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Wireless Electrical Power Transfer System using Resonance Coupling

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Abstract
The process of wireless electrical power transfer has been around for quite some time. Its application in charging of devices wirelessly is ever increasing, especially in charging of portable devices and standalone batteries. It is a flexible and inexpensive way of power transmission. In this paper, we report that a method ofwireless electrical power transmission has been designed and developed. Resonance coupling was adopted to increase the coupling between the transmitter and receiver. This increased the distance of power transmitted between the receiver and transmitter while also giving the receiver some degree of freedom of orientation, considering the size of the receiver's coil. A class D method of power amplification was used because of its high efficiency to reduce the power lost as heat. While distance of the receiver from the transmitter was not improved, miniaturization of the system in such a manner suitable for portable devices charging and powering was achieved. The transmitted voltage can be used to charge a phone, turn on a lamp etc.
Keywords: *electrical power transfer; receiver; resonance coupling; transmitter; wireless.*

I. Introduction

The idea of transmitting power through the air has been around for over a century, with Nikola Tesla's pioneering ideas and experiments perhaps being the most well-known early attempts to do so(Tandon et al., 2013);(Augustine & Duke, 2014);(Saravanan, Subhashini, & DiZneshkumar, 2014). He had a vision of wirelessly distributing power over large distances using the earth's ionosphere. Though the project had not met its needs, the commencement of this research by Tesla has illuminated the scientists and the field has now achieved greater heights with good results (Likhar et al., 2014);(Liu, Yıldırım, Pawełczak, & Warnier, 2016). Using an electronic device, perhaps a mobile phone, and you need to recharge the battery, then one will probably have to get a charger and connect the phone to the wire. But what if you could charge it without having to connect it to a power source with wires? Though still in the early stages, several electronic companies are beginning to roll out devices that can wirelessly transmit power. Wireless power transmission could one day allow us to generate solar power on a satellite and beam it down to Earth, transmit power to a water treatment plant for a disaster relief operation or power a flying communication relay station from a terrestrial station. There are a few engineering hurdles yet to overcome to make this technology viable to today's investors, but with the rising demand for energy and the rapid improvements being made it is just a matter of time before wireless power transmission becomes an industry of its own (Jiang, Chau, Liu, & Lee, 2017);(Tandon et al., 2013).

Wireless power transmission (WPT) currently around is based on the principle of electromagnetic induction(Pravin, Narayanan, Balaganesh, Manikandan, & Saravanan, 2014);(Liu, Yıldırım, Pawełczak, & Warnier, 2016).Electromagnetic induction works on the concept of a primary coil generating a predominantly magnetic field and a secondary coil being within that field so a current is induced within its coils. This causes the relatively short range because the two coils need to be in close contact for any substantial power to be transferred across and for more power to be transferred the coils size need to be increased too. A physics research group, led by Marin Soljacic, at the Massachusetts Institute of technology (MIT) demonstrated wireless powering of a 60W light bulb with 40% efficiency at a 2m distance using two 60 cm-diameter coils in 2007(R, Gayathri, R, & Yashwanth, 2014);(Khayrudinov, 2015). In 2008, Intel reproduced the MIT group's experiment by wirelessly powering a light bulb with 75% efficiency at a shorter distance. MIT team experimentally demonstrates wireless power transfer, potentially useful for powering laptops, cell phones without any cords (Tandon et al., 2013).

While significant progress has been made in improving distance of transmission, miniaturization of the setup, particularly the induction coils remain a challenge. In this work we designed a more portable wireless power transmission device with a reduced coil size, suitable for low power transmission which could find application in charging of mobile phones, laptops and other low power consuming portable devices. And these devices don't have to be in contact with the transmitter as in the case of conventional wireless charging systems.

Resonance coupling method was used here to increase the distance of transmission and at same time lower the power lost to the surrounding while still transmitting power to the receiver tuned at the resonance frequency of the transmitter. In this research work, we will not be talking about the efficiency of the system because the size of the receiving and transmitting coils are not same.

II. Resonance Inductive Coupling

Resonance is a phenomenon that occurs in nature in many different forms. In general, resonance involves energy oscillating between two modes, a familiar example being a mechanical pendulum in which energy oscillates between potential and kinetic forms. In a system at resonance, it is possible to have a large buildup of stored energy while having only a weak excitation to the system. The build-up occurs if the rate of energy injection into the system is greater than the rate of energy loss by the system.

An example of an electromagnetic resonator is the circuit shown in Fig. 1, containing an inductor, a capacitor and a resistor.

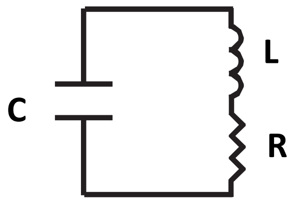

Fig. 1: Example of a resonator

Energy oscillates at the resonant frequency between the inductor (energy stored in the magnetic field) and the capacitor (energy stored in the electric field) and is dissipated in the resistor. The resonant frequency (ω_0) and the quality factor (Q_0) for this resonator are

$$\omega_0 = \frac{1}{\sqrt{(LC)}} \qquad (1)$$

and

$$Q_0 = \frac{\omega 0}{2\Gamma} = \sqrt{\left(\frac{L}{C}\right)\frac{1}{R}} = \frac{\omega 0 L}{R} \qquad (2)$$

The expression for $\mathbf{Q_0}$in equation (2) shows that decreasing the loss in the circuit, i.e., reducing R, increases the quality factor of thesystem. Where R is the resistance of the resonator (inductive reactance mainly).

2.2 Coupled Resonators

If two resonators are placed in proximity to one another such that there is coupling between them, it becomes possible for the resonators to exchange energy. The efficiency of the energy exchange depends on the characteristic parameters of each resonator and the energy coupling rate, κ, between them. The dynamics of the two resonator system can be described using coupled-mode theory (Kurs, *et al.*, 2007) or from an analysis of a circuit equivalent of the coupled system of resonators. One equivalent circuit for coupled resonators is the series resonant circuit shown in Fig. 2.

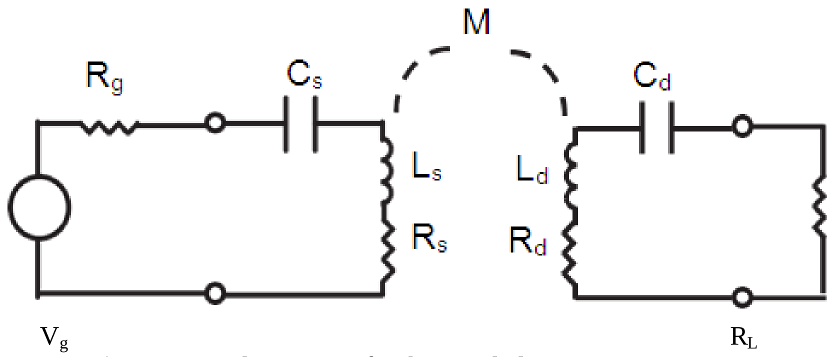

Fig. 2: Equivalent circuit for the coupled resonator system

Here the generator is a sinusoidal voltage source with amplitude V_g at frequency $\omega$with equivalent generator resistance R_g. The source and device resonator coils are represented by the inductors L_s and L_d, which are coupled through the mutual inductance **M**, where

$$\mathbf{M} = k\sqrt{(L_s L_d)} \qquad (3)$$

Each coil combines with a capacitor to form a resonator. The resistancesR_s and R_d are the parasitic resistances (including both ohmic and radiative losses) of the coil and resonant capacitorC_s and C_d for the respective resonators. The load is represented by an equivalent AC resistance R_L.
Analysis of this circuit gives the power delivered to the load resistor, divided by the maximum power available from the source when both the source and device are resonant at ω as

$$\frac{P_L}{P_{g,max}} = \frac{4 \cdot U^2 \frac{R_g R_L}{R_s R_d}}{\left(\left(1+\frac{R_g}{R_s}\right)\left(1+\frac{R_L}{R_d}\right)+U^2\right)^2} \quad (4)$$

Where,

$$U=\frac{\omega M}{\sqrt{R_s R_d}} = \frac{\kappa}{\sqrt{\Gamma_s \Gamma_d}} \quad (5)$$

is the figure-of-merit for this system.
We can choose the generator and load resistances which give the best system performance (or use an impedance transformation network to match to other resistance values). If we select,

$$\frac{R_g}{R_s} = \frac{R_L}{R_d} = \sqrt{1+U^2} \quad (6)$$

then the efficiency of the power transmission as defined above is maximized and is given by,

$$\eta_{opt}=\frac{U^2}{\left(1+\sqrt{1+U^2}\right)^2} \quad (7)$$

Here one can see that highly efficient energy transfer is possible in systems with large values of U.

III. Methodology

In other to achieve this wireless power transfer the following units were constructed and tested independently before combining them together to achieve a system of wireless power transfer.

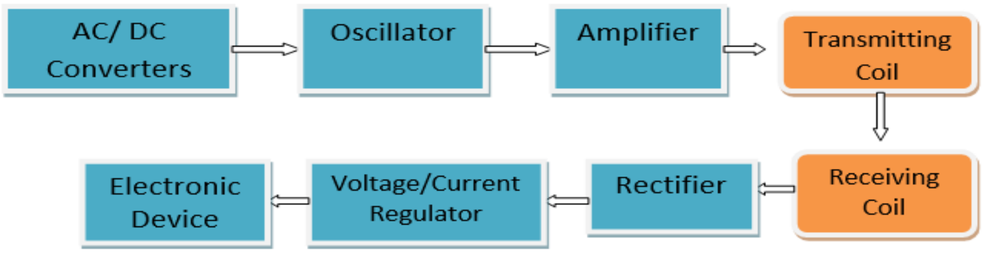

Fig.3.1: Block Diagram Showing Stages of the Wireless Power Transfer

3.1 Computer Software Used

The computer softwares that were used for the design of the project include;
1. Proteus 8.7 Professional; used for the electronic circuit design and simulation of some sections of the circuit.
2. Fritzing; used for visualization of the circuit designed, and
3. SolidWorks; used for spiral design of the coil.

3.2 Circuit Description

The oscillator section is made up a microcontroller (Arduino Nano) and a dedicated chip for frequency generation (AD9833). This section is responsible for setting the frequency at which the power is being transferred. The frequency is set as close as possible to the resonant frequency of the LC circuits of both the transmitting and the receiving end.

The microcontroller is used to program the AD9833 and with some buttons the frequency of the circuit can easily be tuned (up or down) from 1Hz up to 1MHz in steps. This will enable the change of the resonance frequency to that of both the transmitter and receiving LC circuits. Also an LCD has been added to display the transmitting frequency.

The generated frequency is amplified by the operational amplifier (LM318) to about the VCC (+18V) but with little power. This is then fedinto the class D MOSFET transistor configuration for power amplification which is then transmitted out through the LC tank circuit to the receiver at about the resonance frequency. Below is the circuit diagram of the complete work designed on Fritzing.

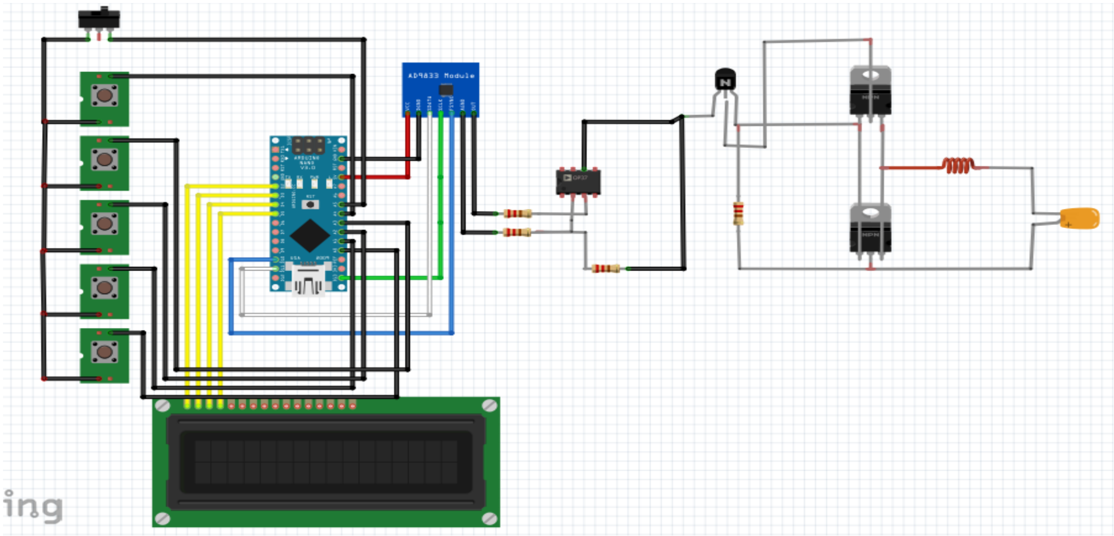

Fig. 3.2: Circuit Diagram of the Complete Transmitter System

3.3 The Transmitting and Receiving coils

The transmitting and receiving coils were designed to have a spiral shape to increase the area and range of coverage of the power transferred. The flat spiral shape was achieved with the use of SOLIDWORKS software to give a more precise dimension of the flat spiral coil.Diameter of the smaller coil designed is 6 cm while that of the bigger coil is 15 cm. With this a significant progress has been achieved in effort to miniaturize wireless power transfer systems for portable devices application.

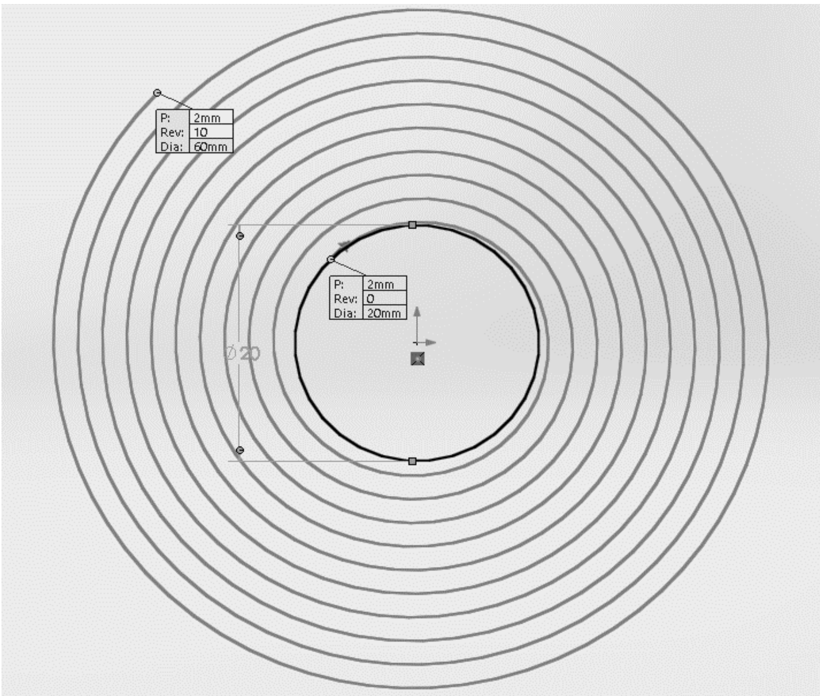

Fig. 3.3: SOLIDWORKS Design of Flat Spiral Coil

The inductance of the coil is calculated using the following formula for flat spiral coil inductor,based on Harold A. Wheeler approximation (Wheeler 1928)

$$L(\mu H) = \frac{r^2 A^2}{(30A - 11Di)} \quad \text{and} \quad A = \frac{(Di + N(w+s))}{2} \qquad (8)$$

where *Di* is the inner diameter in inches, *s* is distance between windings in inches, wis wire diameter in inches, *N* is the number of turns and *D*ois the outer diameter.

3.4 Rectifying Section for the Receiver

After the power has been received by the receiving coil and capacitor tuned to the resonance frequency of the transmitter, the AC is then converted to DC by the use of diodes connected in bridge configuration. This DC is then smoothened to almost a pure DC form by the use of a capacitor connected in parallel to the output.

IV. Results and Discussion

The value of the inductance was gotten by calculation using equation (8) and also by measurement using LC100-A digital LCD and inductance meter. Both values were not exactly the same but vary as shown in table 1 below.

TABLE 1: Table Showing Measured Inductance Values and Calculated Values

Location	Inductance (μH)	
	Measured	**Calculated**
Phone	4.27	6.2
Laptop	15.85	19.26
Transmitter	129	132.5

These inductance values of inductors were chosen to observe how inductance affects the maximum distance the receiver can be from the transmitter and still receive reasonable amount of power.

TABLE 2: Table of values obtained for a load of 4.7KΩ by varying the position of the Receiver when the inductance is **6.20μH.**

DISTANCE OF RECIEVER FROM TRANSMITTER (CM)	OUTPUT VOLTAGE (V)
0	6.50
2	9.30
4	11.00
6	11.50
8	9.10
10	7.00
12	3.50
14	2.90
16	2.00
18	1.5
20	0.8

TABLE 3: Table of values obtained for a load of 4.7KΩ by varying the position of the Receiver when the inductance is **19.26μH.**

DISTANCE OF RECIEVER FROM TRANSMITTER (CM)	OUTPUT VOLTAGE (V)
0	1.50
2	4.30
4	7.00
6	9.80
8	12.70
10	15.80
12	19.70
14	17.00
16	15.70
18	14.50
20	11.60

22	10.20
24	5.00
26	3.80
28	2.90
30	1.60

With an input voltage of 18V, the above tables were gotten by applying a fixed load at the receiver and taking measurements of the voltage across it at certain distances from the transmitter.

4.2 Discussion

The results obtained in Tables 2 and 3 plotted in graphical form. Fig. 8 and 9, show a graph of output voltage against distance of the receiver from the transmitter while using 6.2μH and 19.26μH inductors respectively.

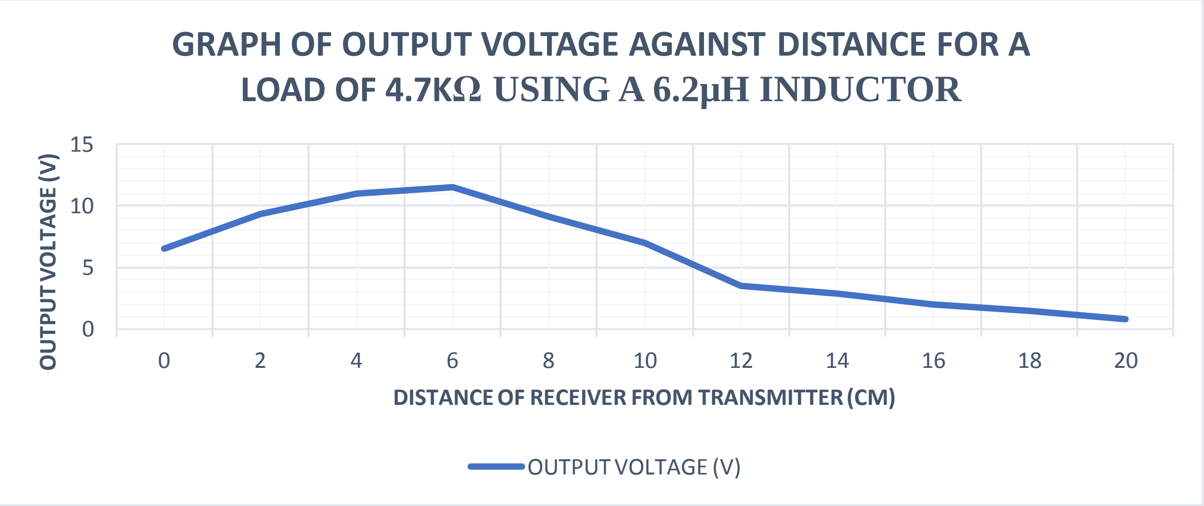

Fig. 8: Graph of Output Voltage against Distance for a Load of 4.7KΩ while using a 6.2μH inductor.

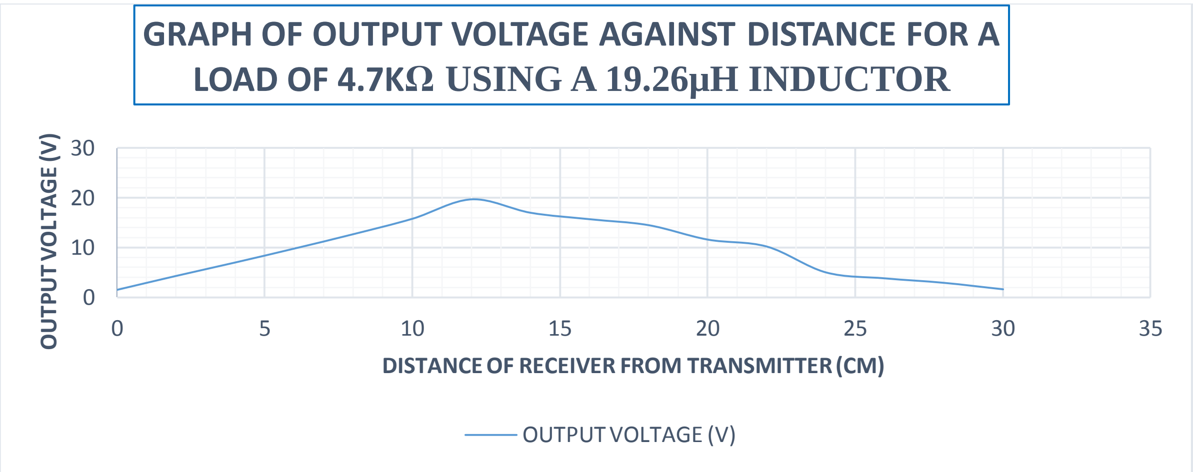

Fig. 9: Graph of Output Voltage against Distance for a Load of 4.7KΩ while using a 19.26μH inductor.

From the graph, we see that as the distance from the transmitter is increased the output voltage at the receiver also increases. It kept increasing until it got to a certain distance in both cases, when 6.2μH and 19.26μH inductors were used respectively. After this distance from the transmitter the voltage starts dropping fast. This means that:

1. Placing the receiver too close to the transmitter does not increase the voltage received that much
2. And placing it far away from the transmitter immediately reduces the received voltage.
3. Also the bigger inductor tends to receive more voltage at longer distances than the smaller on.

Variation in voltage received is as a result of the coupling factor and the quality factor of the resonator of the two inductors, that is, the transmitting and receiving inductors.

Also we can see from the table of values that the voltage at the receiver when 6.2μH and 19.26μH inductors were used vary significantly. This implies that the inductance value of the inductor used in wireless power transmission also affect the amount of power transmitted. This is true and is supported by the equation of the quality factor, equation (2). Here we see that a higher inductance value increases the quality factor and in turn the power transmitted.
The calculation of these parameters were done with equations 3 and 2 respectively. Table 5 below shows the different values of the quality factor of the different inductors used.

TABLE 5: Table of values for the calculated quality factor of the inductors used

Inductor Value (μH)	Quality Factor at 1.055MHz
6.20	327
19.26	725
132.50	3177

The mutual inductance between the transmitting and receiving inductors were found to be $\mathbf{M_{132.5|6.2} = 28.66k}$ and $\mathbf{M_{132.5|19.26} = 50.5k}$ for the 6.2μH and 132.5μH and also the 19.26μH and 132.5μH pairs of inductors respectively.
Other observations noted during the cause of the testing are:
1. That a little deviation from the resonance frequency (around 1.055MHz to 1.03MHz drastically lowered the voltage received.
2. Operating the device at higher resonant frequency increase the allowed orientations and distance of the receiver.
Also the value of the voltage received is not maximum when the transmitting and receiving coils are very close or in contact because of over coupling. This can be rectified by using a series LLC resonant configuration.

V. Conclusion

In this research paper, we have successfully transferred a small amount of power for wireless charging of phone and lighting of a lamp without placing the coils of the transmitter and receiver in contact. Also the receivers could be moved around within a specific region without interrupting the charging or the lamp going off. We hope for a future where devices could be charged and powered without wires and also without having to place the receiver in contact with the transmitter.

Also, from the result obtained it can be seen that the power transmitted and that received can be affected by a whole range of both internal and external factor. To increase the power transmitted, the transmitting and receiving inductor should be significantly large enough. Also the output voltage is seen to be dependent on the distance between the transmitter and receiver. The following deductions were made:
1. To increase the voltage transmitted,
a. The type of amplification method must be one that gives almost a 100% of power amplification.
b. The switching frequency should be the same with the tank circuit (inductor and capacitor) resonance frequency.
2. To increase the voltage received and the freedom of orientation of the receiver,
a. Increase the quality factor of the system to increase the voltage (power) received by increasing the inductor value.
b. Freedom of orientation can be increased by increasing the coupling factor

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