

Poloidal Vector Potential Transformer

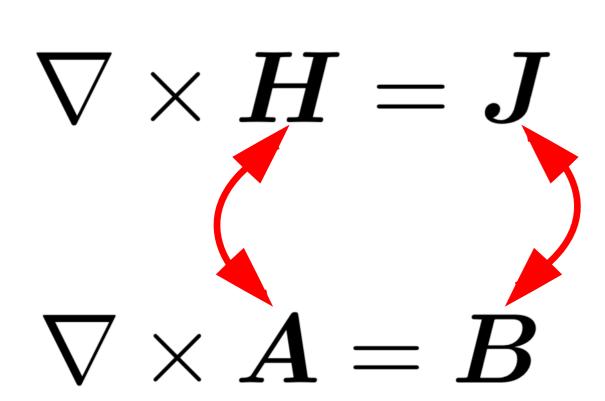


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ABSTRACT

We construct a long and flexible solenoid coil by winding a thin, insulated wire around a slightly thicker core wire. The flexible solenoid resembles a string of a guitar or a piano, and it is wound on a torus in the toroidal direction. In a normal toroidal coil, a wire is wound in the poloidal direction, but in the case of our coil, the flexible solenoid is wound in the toroidal direction. The result is a multi-nested coil. We test the usage of this nested coil in a poloidal vector potential transformer. Since the winding and the core wire are short-circuited at the one end of the flexible solenoid, the current returns through the core wire, so that no net magnetic field is generated from the global current path. There is practically no magnetic field outside the sufficiently long flexible solenoid. Consequently, no magnetic flux is created outside the solenoid; instead, a vector potential exists. The secondary coil of the poloidal vector potential transformer is formed by placing a toroidal coil in the internal cavity of the torus. There is no magnetic flux inside secondary coil, but a finite induced voltage can be observed. The induced voltage is proportional to frequency at low frequencies, but sharply increases at high frequencies. The only issue that the primary coil is very long. Nevertheless, the developed transformer can generate an induced voltage, even if there is no magnetic field inside the secondary coil.

PRINCIPLE



The relationship between magnetic field H, current density J, vector potential A, adn magnetic flux density B is considered according to Maxwell's equations.

 $m{H}$ corresponds to $m{A}$ and $m{J}$ corresponds to $m{B}$.

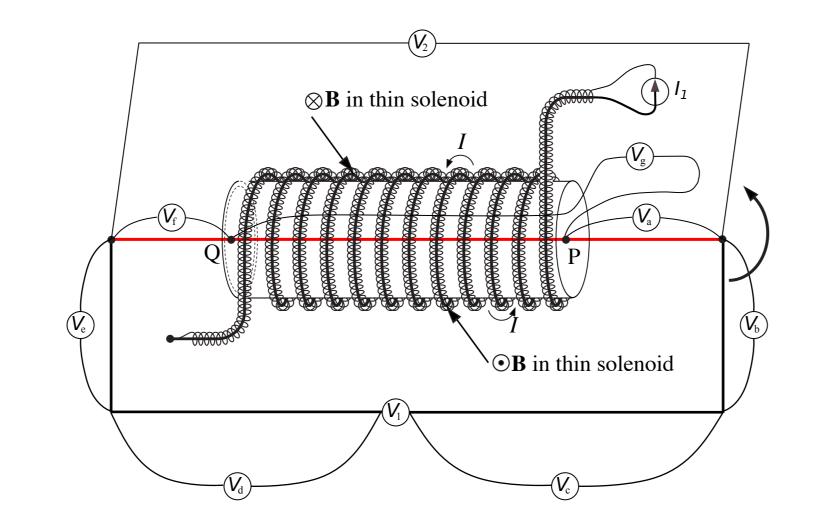


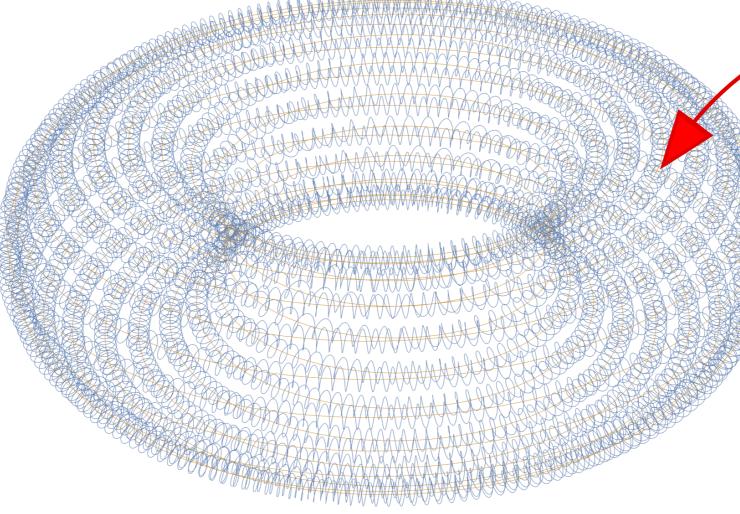
Fig. 1. Presence of magnetic flux in the measurement loop and the voltage

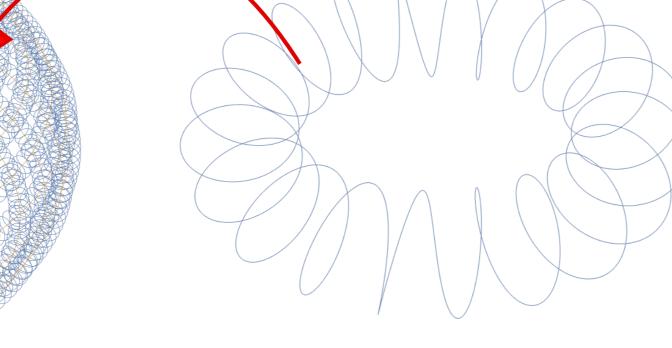
$$V_2 = \int_0^L \mu_0 n_1 n_2 s_2 \frac{dI}{dt} \cdot dr.$$

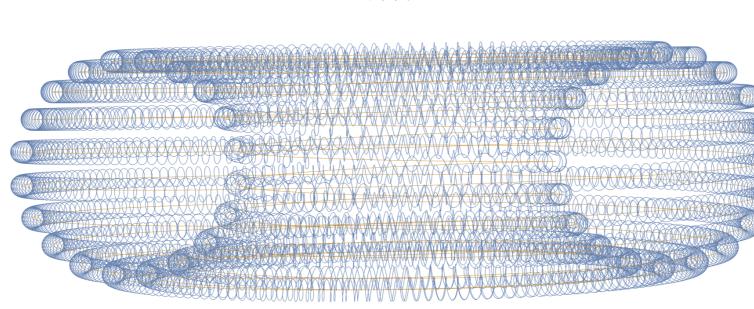
 $\oint_{\mathcal{C}} \mathbf{A} \cdot d\mathbf{l} = \iint_{\mathcal{C}} (\nabla \times \mathbf{A}) \cdot \mathbf{n} \, ds.$

Therefore, the location fo the main voltage induced in tl snap loop remains unknown. If we measure the voltage from V_a to V_f in each section of the loop, then $V_a = V_b = V_c = V_d =$ $V_e = V_f = 0$. From Kirchhoff's voltage law, $V_{PQ} = V_1 - V_2$ $V_a - V_b - V_c - V_d - V_e - V_f = V_1$. Therefore, the loop voltage is generated only in the vector potential coil. Here, based on Faraday's electromagnetic induction and because there is no magnetic flux inside each loop, $V_a = V_b = V_c = V_d = V_e =$ $V_f = 0$ and no voltage is generated. If V_q is connected as in the Fig. 1, in order to measure V_{PQ} with no magnetic flux in the measurement loop, $V_q = 0$, so $V_{PQ} = V_1$ cannot be proved directly. This is because the same voltage, as indicated by the red line between P and Q, is induced in the lead wire on the left side of V_g . Faraday's electromagnetic induction does not provide information on where the voltage is in the loop.

To measure the potential difference between the two points, we consider a conductor placed in a space with a vector potential. Although a line integral with a finite path is sufficient in practice, thanks to the lead wire, the line integral becomes a closed loop integral including the lead wire. Then, using Stokes' theorem, the line integral can be converted into the surface integral, so $B = \nabla \times A$ can be used as an integrand, and the magnetic flux density B is introduced. We think that the inner product of the time derivative of the vector potential and the wire path is the essence of the induced voltage. Moreover, we considered that electromagnetic induction is ossible even if there is no magnetic flux in the loop.







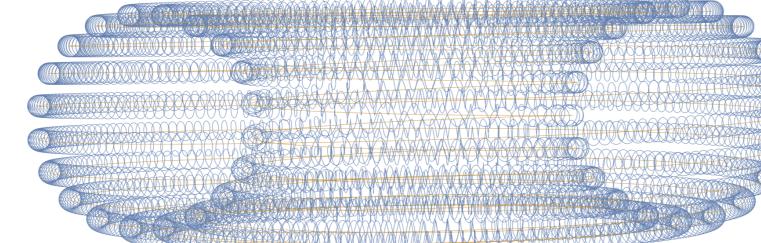


Fig. 2. Primary coil of toroidal vector potential transformer.

TABLE I COIL DIMENSIONS

Description	Symbol	value	Uni
Number of turns per unit length of thin solenoid	n_0	710	turns/n
Number of turns of poloidal coil	N_1	36	turn
Number of turns of secondary toroidal coil	N_2	280	turn
Toroidal central-axis radius	R	60	mr
Toroidal radius	r_1	25	mr
Thin sorenoid radius	s	1.5	mr
Toroidal radius of secondary coil	r_2	14.5	mn

Listing 1. Mathematica code for drawing the primary coil 1 n = 200;

Fig. 3. Toroidal secondary coil, which is placed in torus.

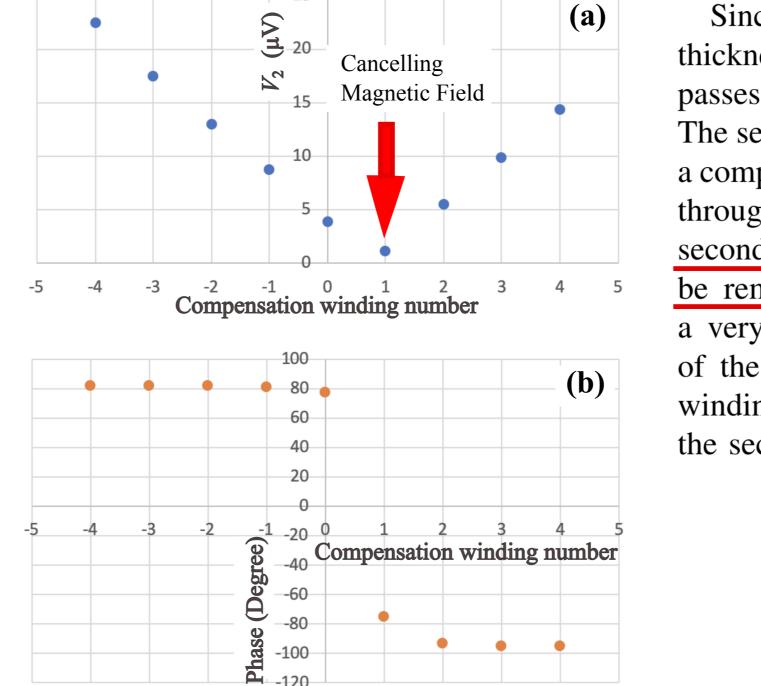
2 N1 = 20;3 R = 10;4 r = 4;5 s = 0.4;

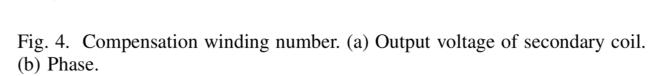
6 ParametricPlot3D[{{ 7 R Cos[N1 t] + r Cos[t] Cos[N1 t] + sCos[n N1 t Cos[t/4]] Cos[N1 t],8 R Sin[N1 t] + r Cos[t] Sin[N1 t] + s

Cos[n N1 t Cos[t/4]] Sin[N1 t],9 R Sin[t] r/R + s Sin[n N1 t Cos[t 10 {R Cos[N1 t] + r Cos[t] Cos[N1 t],11 R Sin[N1 t] + r Cos[t] Sin[N1 t], 12 R Sin[t] r/R

14 {t, -Pi, Pi}, PlotPoints -> 5000, Boxed -> False, Axes -> False]

EXPERIMENTAL RESULT and DISCUSSION





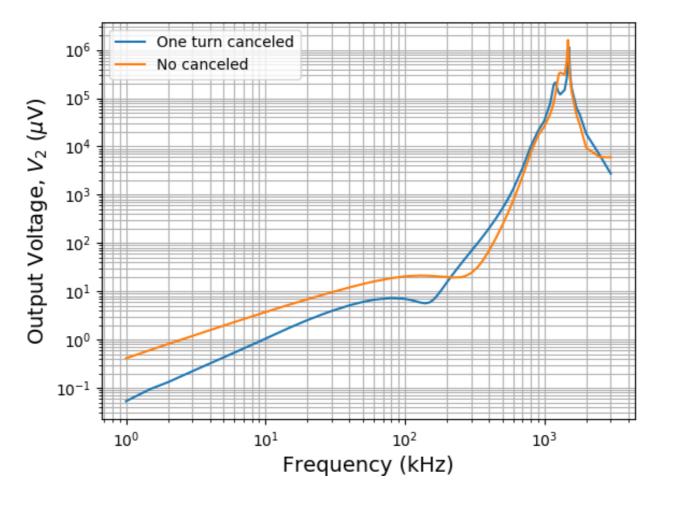


Fig. 2. frequency characteristics of the secondary voltage

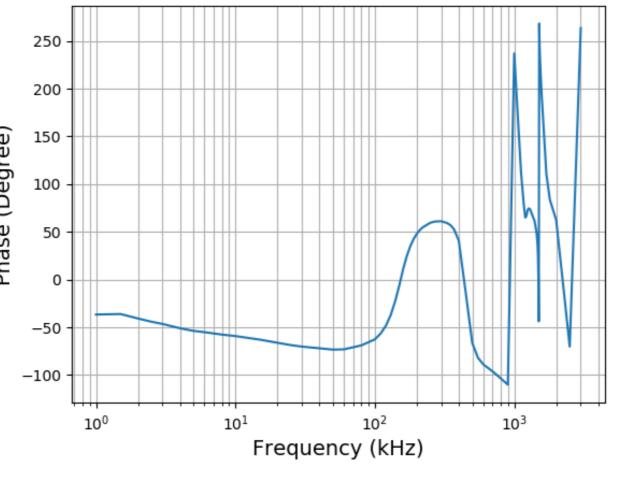
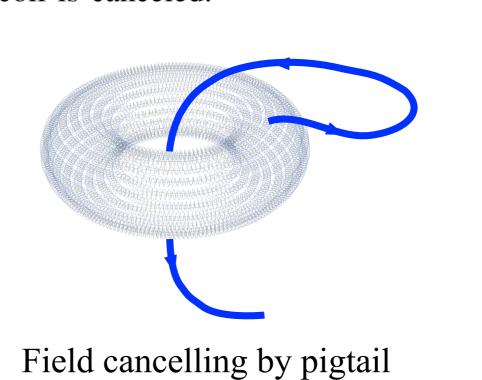


Fig. 6. Frequency characteristics of phase difference of secondary voltage with respect to primary current.

Since the actual coil is a flexible solenoid coil with a finite thickness that is wound around the serface of the torus, it passes through the hole in the center of the torus only once. The secondary coil is a one-round toroidal coil. Hence, there is a component of one-turn loop. The flexible solenoid coil passes through this loop once. That is, the magnetic flux passes the secondary coil and the contribution of this component must be removed from signal. Therefore, the pigtail, one end of a very long flexible solenoid coil, is inserted into the hole of the torus. The insertion direction is opposite to the first winding direction. In this way, the magnetic flux coupling to the secondary coil is canceled.

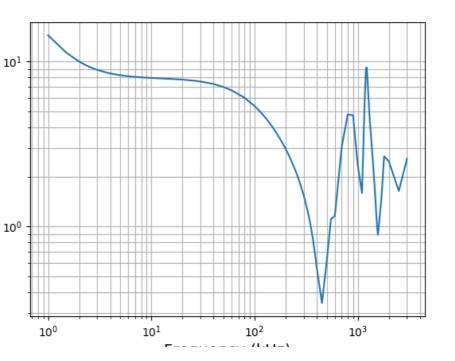


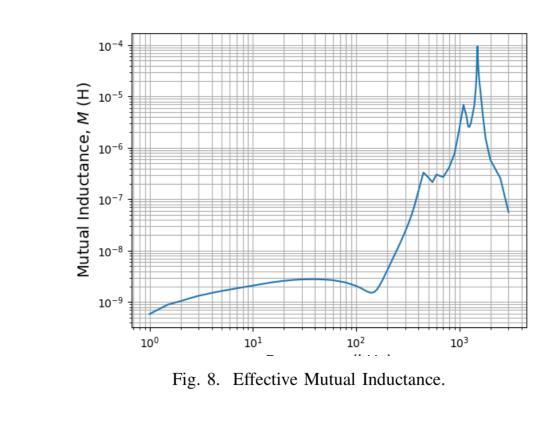
After careful cancellation of the magnetic flux, the frequency characteristics of the secondary voltage of the poloidal vector potential transformer are measured (Fig. 5). The orange line corresponds to the case where the number of compensation turns is zero, and the blue line corresponds to the case where the number of turns is +1. In a frequency range sufficiently lower than that of the dominant pole, a voltage proportional to the first derivative of time is generated despite the absence of magnetic flux. That is, the secondary coil can be driven from the outside by using the poloidal vector potential coil. Therefore the vector potential generated from the intermittent solenoid coil is superposed to generate rotation and the magnetic field is re-formed. In the 200 kHz -1 MHz range, the output voltage changes by as much as 80 dB/dec.

Fig. 6 shows the phase difference of the output voltage with respect to the input current with the compensation. It has goes through four resonances, i.e. in-phase, until the peak voltage is achieved.

Fig. 7 shows the frequency characteristics of the primary current, which becomes inductive starting from around 10 kHz. Then, the current decreases, and it reaches a minimum around 40 kHz. At this point, it becomes capacitive and the current increases again.

In the case of a normal magnetic transformer, the output voltage decreases at a high frequency, where the primary current becomes capacitive, but the voltage of the transformer increases 10,000 times due to frequency changes over a decade. In a general magnetic transformer, a secondary coil is arranged in parallel with a vector potential generated by the primary coil.





Initially, we considerd that this multiple interaction could generate a large voltage. However, if that were the case, that characteristic should also appear at low frequencies. The sudden voltage increase at high frequencies may be due to the displacement current being driven by the line voltage underlying the winding resistance and flowing through a stray capacitance between the windings. Since the vector potential generated from this displacement current is parallel to the secondary winding in the poloidal direction, a potential can be generated in the secondary winding. The vector potential generated by this displacement current adds to the rotation of the vector potential in the hollow space of the torus and may be equivalent to the magnetic flux.

Fig. 8 shows the mutual inductance M, $M = V_2/(j\omega I_1)$. The change normalized by the frequency dependence of the primary current is confirmed.

SUMMARY

We created a poloidal vector potential transformer, which consisted of a primary coil with a thin and long flexible solenoid coil wound in the toroidal direction on the surface of the torus, and a toroidal secondary coil placed inside the torus. A global current return path and pigtail compensation winding were provided to prevent the magnetic flux from passing through the secondary coil. When the electrical characteristics of this coil were measured, a secondary voltage was observed even though there was no magnetic flux inside or outside the secondary coil. At high frequencies, the toroidal secondary coil was driven from the outside by the vector potential generated by the displacement current via the coil-to-coil capacitance. Hence, a steep frequency response of 80 dB/dec was obtained. This transformer is unique in that no magnetic flux exists inside the secondary coil, but it is rather driven from the outside. This transformer, however, has certain disadvantages. First, the resistance is high because the primary winding is very long. However, if a superconducting wire is used, a large amount of the current can flow and the output voltage will increase. In addition, since the vector potential can affect quantum interference, the vector potential coil and superconducting technology are highly compatible, and many applications can be expected.

Reference

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- [2] Masahiro Daibo, et al., "Vector potential coil and transformer," IEEE Transactions on Magnetics, Vol. 51, No. 11, pp. 1-4, 2015. [3] Masahiro Daibo, et al., "Vector-potential transformer with a superconducting secondary coil and superconducting magnetic shield," IEEE Transactions on Applied Superconductivity, Vol. 26, No. 3, pp. 1-4, 2016.
- [4] Masahiro Daibo, et al., "Vector-potential transformer with a superconducting secondary coil and superconducting magnetic shield," IEEE Transactions on Applied Superconductivity, Vol. 26, No. 3, pp. 1-4, 2016.