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ORIGINAL ARTICLE

High voltage magnetic pulse generation using capacitor discharge technique

M. Rezal [a,*], Dahaman Ishak [b], M. Sabri [a]

[a] Universiti Kuala Lumpur, Malaysian Spanish Institute, Lot 13-16, Kulim Hi-Tech Park, 09000 Kulim, Kedah, Malaysia
[b] School of Electrical & Electronic Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia

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Abstract A high voltage magnetic pulse is designed by applying an electrical pulse to the coil. Capacitor banks are developed to generate the pulse current. Switching circuit consisting of Double Pole Double Throw (DPDT) switches, thyristor, and triggering circuit is developed and tested. The coil current is measured using a Hall-effect current sensor. The magnetic pulse generated is measured and tabulated in a graph. Simulation using Finite Element Method Magnetics (FEMM) is done to compare the results obtained between experiment and simulation. Results show that increasing the capacitance of the capacitor bank will increase the output voltage. This technology can be applied to areas such as medical equipment, measurement instrument, and military equipment.

1. Introduction

Research on magnetic field generation and application for non-destructive pulse magnetic field shows that the developed system can generate high magnetic field without destroying the magnets [1]. Several methods for generating magnetic field are studied and results show that for nondestructive coil, the peak field depends on the strength of the conductor material [2]. High voltage is required to obtain a high magnetic pulse and capacitor bank is suitable as a pulse source [3]. Fig. 1 shows the schematic diagram of the condenser bank circuit. A high DC voltage is required to charge the 3.3 kV, 9000 μF condenser bank. Ignitron with current capacity of 450 kA is used as the switching device in the condenser circuit.

Multilayer coils are able to generate high magnetic field without destroying the coils [4]. A multi-layer magnet model is shown in Fig. 2. A magnetic pulse is created when a high voltage from a capacitor bank is connected to a coil. A pulse current will flow through the coil resulting in a high magnetic pulse inside the coil. The coil is made of an insulated copper wire and it is covered with galvanized iron. The coil strength can be increased by reinforcing with a uniaxial wrap of fibers [5]. Nonlinear partial differential equations with a field-dependent relative differential permeability are able to solved problems involving intense magnetic field in soft ferromagnetic materials [6]. Pulsed magnet can be designed using computer analysis to reduce the pulsed magnet development time [7]. A capacitor bank with a different value of voltage and capacitance is set up and connected to the coil. This is done to study the magnetic field relationship between voltage and capaci-

* Corresponding author.
E-mail addresses: mrezal@unikl.edu.my (M. Rezal), dahaman@usm.my (D. Ishak), msabri@unikl.edu.my (M. Sabri).
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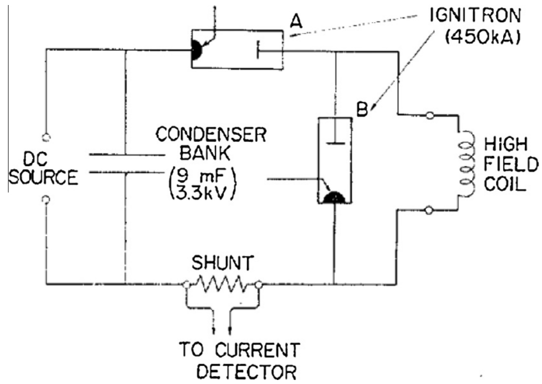

Figure 1 Schematic diagram of condenser bank circuit [3].

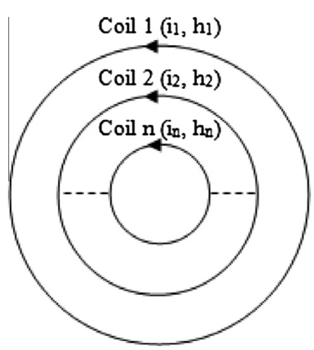

Figure 2 Schematic model of n-layer magnet coaxially arranged from coil 1 to n [4].

tance. A current sensor and voltage probe are used to measure the magnetic field and voltage across the coil. A search coil is used to measure induce voltage cause by the magnetic field of the coil. The magnetic flux of the coil can be calculated from the induced voltage by integrating the area under the graph of the induced voltage versus time.

2. Mathematical model

2.1. Magnetic field generated by the coil

The magnetic field along the axis of a wire loop is illustrated in Fig. 3 and can be evaluated from the Maxwell's equation as shown in Eq. (1) [8,10]. K is a closed curve around area F, H is the magnetic field strength, I is the current flowing through

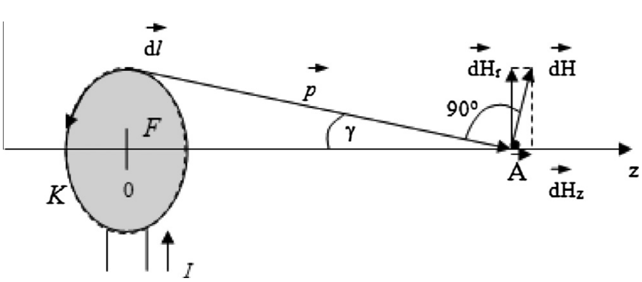

Figure 3 Magnetic flux density from wire loop [10].

area F, and D is the electric flux density. The electric flux density is equal to zero when wire is supplied with direct current. Then Eq. (2) is obtained for $D = 0$.

$$\oint_K \vec{H} d\vec{s} = I + \int_F \vec{D} d\vec{f} \tag{1}$$

$$\oint_K \vec{H} d\vec{s} = I \tag{2}$$

Referring to Biot-Savart's Law [9,10], the magnetic field intensity dH produced at a point A, as shown in Fig. 3, by the differential current Idl is proportional to the product Idl and the sine of the angle between the element and the line joining A to the element and is inversely proportional to the square of the distance p between A and the element. Then Eq. (2) can be written as Eq. (3).

$$d\vec{H} = \frac{I}{4\pi} \frac{d\vec{l} \times \vec{p}}{p^3} \tag{3}$$

The vector dl is perpendicular to p and dH lies in the plane of the drawing, so that,

$$dH = \frac{I}{4\pi p^2} dl = \frac{I}{4\pi} \cdot \frac{dl}{R^2 + z^2} \tag{4}$$

dH can be resolved into a radial dH_r and axial dH_z component. The dH_z components have the same direction for all conductor elements dl and the quantities are added; the dH_r components cancel one another out, in pairs. Therefore,

$$H_r(z) = 0 \tag{5}$$

and

$$H(z) = H_z(z) = \frac{I}{2} \cdot \frac{R^2}{(R^2 + z^2)^{3/2}} \tag{6}$$

along the axis of the wire loop, while the magnetic flux density,

$$B(z) = \frac{\mu_0 I}{2} \cdot \frac{R^2}{(R^2 + z^2)^{3/2}} \tag{7}$$

where $\mu_0 = 1.2566 \times 10^{-6}$ H/m is the permeability of free space. If there is a small number of identical loop close together, the magnetic flux density is obtained by multiplying by the number of turns N. The magnetic flux density of a

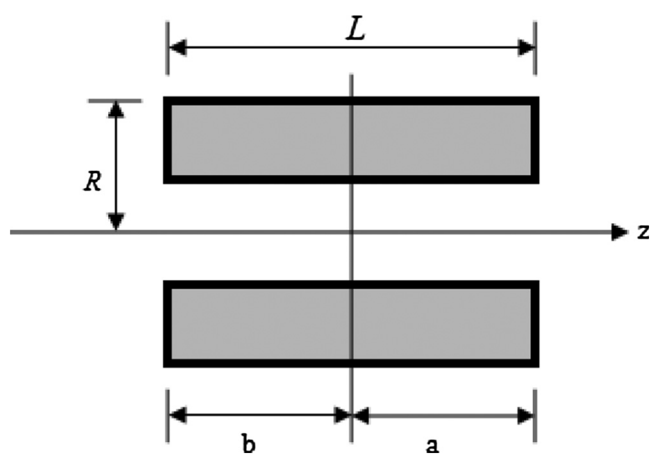

Figure 4 Cross-sectional view of coil.

uniform wound coil of length L and N turns is calculated by multiplying the magnetic flux density of one loop by the density of turns N/L and integrate over the coil length. Referring to Fig. 4, Eq. (8) shows the magnetic flux density for multiple wound coils [10].

$$B(z) = \frac{u_0 IN}{2L}\left(\frac{a}{\sqrt{R^2+a^2}} - \frac{b}{\sqrt{R^2+b^2}}\right) \quad (8)$$

$$a = z + \frac{L}{2} \quad \text{and} \quad b = z - \frac{L}{2}$$

where μ_0 is the permeability constant in H/m, I the current in Ampere, N the number of coil turns, L the length of coil in cm, and R is the radius of coil.

2.2. High voltage capacitor banks standard and safety measures

Due to high voltage capacitor banks experiment, precaution and safety measures need to be taken seriously. An insulated glove is required during experimental work. Safety shoes and protective eyewear also play an important rule to protect from electrocuting and overcharge capacitor that may explode [11]. Safety and work procedures during electrical work can be applied to minimizing the accident [12]. A standard handling with high voltage capacitor banks can be used in designing a series capacitor bank [13].

3. Research methodology

The first step is to simulate magnetic field developed by designing a coil using FEMM [14]. The magnetic field of the coil is analyzed by varying the applied voltage and the value of capacitance respectively. The results obtained are then tabulated in a graph. After optimized values are obtained, a hardware module is prepared and built to measure the actual magnetic field generated by the designed coil by setting the values of voltage and capacitance as same as the simulation model. Then the results are compared between simulation and experiment to determine the discrepancies. Fig. 5 shows the block diagram of the design steps for the magnetic pulse generation.

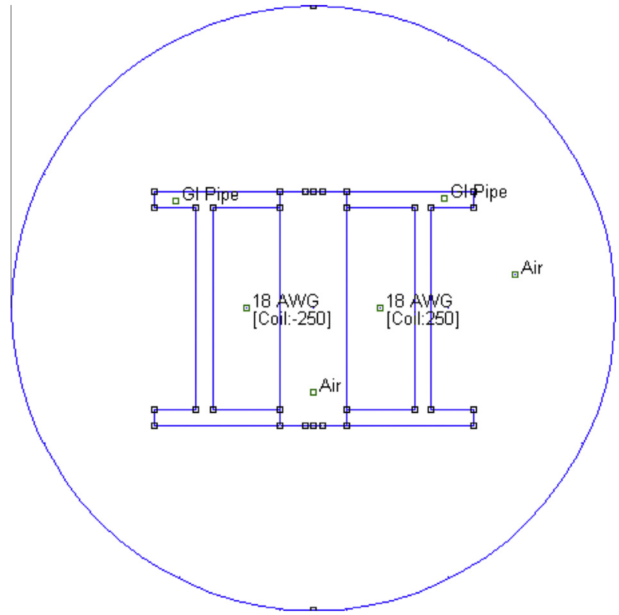

Figure 6 Coil is simulated using FEMM.

Table 1 Parameters for the coil.

Parameters	Values
Resistance	1.531 Ω
Inductance	16.1 mH
Length	6 cm
Inner diameter	2 cm
Outer diameter	6 cm
Washer dimension (Width × length × height)	(0.5 × 12.5 × 7.5) cm

3.1. Finite element analysis

The propose coil is modeled in FEMM by building it vertically in half as shown in Fig. 6. The model is set as an axi-symmetric type and unit length is in centimeters. The coil is made from 18 AWG insulated copper wire with 500 turns. It is covered with Galvanized Iron (GI) pipe which has a magnetic permeability of 100.

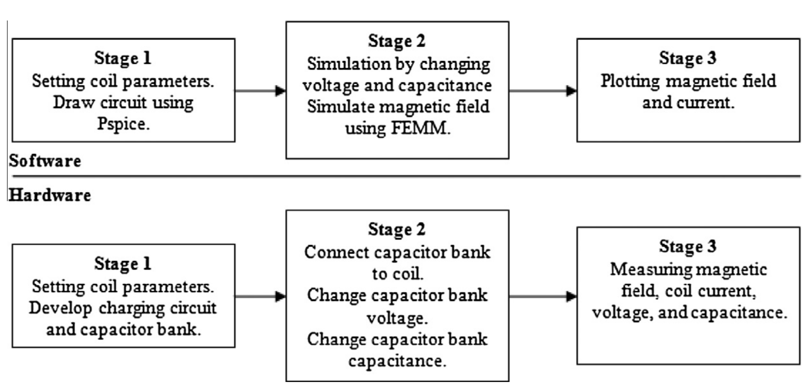

Figure 5 Design step.

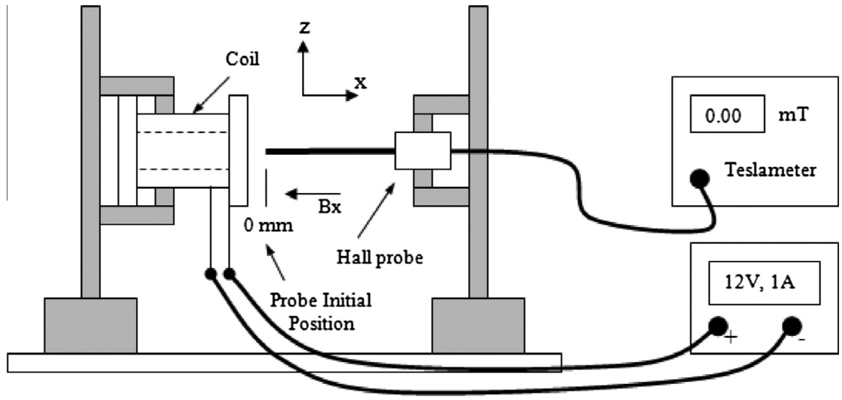

Figure 7 Coil magnetic field measurement.

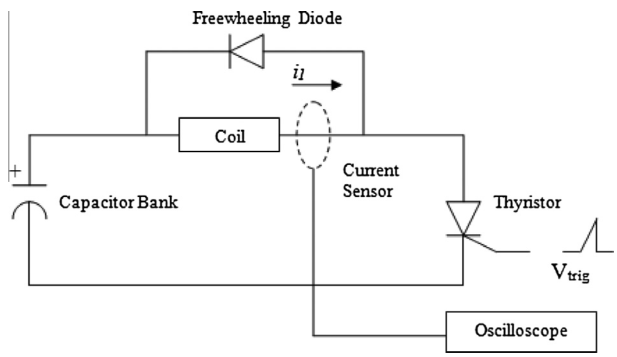

Figure 8 Current sensors measured coil current.

3.2. Coil design and implementation

The coil is designed with parameters as shown in Table 1. The coil is made from 18 AWG copper wire with 500 turns. The coil is covered with a galvanized iron. The coil is wound using winding machine. It has a 10 layer winding and each layer car-

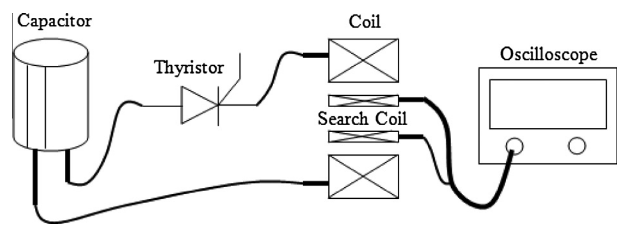

Figure 9 Induced voltage measurement setup.

ries 50 tons. The total weight of the coil is about one kg. Two terminals for connecting the coil to DC voltage source are made using terminal connector. The galvanized iron is cut in two to reduced eddy current effect.

3.3. Magnetic field measurement

The magnetic flux density generated by the coil is measured using Teslameter. The coil and Hall probe are set in horizontal axis and a stand is used to hold them as shown in Fig. 7. The

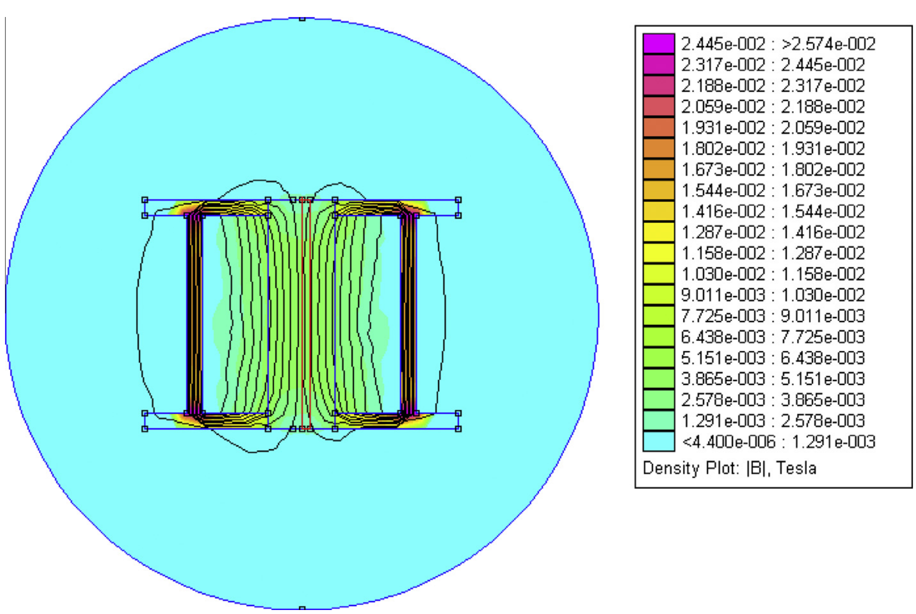

Figure 10 Magnetic fields generated by the coil.

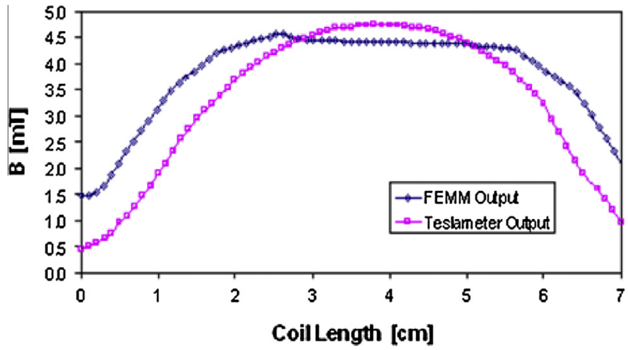

Figure 11 Comparison of magnetic field between FEMM and Teslameter.

zero adjustment in Teslameter is adjusted until the LED display shows zero value. The hall probe is moved inside the coil for every 1 mm increment and Teslameter will display the magnetic flux reading for every 1 mm increment inside the coil. The hall probe is moved until it reaches the end of the coil.

3.4. Current measurement

Fig. 8 shows that the current sensor is connected in series with the coil. Capacitor bank is initially charged and thyristor is used as a switch to connect coil with the capacitor bank. A freewheeling diode is connected parallel with the coil to protect thyristor from the back emf produced by the coil. When the thyristor is triggered (turn-on), current will flow through the coil and current sensor will detect the current pulse and sent the signal to the oscilloscope. The oscilloscope will record the current pulse and save it on the hard drive.

3.5. Induced voltage measurement

The induced voltage is measured using a search-coil. The search-coil is made from 27 AWG copper wire and has 260 turns. The search-coil is located inside the coil and connected to the oscilloscope. Fig. 9 shows the induced voltage measurement setup.

4. Empirical findings

The results are divided into three parts; numerical result, experimental result, and lastly the coil current and capacitor voltage.

4.1. Numerical result

The magnetic field distribution generated by the coil is shown in Fig. 10 when the coil is supplied with 1 A DC current. The magnetic flux density increases from the edge toward the middle of the coil. By selecting the area inside the coil, the magnetic flux density inside coil can be measured and plotted as shown in Fig. 11.

4.2. Experimental result

Data obtained from the simulation and the experiment are recorded and compared as shown in Fig. 11. It shows the

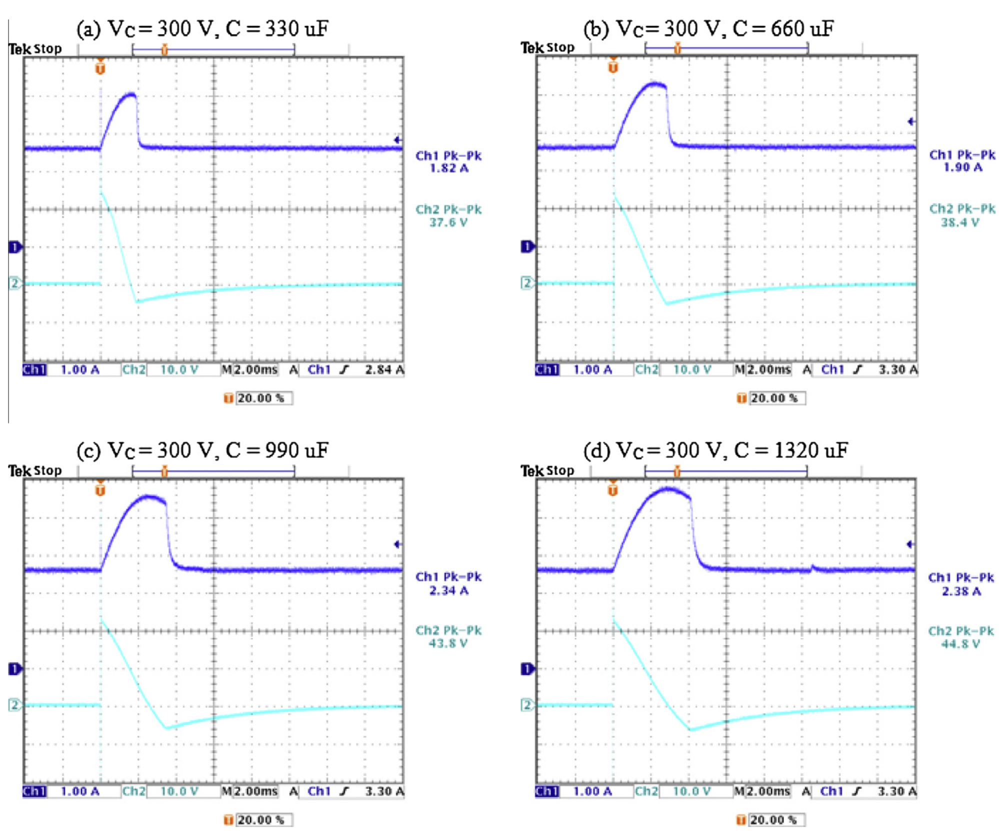

Figure 12 Coil current and voltage across capacitor for different capacitance values.

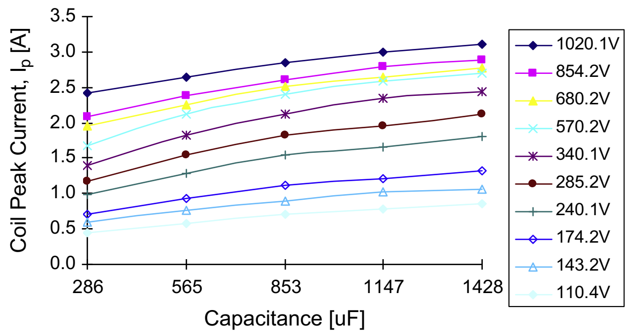

Figure 13 Coil peak current at different applied voltage and capacitance.

magnetic field developed inside the coil when it is supplied with a constant DC source. The magnetic field at the center of the coil is higher than the edge of the coil.

4.3. Coil current and induced voltage

The coil current and the capacitor voltage are shown in Fig. 12. The upper waveform is the coil current, while the bottom is the voltage across the capacitor. Capacitor bank is initially charged to 300 V. An electrolyte capacitor with rating of 400 V, 330 μF is used in the design. The capacitance is increased by adding capacitors in parallel. The search-coil is located inside the coil and connected to the oscilloscope. Referring to Fig. 12, it can be concluded that by increasing the capacitance, the peak value of coil current and capacitor voltage will also increase. Fig. 13 shows the effect of the coil current when the capacitance is increased. Larger capacitor will be able to store more energy, resulting in higher current flowing in the coil. Hence, the magnetic pulse can be increased as the coil current increases.

5. Conclusions

High voltage magnetic pulse has been developed by applying high voltage capacitor bank. The pulse current rise and fall time is dependent on the values of R, L and C in the circuit. The coil current is proportional to the applied voltage and capacitance.

6. Recommendation

The current pulse has to be controlled by a system that is able to set the rise and fall time of the pulse current. Studies on the magnetic reluctance and hysteresis are important in identifying the factors affecting the magnetic pulse density. The Electromagnetic Interference (EMI) effect is also a major concern in coil design as to prevent it from causing electronic components malfunction.

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