

Figure 8: ZVS condition for Class-E circuit

Table 2
Simulated values of Vds, Vout, Ids and Vgs.

Characteristic	Value
Voltage Output, V_{out}	4.6 V
Voltage Gate-To-Source, V_{GS}	5.0 V
Voltage Drain Source, V_{DS}	11.7 V
Current Drain Source, I_{DS}	3.0 A

D. APT System through Air Medium

The measurement of the AC voltage output from transmitter to receiver is taken as shown in Figure 9. The measurement is done from the distance of 1cm to 10cm. The allignment of transducer must be positioned perfectly to ensure the wave is propagating well. If transmitter transducer and receiver transducer are not in the straight line position, then, the signal cannot be transmitted to receiver. This situation is happening because of ultrosonic transducer is propagating the ultrasonic wave signal as same as the light beam wave signal. It only can be refracted, focused and reflected if the angle other then in 90 degree. Ultrasonic waves travel in a straight line and at a constant speed until they encounter a surface or at a greater distance.

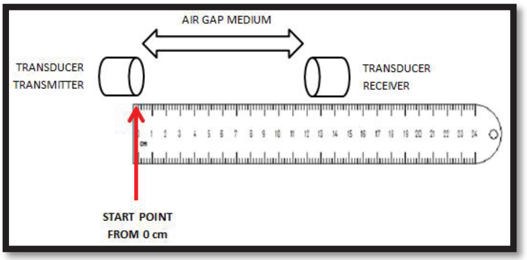

Figure 9: Point to point different measurement taken

Table 3 shows output voltage at different distance. This is then plotted in Figure 10.

Table 3
Output voltage measured value by distance

Point	Distance (cm)	Voltage (V)
1.	1.0	2.61
2.	2.0	2.53
3.	3.0	2.37
4.	4.0	2.17
5.	5.0	1.97
6.	6.0	1.69
7.	7.0	1.45
8.	8.0	1.29
9.	9.0	1.01
10.	10.0	0.96

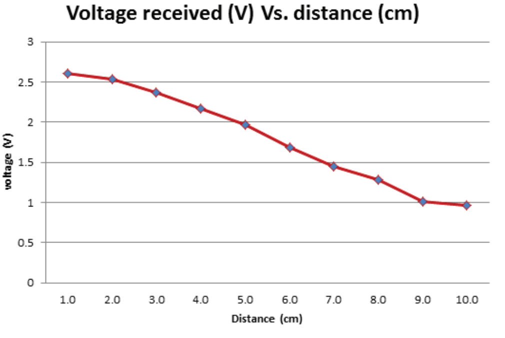

Figure 10: Graph voltage received (V) versus Distance (cm)

E. APT System through Metal Block

The metal block is chosen as a second medium to be experimented here. In specific, the material used is aluminum that consists of acoustic impedance characteristic, Z value of 40.6. Aluminum material is one of the materials with higher characteristic acoustic impedance than other materials such as shown in Table 4.

Table 4
Characteristic Acoustic Impedance Metal Materials.

Material	V1	ρ	Z
Alumina	10520	3.85	40.6
Aluminum rolled	6420	2.70	17.33
Beryllium	12890	1.87	24.10
Germanium	5410	5.47	29.6
Iron cast	4600	7.22	33.2
Magnesium	5800	1.73	10.0
Lead	2200	11.2	24.6
Silver	3600	10.6	38.0
Tin	3300	7.3	24.2
Zinc	4200	7.0	29.6

*Vl=longitudinal sound velocity [m/s]
*ρ =density
*Z = acoustic impedance [MRayls=(kg/(sxm2)x106]

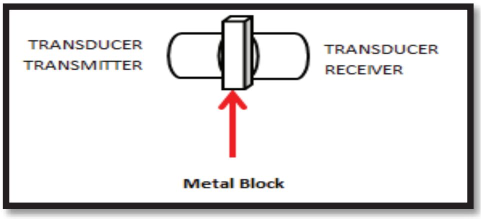

Figure 11: Positioning Of Metal Block between Transducer Transmitter And Receiver

Figure 11 shows how we positioned the transmitter and receiver with metal block as a medium. Safelon tape is used on the surface of the metal block to prevent from occurring short circuit between two transducer with metal block. Both of the transducer must be attached very close to the surface of the metal block without having any air gap between two transducer. This process is done to prevent the occurrence of any reflected and reafraction of the acoustic waveform signal produced by the transducer transmitter. The measurement of the AC voltage output from the transducer receiver is taken after the metal block position. The resulted measurement after the metal block taken at the oscilloscope shown in Figure 12.

As the result shows in Figure 12, the voltage value after metal block cannot be obtained. The voltage values from the oscilloscope were in error stage. This situation happens due to some aspect like inappropriate use of the types of transducer, matching impedance mismatch between the transducer and the metal block and environmental conditions around.

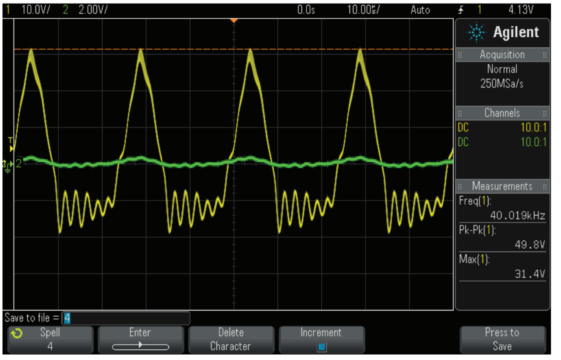

Figure 12: Oscilloscope Result Taken After Metal Block At The Transducer Receiver

IV. CONCLUSION

The APT system with air medium and metal medium has been completed in this work. However, only APT system through air medium managed to transmit power. The APT system through metal block failed to transmit power due to inappropriate type use of transducers (both at transmitter and receiver). On top of that, the Push-Pull and Class E converter has also been designed in this work. Future works are; 1. Improve efficiency of developed APT system by designing a better Class E converter as the current one has a problem of variation in ZVS condition when transmitting, 2. Properly select the perfect type of transducers to be used for metal medium.

ACKNOWLEDGMENT

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