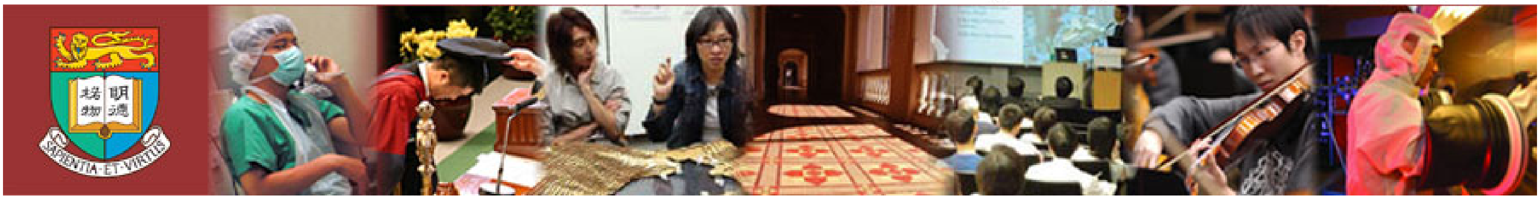

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# Letters

## Two- and Three-Dimensional Omnidirectional Wireless Power Transfer

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***Abstract*—Nonidentical current control methods for 2- and 3-D omnidirectional wireless power systems are described. The omnidirectional power transmitter enables ac magnetic flux to flow in all directions and coil receivers to pick up energy in any position in the proximity of the transmitter. It can be applied to wireless charging systems for low-power devices such as radio-frequency identification devices and sensors. Practical results on 2-D and 3-D systems have confirmed the omnidirectional power transfer capability.**

***Index Terms*—Inductive power, magnetic resonance, wireless power transfer.**

### I. Introduction

WIRELESS power pioneered by Tesla a century ago can be classified as radiative and nonradiative. In communication, omnidirectional antenna is a class of antenna that radiates signals in all directions [1]. For nonradiative applications, most of the low-power [2]–[4] and medium/high-power [5] wireless power applications have their power flow guided by coil resonators. In many low-power applications such as sensors and radio-frequency identification (RFID) devices, replacing the batteries has been a maintenance problem in industry. A well-designed omnidirectional wireless charging system is therefore a highly attractive and economic option for charging a multiple of devices simultaneously. Based on 2-D magnetic structures, the studies in [6] and [7] have described how magnetic flux can be controlled in different directions on a 2-D plane. In this letter, a patent-pending control methodology [8] for omnidirectional wireless charging systems is presented. It has been studied with the aid of time-domain finite-element magnetic field simulations and practically tested in hardware prototypes.

### II. Omnidirectional Wireless Power Systems With Orthogonal Coils

So far, the majority of the nonradiative wireless power systems have the power flow either in one direction (i.e., 1-D power flow) or two directions on the same plane (i.e., 2-D power flow). However, two recent reports explore the possibility of omnidirectional wireless power. In [9], the use of orthogonal coils is proposed to reduce the effect of small mutual inductance when the receiver coil is perpendicular to one of the transmitter coil (see Fig. 1). Their approach considers the open-ended coils as antennas, and use the parasitic coil inductance and capacitance to form an equivalent *LC* circuit. Because the coils are considered as antennas, such a design approach (based on impedance matching or the maximum power transfer (MPT) theorem) would have the following limitations.

1) The length of the wire used to implement the resonant circuit is comparable to the wavelength at the resonance frequency. Both of the transmitter and receiver coils are one quarter of the wavelength at the resonant frequency. This approach is therefore dimension dependent and is restrictive in terms of the relative sizes of transmitter and receiver coils.
2) Due to the usually low parasitic capacitance in open-ended coil, the resonant frequency and therefore the operating frequency is usually high. High-frequency ac power sources are usually more expensive than low-frequency ac power sources.

In [9], two separate orthogonal coils are driven by a single power source with the same ac current (i.e., the two separate coils are connected in series). This is why the receiver coil can pick up maximum power at an angle of 45° between the two orthogonal transmitter coils. This result is reasonable because at 45°, the vectorial sum of the two coaxial magnetic field vectors from

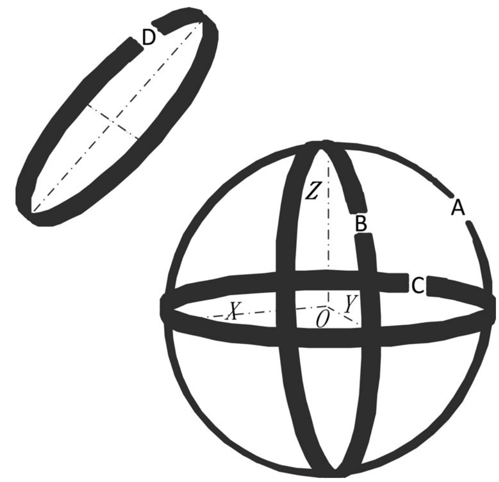


Fig. 1. Use of three separate orthogonal coils A, B, and C connected in series as a transmitter structure for wireless power transfer reported in [10].

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the two orthogonal coils is maximum if the two coil currents are identical. Wang *et al.* [9] also suggest the extension to the 3-D structure based on three separate orthogonal coils that are connected in series and fed by the same current.

In [10], a three-coil receiver structure with three orthogonal open-ended coils is placed inside a similar but larger three-coil transmitter structure also with open-ended coils. The three orthogonal transmitter coils are connected in series and driven with the same ac current. It was demonstrated that wireless power transfer to the three-coil receiver unit can be achieved regardless of the orientation of the receiver unit inside the transmitter structure. However, this orientation-insensitive feature is only possible if the receiver has three orthogonal coils. For RFID tags applications, it is more likely to have a single planar coil in the RFID tag as a receiver coil. So, the approach in [10] is not suitable for a single-coil receiver.

In summary, the magnetic resonance techniques were used in [9] and [10]. If impedance matching based on the MPT method is adopted, according to [4] and [11], the system energy efficiency will not exceed 50%. So, this project employs the maximum energy efficiency (MEE) approach. The use of the same current in the orthogonal coils (i.e., identical current control) also does not generate magnetic field vector that points in all directions in a 3-D manner—which is an essential feature for true omnidirectional wireless power transfer. The next section will introduce the nonidentical current control methods.

## III. Control Methods for Omnidirectional Wireless Power Systems

Fig. 1 shows a typical winding structure of a 3-D omnidirectional transmitter comprising three orthogonal coils in the $x$-, $y$-, and $z$-plane. In practice, each coil is connected to a series capacitor to form a coil resonator. Each resonator is driven by an ac power source. For genuine omnidirectional wireless power transfer, it is necessary for the orthogonal coils current to be nonidentical [8]. The three coil currents can generally be expressed as follows:

$$\mathrm{I}_1 = I_{m1} \sin(\omega t) \tag{1}$$

$$\mathrm{I}_2 = I_{m2} \sin(\omega t + \alpha) \tag{2}$$

$$\mathrm{I}_3 = I_{m3} \sin(\omega t + \beta) \tag{3}$$

where $\omega$ is the angular frequency of the currents, $t$ is the time variable, $I_{mx}$ is the current magnitude of coil-$x$ (for $x = 1$, 2, 3), and $\alpha$ and $\beta$ are two angular displacements. To achieve omnidirectional wireless power transmission, rotating magnetic field vectors can be generated by either: 1) current amplitude modulation; 2) phase angle control; or 3) frequency modulation [8].

First, the amplitude modulation control is illustrated with the following example. Let $I_{m1} = I_m, I_{m2} = I_m \sin(\omega_2 t), I_{m3} = I_m \sin\left(\omega_2 t + \frac{\pi}{2}\right), \alpha = \frac{\pi}{2}$, and $\beta = \frac{\pi}{2}$, where $\omega_2$ is another angular frequency different from $\omega$. Equations (1)–(3) become

$$\mathrm{I}_1 = I_m \sin(\omega t) \tag{4}$$

$$\mathrm{I}_2 = [I_m \sin(\omega_2 t)] \sin\left(\omega t + \frac{\pi}{2}\right) \tag{5}$$

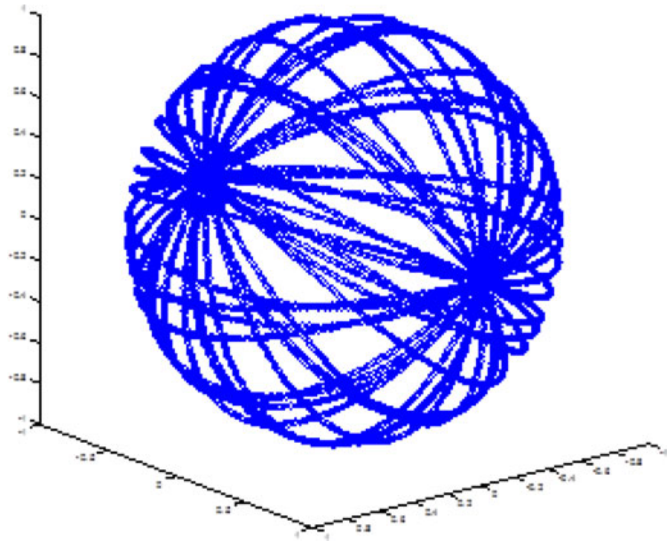

Fig. 2. Trajectory of the magnetic field vector from viewpoint [1 1 1] of a 3-D omnidirectional wireless power transmitter under the current amplitude modulation control.

$$\mathrm{I}_3 = \left[I_m \sin\left(\omega_2 t + \frac{\pi}{2}\right)\right] \sin\left(\omega t + \frac{\pi}{2}\right). \tag{6}$$

In this particular case, the magnitude of $\mathbf{I}_1$ is constant. The magnitudes of $\mathbf{I}_2$ and $\mathbf{I}_3$ vary with two sinusoidal envelopes that are 90° out of phase. This system is studied with the coupled circuit model used in [12]–[14] and an electromagnetic field solver [15]. The current values and the phase angles are calculated and sampled over several excitation cycles at the fundamental angular frequency $\omega$. The datasets obtained in a time sequence are recorded and the magnetic fields are plotted so that the peaks of the magnetic field vectors can be obtained. The movements of the peak magnetic field vectors are then traced to form the trajectory. The trajectory of the magnetic field vectors for several excitation cycles is plotted in Fig. 2. It can be seen that the magnetic field vectors rotate periodically in all directions, confirming the omnidirectional nature of the wireless power transmission.

Second, the frequency modulation control can be achieved for (1)–(3) in various ways. For example, by putting

$$\alpha = k\beta \tag{7}$$

$$\alpha = |\alpha_m| \sin(\omega_2 t) \tag{8}$$

where $k$ is a real number, $\omega_2$ is the angular frequency of the phase-angle variation, and $\alpha_m$ is the constant coefficient. Third, for phase angle control, one can simply excite the system with the three orthogonal coil currents with the same current magnitude according to (1)–(3) but with a phase shift according to (7).

It should be noted that the 3-D wireless power transmitter can be reduced to a 2-D one if only two coils are excited with electric currents. For example, if the coil on the $z$-plane is not used, appropriate current excitation of the coils on the $x$-plane and $y$-plane (i.e., the green and red coils in Fig. 3) can still create a rotating magnetic field over the *xy* plane in a 2-D manner.

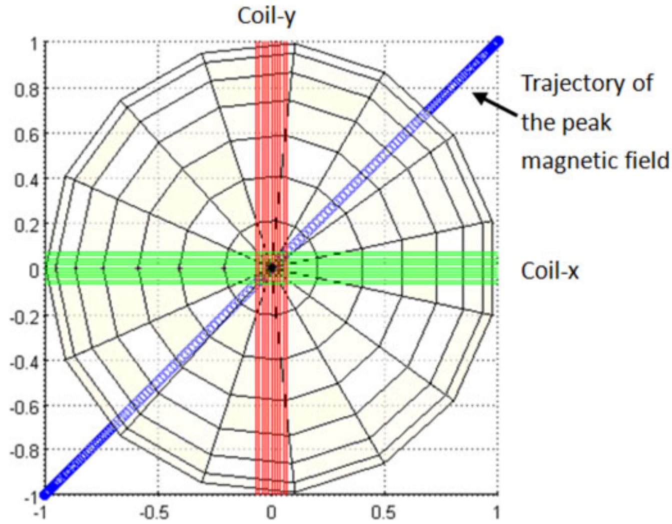


Fig. 3. Trajectory of a 2-D transmitter under the identical current control with three identical currents without phase shift (view ([0 0 1]—i.e., top view from the $z$-axis).

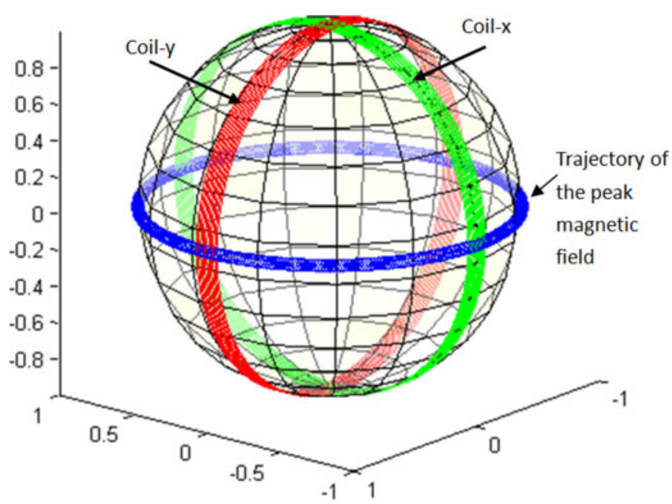


Fig. 4. Trajectory of the arrow-head of the peak magnetic field vector under the nonidentical current control (the same current amplitude with 90° phase shift in coil-x and coil-y) in a 2-D transmitter.

For a 2-D omnidirectional power system, if the identical current control is used, computer simulation shows that the ac magnetic flux essentially points at two directions. Fig. 3 shows the trajectory of the peak magnetic field vector of the 2-D transmitter system when the two transmitter coil currents are identical. It can be seen that the trajectory is a straight line (i.e., the blue line in Fig. 3), indicating that the magnetic flux points in two directions that are along the 45° between the planes of the transmitter coil-x and coil-y. If a phase shift of 90° is introduced between the currents in coil-x and coil-y, the trajectory of the peak magnetic field vector is plotted in Fig. 4. This trajectory is a circle (i.e., the blue circle in Fig. 4), meaning that the magnetic field vector rotates in a full circle and covers all directions on the 2-D plane.

Fig. 5. Photograph showing that three LED loads are powered by three receiver resonators placed around a 2-D omnidirectional wireless power transmitter excited with two coil currents of the same magnitude but with a phase angle difference of 90°.

## IV. Practical Verification

### A. Two-Dimensional Omnidirectional Wireless Power System

A 2-D omnidirectional wireless power transmitter with two orthogonal coils in the $x$- and $y$-plane has been setup up as shown in the center of Fig. 5. The two coils are wounded on a plastic sphere, and two capacitors $C_1$ and $C_2$ are connected in series with them, $C_1$=$C_2$ = 0.76 nF. They are excited with $\mathbf{I}_1$ and $\mathbf{I}_2$ of (1) and (2), respectively, with $I_{m1}$=$I_{m2}$ = 800 mA, $\alpha = \pi/2$, and an angular frequency of 3 330 000 rad/s. The coil-x and coil-y are identical and each has 14 turns and a diameter of 25.4 cm. The self-inductance is 116.28 $\mu$H. Three single coil-resonators are used as three separate receiver units. Each receiver unit is loaded with four 1 W LED devices. The coil in each receiver unit has 11 turns and a diameter of 30.7 cm. Its self-inductance is 88.57 $\mu$H. Each coil has a capacitor $C$ connected in series, $C$ = 1 nF. The three receiver units are arbitrarily placed around the 2-D omnidirectional transmitter. It can be seen that all of the three LED loads are lit wirelessly.

In order to differentiate the significance of the amplitude modulation, tests are conducted with 1) identical currents in both transmitter coils; and 2) nonidentical currents. The peak value of the transmitter coil currents is set to 1 A at an operating frequency of 530 kHz. One receiver coil is placed at different points with its coil center being 30 cm away from the center of the transmitter coil.

Fig. 6 shows the theoretical and measured energy efficiency of the tests when identical currents are used in the transmitter

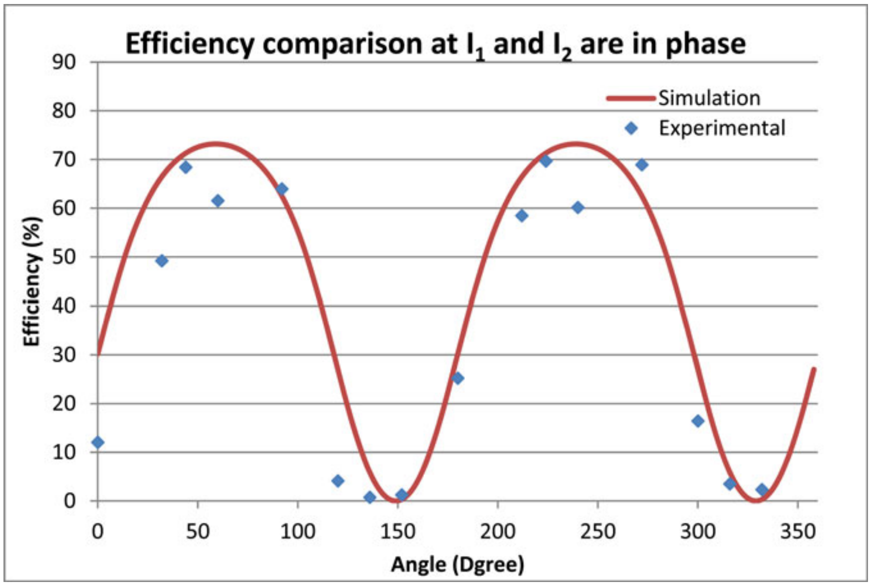


Fig. 6. Measured and theoretical energy efficiency under the identical current control.

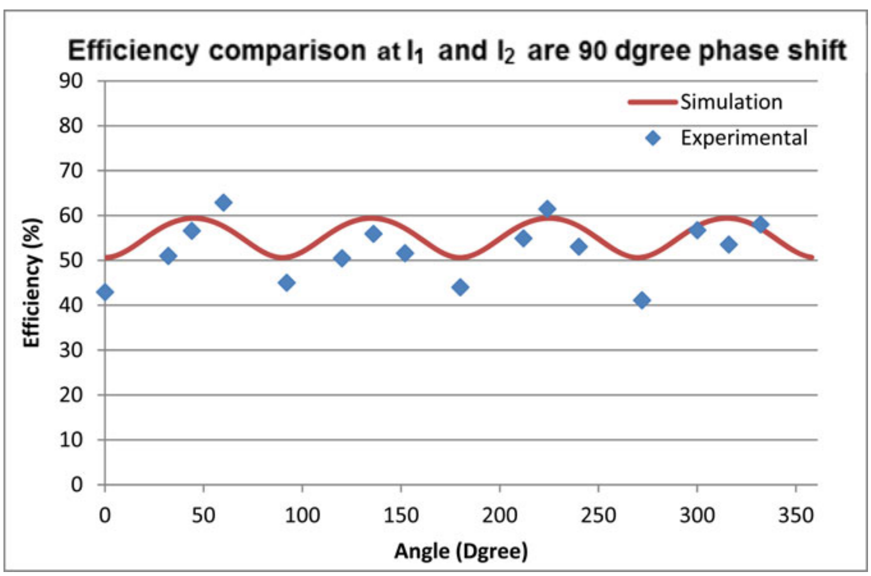


Fig. 7. Measured and theoretical energy efficiency under the nonidentical current control.

coil-x and coil-y. The theoretical values are computed using the coupled circuit equation previously reported in [12]–[14]. Some differences between the practical measurements and theoretical ones are expected because the *LC* values of the coil resonators are not exactly identical due to the component tolerance. In addition, any slight error in the distance between the receiver coil and the transmitter coil will lead to practical measurements different from the ideal theoretical values. Despite these practical issues, the practical measurements are largely consistent with the theoretical values. It can be seen that the power transfer occurs efficiently only in two directions. In other directions, the power transfer efficiency is low. These set of measurements indicate that the identical current control does not lead to true omnidirectional power transmission on a 2-D plane.

Fig. 7 shows the theoretical and practical energy efficiency when the two transmitter coil currents have a phase shift of 90°. Although the peak energy efficiency is less than that of the identical current control, the energy efficiency is much more even over the entire angular range within a circle when the nonidentical current control is employed. This set of results therefore confirms the omnidirectional wireless power transfer capability of the proposed nonidentical current control on the 2-D plane.

### *B. Three-Dimensional Omnidirectional Wireless Power System*

A 3-D omnidirectional system has been constructed for practical evaluation. Three excitation windings with angular

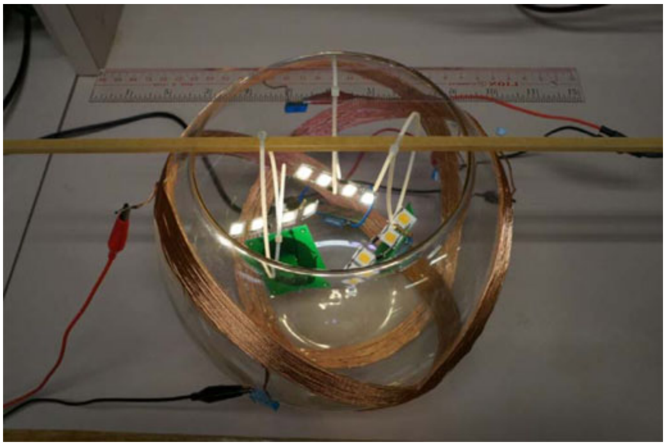

Fig. 8. Practical demonstration of a 3-D omnidirectional wireless power transfer system based on three excitation coils with angular displacements and identical current control.

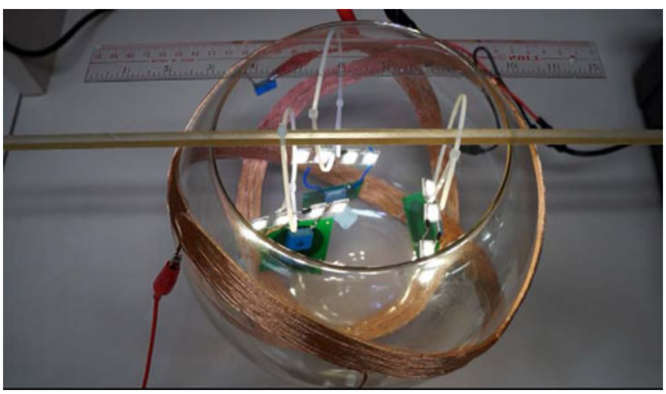

Fig. 9. Practical demonstration of the 3-D omnidirectional wireless power transfer system based on three excitation coils with angular displacements and the proposed nonidentical current control.

displacement are wound on the outer surface of a glass bowl. Three loads are located inside the bowl. Each load consists of a planar printed-circuit board spiral winding, a rectifier, and four 1 W LED devices. The three loads are hung inside the glass bowl with the planes of the receiver spiral windings pointing at different directions. This setup simulates the random locations of the loads inside the 3-D omnidirectional wireless power transmitter.

Fig. 8 shows the photograph of the system under the identical current control with $I_m = 250$ mA. $\alpha = 0$ and $\beta = 0$ in (1)–(3). It can be seen that only two sets of LED loads are turned ON, while one set of LED load fails to receive wireless power. Under the proposed nonidentical current control method, the three windings are excited with three-phase currents with a peak magnitude of 250 mA and 120° displacement, i.e., for (1)–(3), $I_m = 250$ mA. $\alpha = 2\pi/3$ and $\beta = -2\pi/3$. This phase angle approach is a type of nonidentical current control. All sets of LED loads are turned ON as shown in Fig. 9.

## V. Conclusion

Nonidentical current control for 2-D and 3-D omnidirectional wireless power transmission has been proposed and tested. It has been theoretically and practically confirmed that the proposed nonidentical current control methods can generate magnetic field in all directions and lead to true omnidirectional wireless power transfer capability. The computer-aided simulation results have confirmed the 3-D omnidirectional power transmission trajectory of the magnetic field vectors. When reduced to a 2-D system, magnetic flux can point at all directions on a 2-D plane. Practical results for both 2-D and 3-D systems have been obtained to confirm the proposed concepts. Instead of using the MPT method which requires impedance matching and has severe energy efficiency limitation of not higher than 50%, the proposed approach employs the MEE method. Consequently, the system energy efficiency higher than 50% is possible.

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