# Power Frequency Magnetic Field Reduction Method for Residents in the Vicinity of Overhead Transmission Lines Using Passive Loop

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**Abstract** – A power frequency magnetic field reduction method using passive loop is presented. This method can be used to reduce magnetic fields generated within the restricted area near transmission lines by alternating current overhead transmission lines. A reduction algorithm is described and related equations for magnetic field reduction are explained. The proposed power frequency magnetic field reduction method is applied to a scaled-down transmission line model. The lateral distribution of reduction ratio between magnetic fields before and after passive loop installation is calculated to evaluate magnetic field reduction effects. Calculated results show that the passive loop can be used to cost-effectively reduce power frequency magnetic fields in the vicinity of transmission lines generated by overhead transmission lines, compared with other reduction methods, such as active loop, increase in transmission line height, and power transmission using underground cables.

**Keywords**: Passive loop, Power frequency, Transmission lines, Magnetic field reduction, Reduction ratio

## 1. Introduction

Whether power frequency magnetic fields generated by alternating current transmission lines have harmful biological effects on the human body or not is still a controversial issue. Several studies on in vivo and in vitro epidemiology have been carried out to find evidence of a link between power frequency magnetic fields and cancer [1–7]. Most of the concern about transmission lines and cancer mainly stems from epidemiological studies of people living near transmission lines, and epidemiological studies of people working in "electrical occupations". However, laboratory studies have little evidence linking power frequency magnetic fields and cancer. In these circumstances, the World Health Organization has maintained a precautionary principle, which states that when there are indications of possible adverse effects, although they remain uncertain, the risks from doing nothing may be far greater than the risks of taking action to control these exposures [8]. The precautionary principle shifts the burden of proof from those suspecting a risk to those who discount it. The WHO recommends that government and industry provide the public with safe and low cost ways to reduce exposures to electromagnetic fields, which includes power frequency magnetic field.

There are several power frequency magnetic field reduction methods. These are increase in the height of transmission lines, power transmission using underground cables, active loop, and passive loop.

Among these methods, the passive loop is the most cost-effective power frequency magnetic field reduction method. In particular, it can be cost-effectively applied to the restricted area near the transmission lines where people live and the magnetic fields produced by transmission lines have to be reduced to an exposure level safe for human health. Up to now, the passive loop is considered as a response to the recommendation of the WHO to provide safe and low cost magnetic field reduction ways for the public.

In this paper, a magnetic field reduction algorithm for the restricted area near transmission lines based on the passive loop is described. Further, related equations are explained. The proposed power frequency magnetic field reduction method is applied to a scaled-down transmission line model, and the lateral distribution of the reduction ratio between magnetic fields before and after a passive loop installation is calculated to evaluate magnetic field reduction effects.

## 2. Power Frequency Magnetic Field Reduction Using Passive Loop

### 2.1 Fundamental magnetic field reduction principle

A typical passive loop consists of a loop of conducting wire and capacitor for reactance compensation of the passive loop. Fig. 1 shows an example of a passive loop installation for power frequency magnetic field reduction

within the restricted area in the vicinity of transmission lines. The fundamental principle of magnetic field reduction by passive loop is based on Faraday's Law of Induction [9]. Magnetic fields generated by transmission lines pass through the area enclosed by a passive loop of conducting wires. The electromotive force in the passive loop is generated proportionally to the rate of change of the magnetic flux. Owing to the cancellation of magnetic fields generated by transmission lines and those generated by the passive loop within a residential area (Fig. 1), the magnitude of magnetic fields are lower than those generated by transmission lines only.
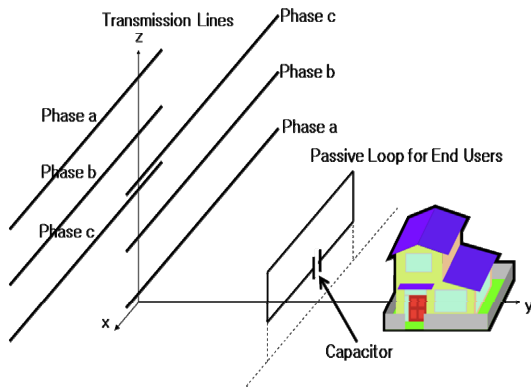


**Fig. 1.** Passive loop for power frequency magnetic field reduction within the restricted area near transmission lines
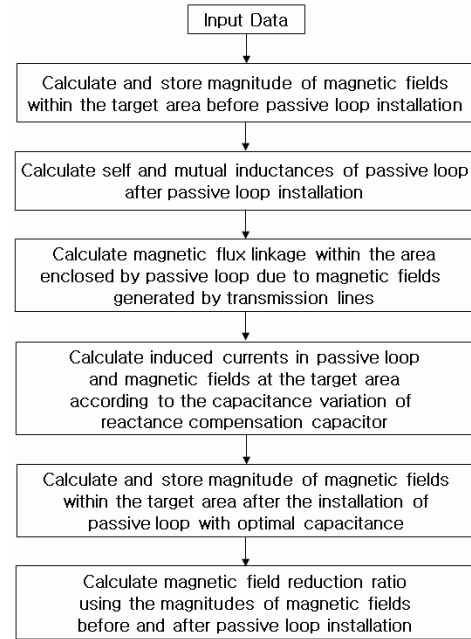
## 2.2 Magnetic field reduction algorithm

Fig. 2 shows an algorithm for power frequency magnetic field reduction within the restricted area in the vicinity of transmission lines. The following are included as data input: geometry data of transmission lines, which include coordinate, height, length, and radius of transmission lines; magnitude and phase of transmission line currents; position, geometry, and number of turns of passive loop; capacitance range for reactance compensation; and target area for magnetic field reduction.

## 2.3 Magnetic field calculation before passive loop installation

Magnetic fields within the target area before the installation of passive loop are calculated based on the Biot-Savart law [9]. Fig. 3 shows a transmission line parallel to the x-axis and the line current. I[A], flows in this transmission line. Magnetic field intensity at point P(x,y,z) is calculated using (1).

$$\vec{H} = \frac{I}{4\pi} \int_{line} \frac{\vec{dl} \times \vec{R}}{R^3}, \qquad (1)$$

where



**Fig. 2.** A magnetic field reduction algorithm
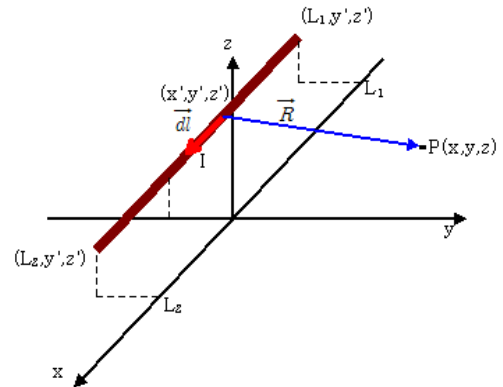


**Fig. 3.** Magnetic field at point P(x,y,z), in which the line current is parallel to the x-axis

$$\vec{dl} = dx' \hat{x},$$
$$\vec{R} = (x - x')\hat{x} + (y - y')\hat{y} + (z - z')\hat{z}.$$

After the integration of $L_1$ to $L_2$ with variable x, the magnetic field intensity at point P(x,y,z) because of finite line current is expressed as follows:

$$\vec{H} = \frac{I}{4\pi} \frac{(z - z')\hat{y} - (y - y')\hat{z}}{(y - y')^2 + (z - z')^2} \times$$

$$\left\{ \frac{x - L_2}{\sqrt{(x - L_2)^2 + (y - y')^2 + (z - z')^2}} - \right.$$

$$\left. \frac{x - L_1}{\sqrt{(x - L_1)^2 + (y - y')^2 + (z - z')^2}} \right\} \qquad (2)$$

Magnetic field intensity at point P(x,y,z) because of transmission lines can be calculated from the vector summation of the contribution of each transmission line.

## 2.4 Calculation of Self and Mutual Inductances of Passive Loop

The general shape of a passive loop for magnetic field reduction within the restricted area in the vicinity of transmission lines is of the grid type. In this section, self and mutual inductances of passive loop consisting of two grids (Fig. 4) are calculated.
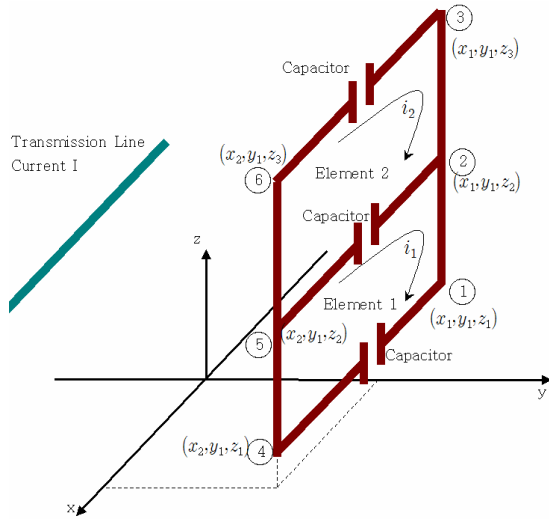


**Fig. 4.** The passive loop consists of two grids

To calculate the self inductance of the passive loop, the magnetic flux linkage with the area enclosed by the element m of the passive loop because of induced current in the element m of the passive loop should be calculated. Given that the passive loop shown (Fig. 4) is parallel to the x-z plane, the magnetic field intensity on the surface of the passive loop because of induced current in conductor ①-④ of element 1 is expressed as (4).

$$\vec{H} = \frac{i_1}{4\pi} \frac{1}{(z-z_1)} \times$$
$$\left\{ \frac{x-x_2}{\sqrt{(x-x_2)^2 + (z-z_1)^2}} - \frac{x-x_1}{\sqrt{(x-x_1)^2 + (z-z_1)^2}} \right\} \quad (4)$$

The magnetic flux linkage with element 1 of the passive loop because of the induced current in conductor ①-④ of element 1 can be obtained from (5).

$$\Phi = \int_{z_1}^{z_2} \int_{x_1}^{x_2} B \, dx \, dz$$
$$= \int_{z_1}^{z_2} \int_{x_1}^{x_2} \mu H \, dx \, dz \quad (5)$$

Magnetic flux linkage with element 1 because of the induced current in other conductors of element 1 can be calculated similarly. Self inductance of element 1 of the passive loop is given as the ratio of net magnetic flux linkage with the area enclosed by element 1 because of the induced current in element 1 to the induced current in element 1.

Mutual inductance is the ratio of net magnetic flux linkage with the area enclosed by element n because of the induced current in element m to the induced current in element m. Magnetic flux linkage with the area enclosed by element n because of the induced current in element m to the induced current in element m can be calculated by (5).

## 2.5 Calculation of induced electromotance in passive loop

According to Faraday's Law of Induction, induced electromotance, $V$, in each element of the passive loop because of the change in the magnetic flux generated by transmission lines is given as (6).

$$V = -\frac{d\Phi}{dt}, \quad (6)$$

where $\Phi$ is the magnetic flux linkage with each element of the passive loop because of the current of transmission lines. Thus, calculation of the magnetic flux linkage is required. Magnetic field intensity at any point because of the current of transmission lines is given as (2). Considering that the passive loop is parallel to the x-z plane, only the y-directional component of the magnetic field intensity is effective for induced electromotance. This happens because the magnetic flux linkage is obtained by the integration of the dot product of the magnetic flux density and the vector representing the element of the area over the surface of each element of the passive loop. This is given as follows:

$$\Phi = \int_S \vec{B} \bullet d\vec{a}. \quad (7)$$

The y-directional component of the magnetic field intensity because of the current of transmission lines is given as (8).

$$\vec{H}_y = \frac{I}{4\pi} \frac{(z-z')\hat{y}}{(y-y')^2 + (z-z')^2} \times$$
$$\left\{ \frac{x-L_2}{\sqrt{(x-L_2)^2 + (y-y')^2 + (z-z')^2}} - \frac{x-L_1}{\sqrt{(x-L_1)^2 + (y-y')^2 + (z-z')^2}} \right\} \quad (8)$$

Magnetic flux linkage with element 1 of the passive loop because of the current of transmission lines can be calculated by (9).

$$\Phi = \int_{z_1}^{z_2} \int_{x_1}^{x_2} \mu H_y \, dx \, dz \qquad (9)$$

Unfortunately integration cannot be obtained analytically. However, if the length of transmission lines is assumed to be sufficiently large, the y-directional component of the magnetic field intensity at any point within the surface enclosed by element 1 of the passive loop because of the current of transmission lines can be reduced to (10).

$$\vec{H}_y = \frac{I}{2\pi} \frac{(z-z')\hat{y}}{(y-y')^2 + (z-z')^2} \qquad (10)$$

By substituting (10) for $Hy$ in (9) and by integrating (9) analytically, the magnetic flux linkage results in (11).

$$\Phi = \frac{\mu I}{4\pi}(x_2 - x_1)\ln\left\{\frac{(y-y')^2 + (z_2-z')^2}{(y-y')^2 + (z_1-z')^2}\right\} \qquad (11)$$

After calculating each magnetic flux linkage because of the current of each transmission line and the net magnetic flux linkage, induced electromotance, $V$, can be obtained by (6).

## 2.6 Calculation of induced currents in passive loop

Induced currents in the passive loop can be obtained by (12). The elements of the impedance matrix are shown in the following equation:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}, \qquad (12)$$

where $V_k$ and $i_k$ are the induced electromotance and the induced current in element k of the passive loop, respectively. The impedance matrix consists of self and mutual inductances calculated in Section 2.4. The capacitance of the reactance compensation capacitor is included in the diagonal elements of the impedance matrix.

## 2.7 Magnetic field calculation after passive loop installation

The magnetic field at any point within the target area after passive loop installation is generated because of both the currents of transmission lines and the induced currents in the passive loop. The magnetic field generated by the transmission lines and the conductors of the passive loop parallel to the x-axis can be obtained by (2). The magnetic

field generated by the conductors of the passive loop parallel to the z-axis, as shown in Fig. 5, can be obtained by (13).
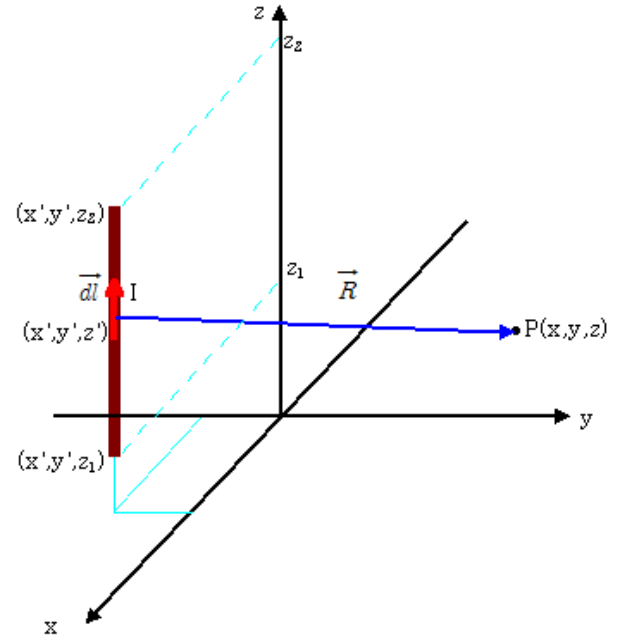


**Fig. 5.** Magnetic field generated by current flowing in the vertical conductor of a passive loop

$$\vec{H} = \frac{I}{4\pi}\frac{(x-x')\hat{y}-(y-y')\hat{x}}{(y-y')^2+(z-z')^2} \times$$

$$\left\{ \frac{z-z_2}{\sqrt{(x-x')^2+(y-y')^2+(z-z_2)^2}} - \frac{z-z_1}{\sqrt{(x-x')^2+(y-y')^2+(z-z_1)^2}} \right\} \qquad (13)$$

## 2.8 Magnetic field reduction factor

The magnetic field reduction factor is defined as follows:

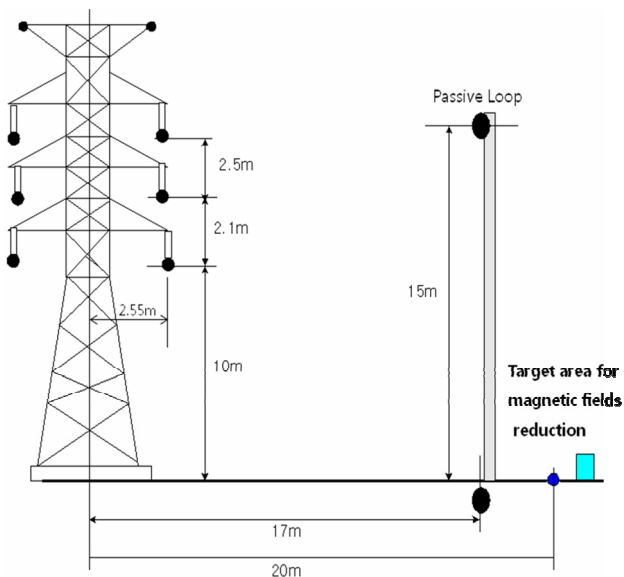$$FRF = \left(1 - \frac{H_A}{H_B}\right) \times 100[\%], \qquad (14)$$

where $H_A$ and $H_B$ are the magnetic field intensities after and before passive loop installation, respectively.

## 3. Case Study and Results

The proposed magnetic field reduction method is applied to a scaled-down transmission line model shown in Fig. 6.

**Fig. 6.** Passive loop and scaled-down transmission line model



**Fig. 7.** Modeling for magnetic field reduction calculation

Transmission lines are double circuit systems consisting of three phases. The root mean square value of the transmission current is 600 A. As shown in Fig. 7, the target area for magnetic field reduction is the restricted area on the surface of the ground 20 m away from the center of a transmission line tower. The passive loop with one grid is installed 17 m away from the center of the transmission line tower. The electrical and the geometrical data of the passive loop are as follows: length: 30 m, height: 15 m, diameter: 1.6 cm, resistivity: 0.0754 Ohm/km, number of turns: 3, and capacitance of reactance compensation capacitor: 10 mF.

Fig. 8 shows the distribution of measured and calculated magnetic field reduction factors along the lateral direction. The magnetic flux densities are 4.3 mG (transmission lines only), 3.25 mG (transmission lines and passive loop conductors), and 2.3 mG (transmission lines, passive loop conductors, and optimal compensation capacitor).

Therefore, the maximum field reduction factor, which is obtainable using the above passive loop, is about 50%.
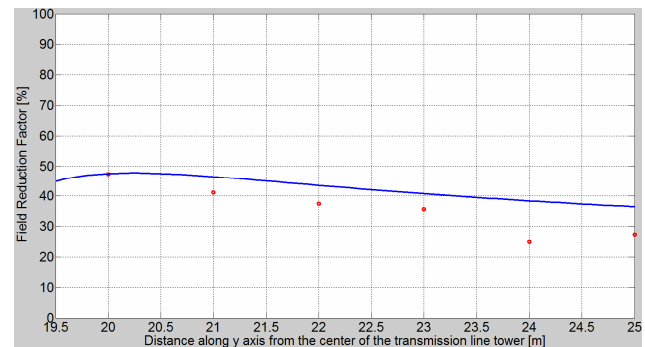


**Fig. 8.** Comparison between calculated (solid line) and measured magnetic field reduction factors

According to ICNIRP guidelines [10], the limit of exposure to a 60 Hz magnetic field for the general public is 833 mG. Nevertheless, countries such as Sweden, Italy, and the Netherlands, have introduced lower limit values than 833 mG, taking into account the effects of long-term exposure. The passive loop can be applied to satisfy the given limit value of the magnetic field. The optimal capacitance is determined to give the highest reduction factor at a point where maximum magnetic field intensity occurs within the target area, with the fixed geometrical data and other electrical parameters of the passive loop. This is possible because other data, except for the number of turns of the passive loop and the capacitance, are predetermined in most cases in consideration of the circumstances of the passive loop installation site. Optimal capacitance varies according to the number of turns of the passive loop.

Among the combinations of the number of turns and the optimal capacitance, the appropriate one can be selected by taking into account the field reduction factor and the installation costs. In this case, the optimal capacitance for maximizing the reduction factor at the point with the highest magnitude of magnetic field intensity within target area is about 10 mF.

There are some differences between measured and calculated magnetic field reduction factors within the target area. The differences occur because of the sagging of transmission lines and the passive loop, which were not taken into account in the proposed method. These may also occur because of measurement errors and other factors. To increase accuracy, a three-dimensional magnetic field reduction algorithm, which considers other factors, including the sags, should be used. However, in a practical point of view, the proposed two-dimensional magnetic field reduction method can be used for the prediction of the magnetic field reduction factor within the target area, where the passive loop is installed.

## 4. Conclusion

A power frequency magnetic field reduction method using a passive loop is presented. This method can be used to predict magnetic field reduction factors within the restricted area near transmission lines, if electrical and geometrical parameters of transmission lines and passive loop are given.

A reduction algorithm is described and related equations for magnetic field reduction are explained. In particular, it is the main advantage of the proposed algorithm compared with other passive loop methods, in which the optimal capacitance of the compensation capacitor can be calculated. This gives the maximum field reduction factor within the target area. The proposed power frequency magnetic field reduction method was applied to a scaled-down transmission line model. In addition, lateral distribution of the reduction ratio between magnetic fields before and after passive loop installation was calculated to evaluate magnetic field reduction effects. Results showed that the maximum field reduction factor is 26% when only passive loop conductors are installed and is about 50% when the optimal compensation capacitor is inserted in a series with passive loop conductors.

Based on the comparison between measured and calculated results, the passive loop can be used to cost-effectively reduce power frequency magnetic fields generated by overhead transmission lines, especially within the restricted area near transmission lines. In addition, it is also cost effective compared with other reduction methods, such as active loop, increase in transmission line height, and power transmission using underground cables. Regardless of some differences between the calculated values and the measured ones, the proposed method is expected to be used to predict the magnetic field reduction factor from a practical point of view.

## Acknowledgments

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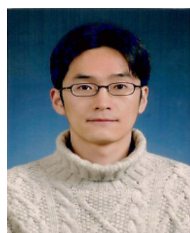


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