The design of inductive power transfer system for fish aquarium using class-E inverter and LCCL impedance matching

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ABSTRACT

Nowadays, the accessories in fish aquarium systems such as water pump, internal filter, and LED light are powered using cables. This will cause to safety issue such as tangled wire, and risk of electric shock. Therefore, this work aims to design a wireless power transfer system to power up the fish aquarium' accessories wirelessly without require any physical connection between source and loads. To be more specific, inductive power transfer (IPT) is used instead of capacitive power transfer (CPT) due to high efficiency ability owned by IPT. Class-E inverter circuit is proposed in this paper to convert DC to AC at nearly 100% efficiency. The inverter provides a low switching loss which is important as the circuit operates at high frequency, 1 MHz operating frequency. Furthemore, LCCL impedance matching circuit is added into receiver part of the system to enhance the efficiency of overall circuit. The analyses were done based on the distance between the coils and the misalignment of the coils against the output power and efficiency. The developed prototype is supplied by 24 V DC and capable to deliver 5 W power. The overall efficiency of the prototype is 87.81%.

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1. INTRODUCTION

Wireless power transfer (WPT) is a transmission of electrical or electromagnetic energy from a power supply to a load without using wires [1]-[3]. WPT makes the movement of devices become more flexible. Basically, WPT consists of transmitter that is connected to the DC supply, which converts the power to a time-varying electromagnetic field or electric field, and receiver which receives the power and convert it back to DC or AC electric current used by an electrical load. Figure 1 is a typical structure of a WPT system [4]. Basically, there are three types of the WPT which are acoustic power transfer (APT) [5], [6], capacitive power transfer (CPT) [7]-[9] and inductive power transfer (IPT) [10]-[12].

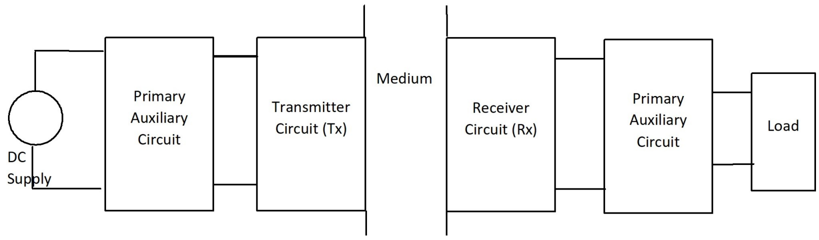


Figure 1. Common block diagram of wireless power transfer system [4]

Capacitive power transfer (CPT) utilises electrical field in transferring the power to the loads, meanwhile, inductive power transfer (IPT) uses magnetic field to transfer power to loads. This provides a more convenient to CPT in order to transfer power especially in a metal environment due to its ability to penetrate the metal shielding environmet and IPT has a weak anti-interference ability [4], [13], [14]. However, the CPT system is a very challenging to be designed and always produces a low output efficiency. This is true as normally CPT system requires one to use a very small coupling capacitance (normally in nanofarad or picofarad) to realise the system in real applications. Therefore, the system requires a high quality factor and hence make the system very sensitive to the parameter variations. This provides a main advantage in applying IPT system to the real system applications rather than CPT system [15], [16]. Figure 2(a) shows the structure for CPT and Figure 2(b) represents the IPT system, respectively [17].

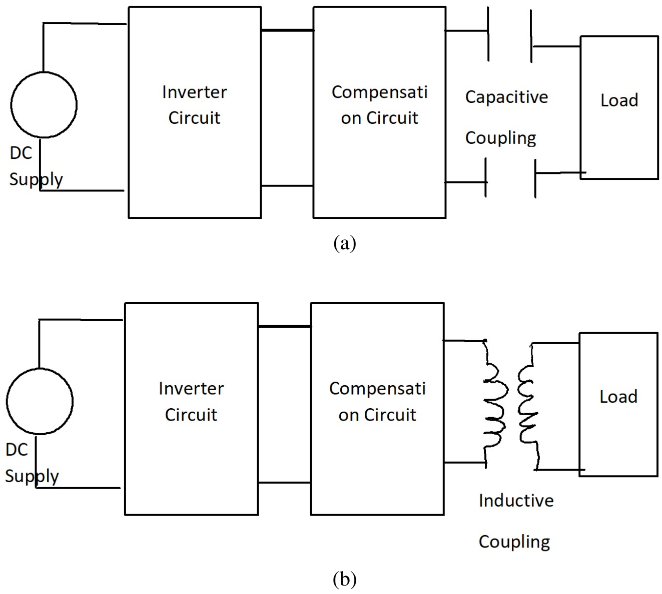


Figure 2. The common structure of CPT and IPT (a) CPT system and (b) IPT system [17]

Class-E inverter consists of a single switching element and has huge power handling capability compared to other type of inverters. The class-E inverter can generate large currents at high frequency in the range of kilohertz to megahertz. The main function of the class-E inverter is to reduce switching losses even at high frequency. It can achieve a theoretical 100% power efficiency by achieving zero voltage switching (ZVS) and zero-voltage derivative switching (ZVDS) [18]-[21]. Generally, the misalignment of the coils in IPT system will cause the overall efficiency of the system decreases significantly and therefore the ouput power drops proportionally [22]-[24]. On top of that, the class-E inverter will require less heat sinking and consume less power and therefore having lower manufacturing costs [25]. The contribution of this paper can be explained as: i) this work focuses on the design of an inductive power transfer system for fish aquarium system based on class-E inverter with copper coils act as inductive coils and ii) the efficiency of the proposed IPT system is improved with the introduction of LCCL impedance matching circuit.

2. RESEARCH METHOD

Transmitter and receiver are the most important part in this work and it can be shown as Figure 3. Transmitter module will transfer the power to receiver wirelessly through magnetic field. The class-E inverter will invert a constant DC voltage supply which received by transmitter into AC voltage supply. MOSFET acts as active device that requires pulse width modulation (PWM) to trigger and achieve optimum operation. A 5 V DC voltage and 0.5 duty cycle is supplied from the generator at 1 MHz to MOSFET driver. The 5 V voltage is supplied to MOSFET driver and 24 V to class-E inverter. Meanwhile, receiver part consists of rectifier module that convert the AC voltage into DC voltage source to be used by the loads. Each of the load in this work will has their own dedicated rectifier circuit. Therefore, a total of two rectifiers are designed separately based on the load specifications because we have two difference loads in this work.

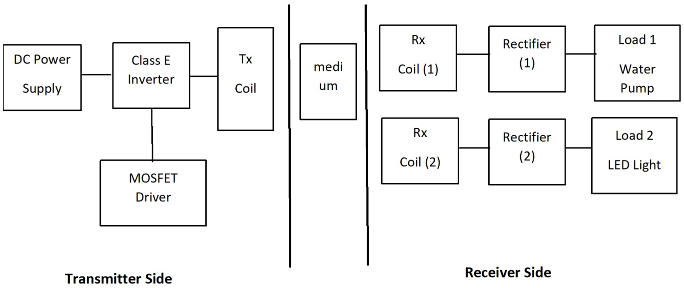


Figure 3. Block diagram of transmitter and receiver

The class-E inverter is designed based on [26]. Figure 4 illustrates the basic components or parameters required for class-E inverter circuit. The power absorbed by the load resistor, R can be obtained by the output power, Po, see (1) since the Po is known, which is 15 W. Therefore, the load resistor value should be $R \leq Ropt$, where $Ropt$ is the optimum value of R.

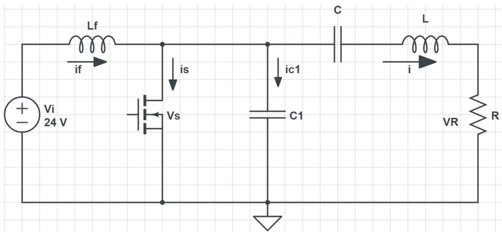


Figure 4. Class-E inverter

$$Po = \frac{8}{\pi^2+4} \times \frac{Vdc^2}{R} \tag{1}$$

$$R = \frac{8}{\pi^2+4} \times \frac{Vdc^2}{Po} \tag{2}$$

Then, with the known R, the shunt capacitor, $C1$, can be calculated as (3).

$$C1 = \frac{8}{R\omega\pi(\pi^2+4)} = \frac{Idc}{\omega\pi Vdc} \tag{3}$$

The series-resonant components which are L and C values are obtained by setting the quality factor, Q to be 10. This quality factor is best to be applied for IPT system as higher Q will result to higher efficiency in achieving sinusiodal output value.

$$C = \frac{1}{\omega R(QL - \frac{\pi(\pi^2-4)}{16}} \tag{4}$$

and

$$L = \frac{QCR}{\omega} \tag{5}$$

3. RESULTS AND DISCUSSION

3.1. Class-E inverter design

The class-E inverter is constructed in MATLAB/Simulink as shown in Figure 5. The basic features of the design are as follows: operating frequency, f, is 1 MHz, DC input supply, V_{DC}, is 24 V, duty cycle, D, is 0.5, loaded quality factor, Q_L, is 10, and desired output power, P_o, is 15 W. The values of the components and other important parameters are shown in Table 1. Based on the Table 1, some differences in the parameters between theoretical calculation and simulation exist because the limitation of the component specifications listed in MATLAB/Simulink. The simulated result for zero voltage switching (ZVS) waveform is shown in Figure 6. ZVS is the condition when the switching devices change their transition state from 'on' state to 'off' state and vice versa. This condition is necessary for the optimum operation that can make the drain efficiency performance reach maximum. From Figure 6, it is obvious that no overlapping between the current and the voltage and therefore the switching losses is zero.

Table 1. Comparison of theoretical and simulation values of class-E parameters

Parameter	Unit	Theoretical	Simulation	Difference (%)
L_f	μF	155.043	155.043	0
$C1$	nF	1.319	1.6	17.56
L	μH	35.251	35.251	0
C	nF	0.812	0.812	0
R	Ω	22.149	22.149	0
I_{DC}	A	0.625	0.583	6.72
V_{DC}	V	24.0	24.0	0
$I_{o,rms}$	A	0.72	0.756	4.76
$V_{o,rms}$	V	19.785	16.75	15.34
P_i	W	15.0	13.992	6.72
P_o	W	14.245	12.663	11.11
η	%	94.97	90.5	4.71

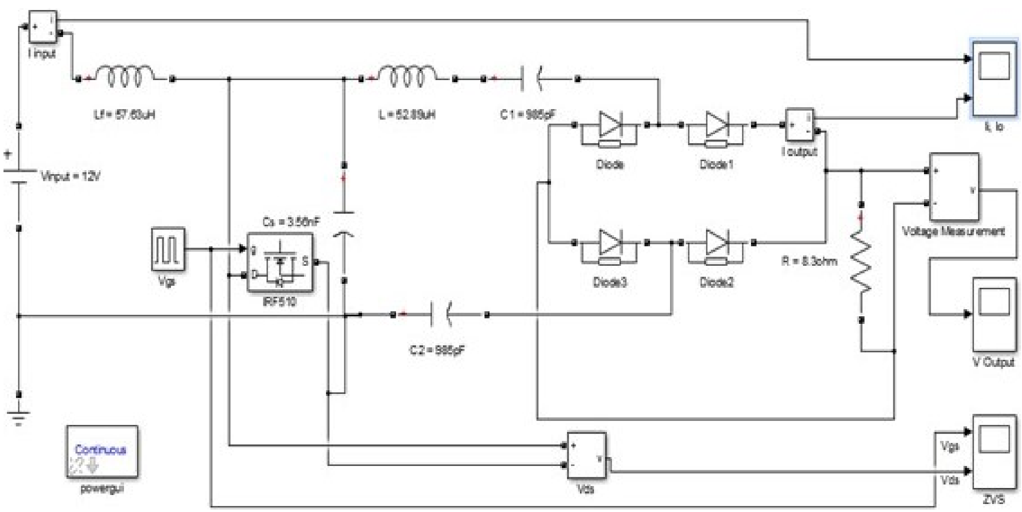


Figure 5. Class-E inverter simulated in MATLAB/Simulink

In order to achieve the optimum ZVS waveform, the shunt capacitor $C1$ is tuned from 1.319 nF to 1.6 nF. During the tuning session, when the value of $C1$ is increased, the width of the current waveform is getting wider. If the $C1$ value exceeded the optimum value, the current waveform of ZVS will strike down to zero when switching operation is 'on' for voltage waveform. This imperfect waveform caused loses and affect the efficiency of the circuit. Based on Figure 7(a), the peak output current is 1.51 A. It is noted that both switch voltages, V_{ds} and V_{gs} are positive at optimum operation. Meanwhile, for Figure 7(b), the output voltage across the load resistor is 22.149 V. The simulated input power, P_i is 13.992 W and the Po is 12.663 W. Therefore, the efficiency of simulated class-E circuit is 90.50%.

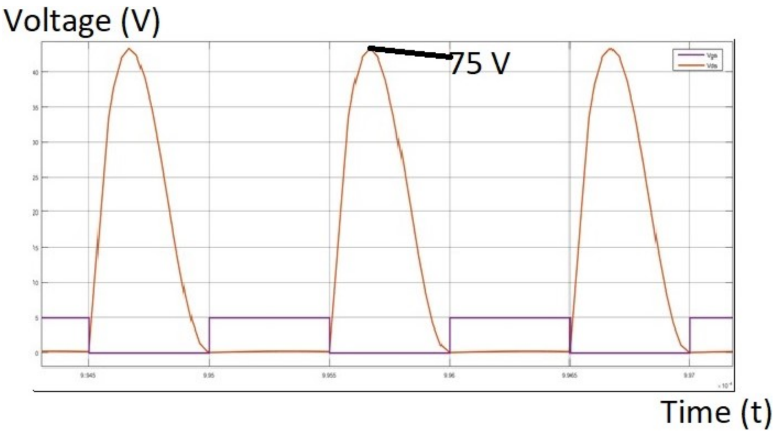
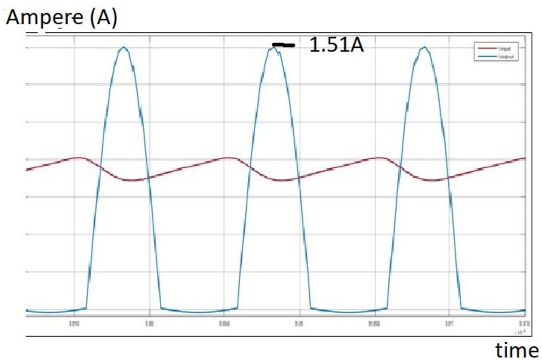
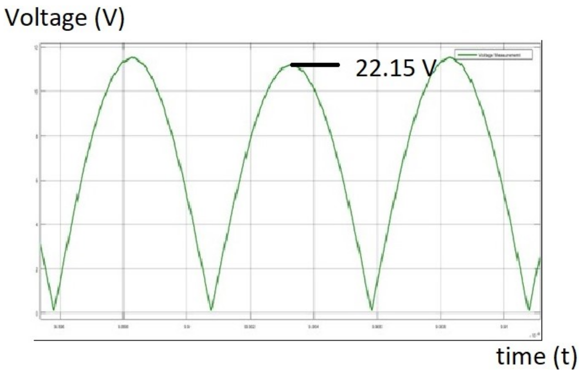


Figure 6. ZVS waveform achieved from simulation and experimental



(a)



(b)

Figure 7. The output current and voltage of simulated class-E circuit (a) current and (b) voltage

The experimental setup for 1 MHz class-E inverter circuit is shown in Figure 8. Based on the simulation value in Table 1, the switch voltage, V_{ds} is 81.67 V and therefore, MOSFET IRF640 is chosen here as a switching device due to fast switching ability and able to handle such voltage. Since the circuit requires to sustain 10 W ouput power, 22 Ω 10 W resistor is used to avoid component damage when current flow through. The 100 µH choke inductor is chosen based on the availabality of the market value.

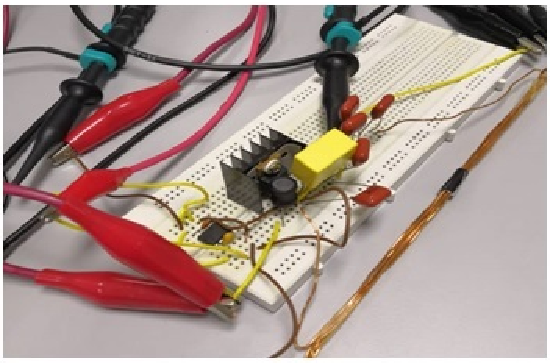


Figure 8. Class-E inverter circuit (experimental work)

The experimental result of this class-E circuit is then given in Figure 9. It is clear from Figure 9 that the ZVS is still in optimum condition and therefore this circuit with the corresponding components value can be used to design the complete wireless aquarium system. The complete list of the components and parameters used to design this class-E circuit experimentally is given in Table 2.

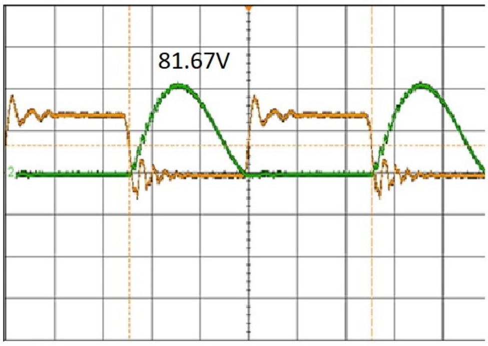


Figure 9. Experimental waveform for V_{gs} and V_{ds}

Table 2. The components use for simulation and experimental works

Parameter	Unit	Simulation	Experimental
L_f	μF	155.043	100
$C1$	nF	1.6	1.49
L	μH	35.251	25.2
C	nF	0.812	2.2
R	Ω	22.149	21.263
I_{DC}	A	0.583	0.57
V_{DC}	V	24.0	24.0
$I_{o,rms}$	A	0.756	0.77
$V_{o,rms}$	V	16.75	15.6
P_i	W	13.992	13.68
P_o	W	12.663	12.012
η	%	90.5	87.81

3.2. Transmitter, Tx and receiver, Rx coils design

Generally, the ratio between transmitter coil and receiver coil are related to Faraday's law. The law basically indicates that the voltage induced is directly proportional to number of turns of coil itself. The maximum power transmitted will be obtained when both coils achive 1:1 ratio of inductance which means both coils are resonate at the same frequency. For this work, the Tx coil used is 25.2 nH. To establish this, a 1 mm diameter copper wire is used with 13 cm lenght and 12.0 cm width and it is arranged arrange as Figure 10. Meanwhile, the Rx coils are shown in Figure 11. The details of design specification of Tx and Rx coils are given in Table 3.

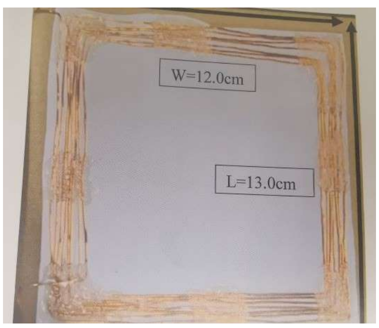


Figure 10. The structure of transmitter coil, Tx

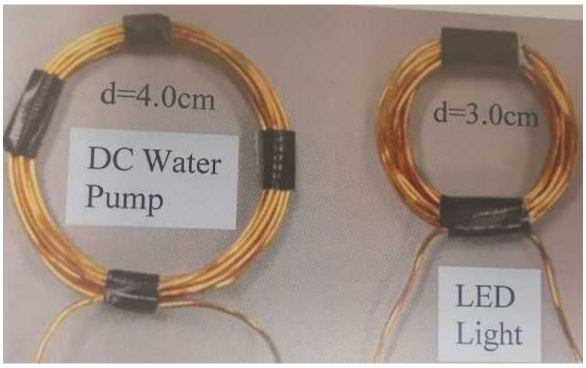


Figure 11. The structure of receiver coils, Rx

Table 3. Design specifications of Tx and Rx

Parameter	Tx	Rx (DC pump - load 1)	Rx (LED - load 2)
Permeability of free space, Wb	1.257×10^{-6}	1.257×10^{-6}	1.257×10^{-6}
Nuber of turns, N	7	5	8
External width of coil, cm	12	4	3
Internal width of coil, cm	10	3	2
Lenght of coil, cm	13	-	-
Inductance of coil, μH	25.2	4.12	5.4

On top of that, for rectifier module, Schottky diodes UF3008 were used as a brdige rectifier for both loads. This kind of diode is used because it has ability to support fast switching and recovery time is faster than P-N diode. Moreover, for better output efficiency and smaller size of the Rx coils, impedance matching circuits were applied. To be exact, the LCCL impedance matching circuit were chosen here. The comparison of the DC water pump (load 1) with and without impedance matching is shown in Table 4.

Table 4. Comparison of DC water pump (load 1) coil with and without impedance matching

Parameter	With impedance matching	Without impedance matching
Inductance, μH	4.12	19.2
Size	Smaller	Bigger
Turns	5	17

3.3. Analysis on distance between transmitter and receiver coils

This section provides findings on the performance of the developed system when the coils experience the distance variations. Here, the analysis is done by moving the transmitter and receiver coils vertically form each other and the output efficiency is measured for each of the variation. The distance covers is from 0.7 cm to 2.5 cm. The maximum efficiency is obtained when the distance is at 0.7 cm which is 87.81% The result is recorded and tabulated at each distance separation from 0.7 cm to 2.5 cm in Table 5. The lowest efficiency is 65.0% at 2.5 cm distance. This finding is important in order to determine the best thickness of the aquarium glass. The details results on this analysis can be found in Table 5.

Table 5. Distance variations analysis over output efficiency

Distance (cm)	Efficiency (%)
0.7	87
0.9	83
1.1	79
1.3	77
1.5	76
1.7	73
1.9	69
2.1	68
2.3	66
2.5	65

3.4. Analysis on misalignment between transmitter and receiver coils

The output power is observed when the transmitter and receiver coils are misaligned to each other. In other words, the alignment of receiver increases horizontally on transmitter coil. The result of the receiver alignment on transmitter coil from 1 cm to 15 cm is shown in Table 6. The efficiency of the design is 87.81% when transmitter coil and receiver coil are aligned to each other. This is because at this alignment, the circuit produces the highest output power which is 1.15 W. The maximum power is transmitted at 10 cm which away from the receiver of DC water pump (load 1). Thus, the LED light do not share the magnetic field beside the DC water pump but opposite. The lowest output power is 0.5 W with the misalignment distance of 15 cm. At 15 cm distance, the receiver coil is out of the range of transmitter coil. Thus, receiver did not detect the magnetic field which is produced by the transmitter coil.

Table 6. Output power vs misalignment variations

Distance (cm)	Output Power (W)
1.0	0.61
3.0	0.84
4.0	0.87
6.0	0.89
8.0	1.01
10.0	1.15
12.0	0.57
14.0	0.57
15.0	0.5

Finally, based on the obtained results, the complete prototype for this wireless aquarium system has been developed as shown in Figure 12. Please be noted that two loads, namely LED light and DC water pump were used in this work. Each of the load has dedicated coil and rectifier circuit. The proposed method was successfully power up the loads without any physical connection between transmitter and receiver circuits (loads).

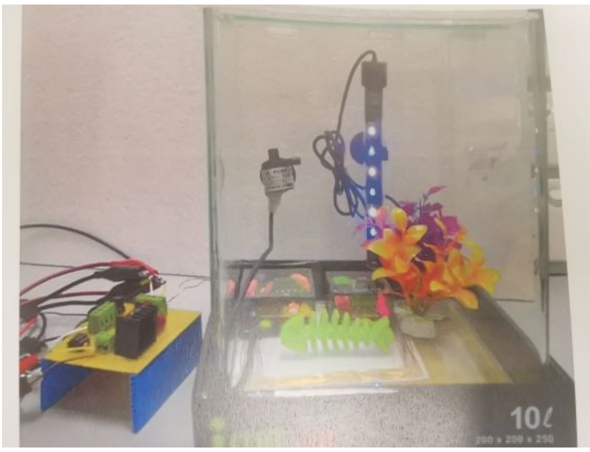


Figure 12. Complete prototype with DC water pump (load 1) and LED light (load 2)

4. CONCLUSION

A prototype of wireless fish aquarium system using class-E inverter has been developed successfully. Two loads, namely DC water pump (load 1) and LED light (load 2) were used in this work. The proposed system produced highest efficiency (87%) when the distance between Tx and Rx is 0.7 cm and misalignment of 10 cm. The implementation of LCCL impedance matching circuit was helped to reduce the size of the Rx coils and also improve the output power of the circuit. For future work, it is recommended to explore on the controller design to maintain the ouput power despite variations in load resistor or distance by adjusting the duty cycle of the switching device.

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