A New Concept of Magnetic Cable for Safe Mobile Power Delivery

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Abstract

Magnetic cables that can deliver high frequency AC electric power safely for flammable or sensitive workplaces preventing from arcs and electric shocks are firstly proposed in this paper. To deliver the power for a long distance, several new magnetic cable structures which drastically reduce the parallel leakage flux by appropriate magnetic shield between the magnetic cables are suggested; hence, the output power can be improved more than ten times. The proposed magnetic cables are fully analyzed and verified by simulations and experiments with good agreement. The output power and efficiency for a prototype magnetic cable of 1.5 *m* long and 1 *cm* gap between parallel cores were measured as 154 *W* and 67 %, where the source current and frequency were 10 *A* and 20 *kHz,* respectively.

1. Introduction

There are harsh workplaces where flammable gases, explosives, and chemicals are used and people are exposed to the risks of electric fires and electric shocks due to the electrical sparks or leakages of electrical cables. Sealing cables, plugs, and sockets have been used for these purposes as a solution, however, they are vulnerable to mechanical breaks and electrical short circuits. To solve these problems, contactless power transfer using inductive coupling [1]-[3] has been proposed, where there is no direct contact or exposure of the naked wire. This solution is clean and safe for benign environments such as clean rooms and wireless conveyer belts, but it is not adequate for unpredictable and mobile applications. Furthermore, it is still vulnerable to mechanical breaks and electrical leakages.

A new concept of "magnetic cable" is proposed in this paper as an extremely safe and flexible wired mobile power delivery device. The cable is composed of two parallel core lines, instead of copper lines, made of high permeability material to reduce series resistance and magnetic shield to prevent the magnetic leakage flux between the core lines. High frequency AC power can be delivered through this magnetic cable together with source and load transformers. The proposed magnetic cable was fully analyzed and verified by simulations and experiments.

2. Design of the proposed magnetic cable

2.1 Configuration

The proposed magnetic cable is composed of two parallel core lines, which are made of high permeability material, and a magnetic shield to reduce magnetic flux leakage. By connecting source and load windings to the magnetic cable and applying AC power input to the source winding, power can be transferred to the load, as shown in Fig. 1. Here, $\Re_p$ is the magnetic resistance representing the magnetic leakage flux and $\Re_s$ is the serial magnetic resistance of the magnetic cable, whereas $\Re_L$ is the load magnetic resistance. The magnetic cable is assumed to be of a cylindrical shape with a radius *r* and a cross section area *A*, where the gap between the core lines is *d* and the length of the cable is *l*, respectively. As the current flows in an electric cable, the magnetic flux Φ flows through the magnetic cable, by which the load voltage is induced in proportional to the number of turns and the operating frequency. The load power is determined by this induced voltage and the load current. To get higher power delivery, the serial magnetic resistance as well as the magnetic leakage flux should be minimized.

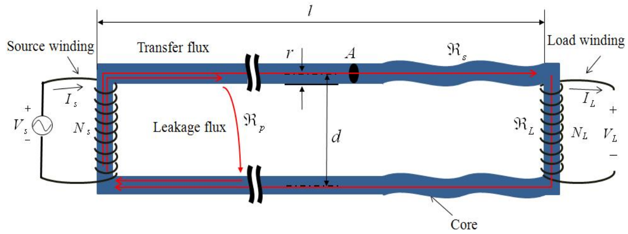
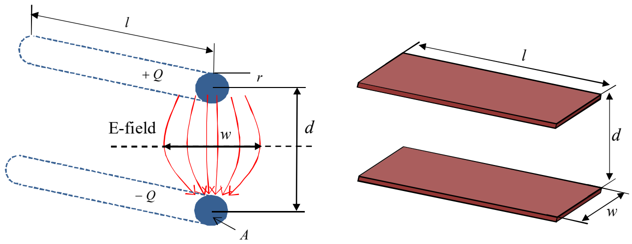


Fig. 1 A concept of the proposed magnetic cable

2.2 Analysis



(a) Two parallel lines (b) Equivalent parallel plates

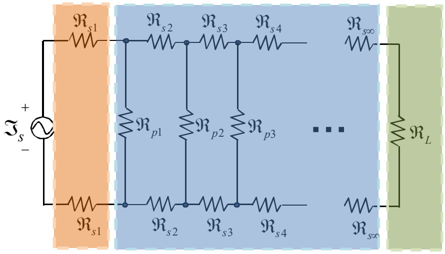
Fig. 2 The analogy of an electrical charge model to calculate the magnetic leakage resistance

To calculate the magnetic leakage resistance of the magnetic cable, an analogy model of two parallel lines with charges +*Q* and –*Q* is used, as shown in Fig. 2 (a). The capacitance of Fig. 2 (a), ignoring fringe effects at the ends, can be calculated as follows:

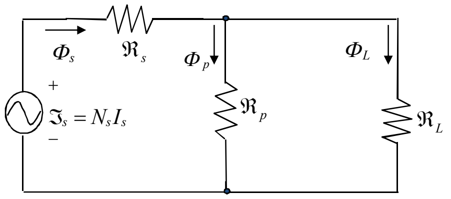
$$C = \frac{Q}{V} = \frac{\pi \varepsilon l}{\ln\left(\dfrac{d-r}{r}\right)} \tag{1}$$

Now a pair of parallel plates, as shown in Fig. 2 (b), which gives the same capacitance as the two parallel line charges, can be found pertaining the gap *d* and length *l* unchanged; hence, the equivalent width *w* of the magnetic cable can be determined as follows:

$$w = \frac{Cd}{\varepsilon l} = \frac{\pi d}{\ln\left(\frac{d-r}{r}\right)}, \quad \Re_p \equiv \frac{d}{\mu_o l w} = \frac{\ln\left(\frac{d-r}{r}\right)}{\mu_o l \pi} \tag{2}$$



(a) An exact but distributed magnetic circuit



(b) A simplified magnetic circuit

Fig. 3 Equivalent magnetic circuits of the proposed magnetic cable

The exact magnetic circuit is composed of infinitesimal distributed serial and parallel magnetic resistances, as shown in Fig. 3 (a). To analyze this complicated magnetic circuit, allowing a little analytical error, a simplified one with lumped circuit elements of $\Re_s$, $\Re_L$, and $\Re_P$ is shown in Fig. 3 (b). Here, $\Re_s$ and $\Re_L$ are as follows:

$$\Re_s = \frac{2l+d}{\mu_s \mu_o A}, \quad \Re_L = \frac{d}{\mu_s \mu_o A} \tag{3}$$

From Fig. 3(b), the load flux and load voltage are determined as follows, where the load voltage is maximized for $\Re_L << \Re_P$ and smaller $\Re_s$ and $\Re_L$.

$$\phi_L = \frac{N_s I_s}{\Re_s + \Re_L // \Re_p} \times \frac{\Re_p}{\Re_p + \Re_L} \tag{4}$$

$$V_L = N_L \omega \phi_L = \frac{\omega N_L N_s I_s}{\Re_s + \Re_L // \Re_p} \times \frac{\Re_p}{\Re_p + \Re_L} \cong \frac{\omega N_L N_s I_s}{\Re_s + \Re_L} = \frac{\omega N_L N_s I_s \mu_s \mu_0 A}{2(l+d)}$$
$$\text{for } \Re_L << \Re_p \tag{5}$$

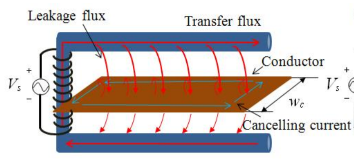
From (5), it is noted that the load voltage or load power increases for higher operating frequency ω, larger numbers of turns, N_s, N_L, larger source current I_s, higher magnetic permeability μ_s, and the area of the core, but decreases for a long magnetic cable.

2.3 Applications

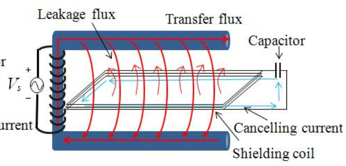
When we consider a longer power delivery, the load voltage is reduced in proportional to the inverse of the magnetic cable length l due to the increase of serial magnetic resistance $\Re_s$, as can be seen from (5). This problem can be treated by enlarging the cross section of the magnetic cable or by using very high permeability magnetic material.

On the other hand, the magnetic cable should be thin for practical applications [4]; hence, the gap between the core lines should be close sufficiently. In this case, however, the load voltage decreases drastically, as identified from (4) and (5), due to $\Re_P$ decrease, as predicted by (2). Therefore, to reduce the gap d is not acceptable for higher power delivery with the magnetic cable.

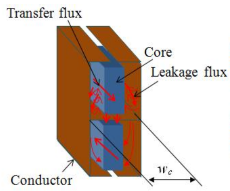
Various structures of magnetic cables to increase the magnetic leakage resistance $\Re_P$ by using magnetic shields are suggested in this paper, as shown in Fig. 4. As the time-varying magnetic leakage flux flows through the conductor or the coil, which is located between the magnetic cores, an induced voltage is generated according to Faraday's law. This induced voltage produces a cancelling current determined by the equivalent circuit impedance of the magnetic shields. In case the conductor or the coil is purely inductive and no resistive, the phase of the cancelling current is exactly opposite to the leakage flux. Therefore, the leakage flux is nullified by the flux of cancelling current, which results in a drastic increase of the magnetic leakage resistance $\Re_P$ and a significant decrease of the gap d.



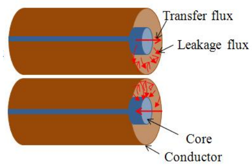
(a) Plate-type conductor shield



(b) Shielding coil with a capacitor



(c) Square-type conductor shield



(d) Cylinder-type conductor shield

Fig. 4 Magnetic shields for nullifying the magnetic leakage flux

A simple plate-type conductor shield is shown in Fig. 4 (a). The shielding coil is short-circuited with a capacitor to provide more cancelling current by reducing the reactance of the LC tank, as shown in Fig. 4 (b). The conductor shields, as shown in Figs. 4 (c) and (d), wrap the cores with small isolation gaps so that the magnetic leakage flux is more tightly bounded inside the conductor shields than Fig. 4 (a). If the conductor shields were perfectly wrapping the cores without any isolation gaps, then induced circulating currents could flow through the conductor shields; then, no power transfer might occur because of the nullifying reverse magnetic flux.

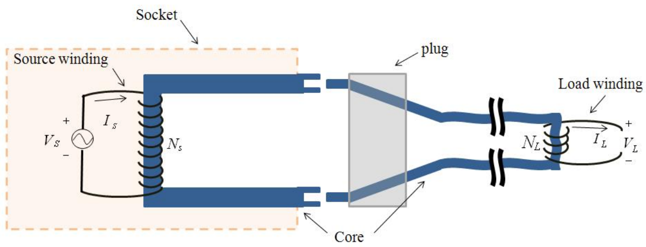
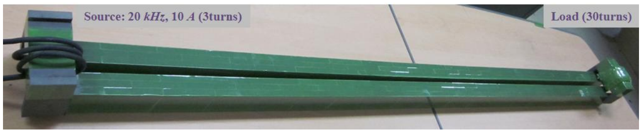


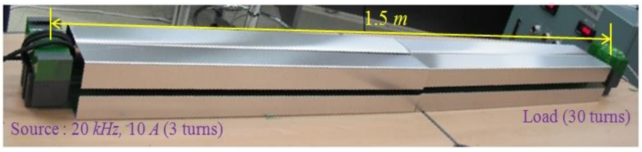
Fig. 5 A magnetic socket and plug

An example of the magnetic socket and plug using the magnetic cable is shown in Fig. 5. Unlike an electical socket and plug, the magnetic socket and plug is electric spark-free, electric shock-free, and contact resistance-free even though the magnetic cable is exposed to the air or touched by people. This socket and pug is robust to the air-gap between contacts. These features make it possible for the magnetic cable to use under very harsh environments where it could be broken or torned out, but there is no explosion, fire, or electric hazard even in the case.

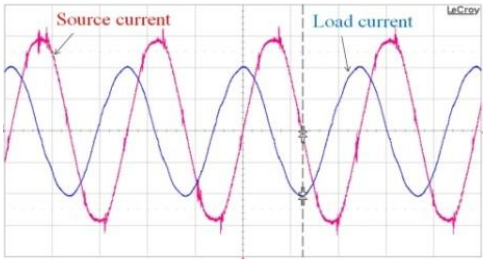
3. Simulation and experiment verifications



(a) The magnetic cable without conductor shields

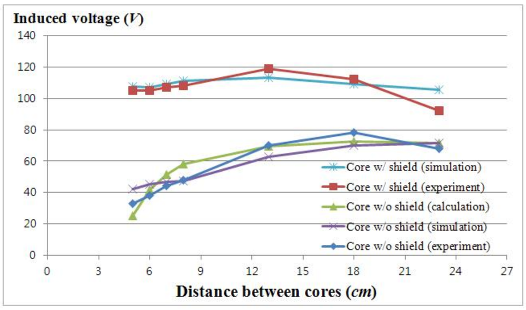


(b) The magnetic cable with square-type conductor shields

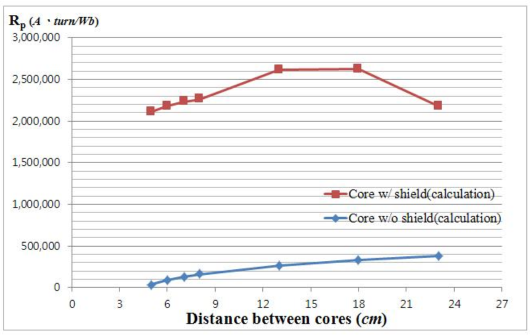


(c) The waveforms of the source and load currents

Fig. 6 A prototype of the magnetic cable



(a) Load voltage with no load



(b) R_p variation along the gap d

Fig. 7 Comparison of simulation, calculation, and experiment results

A prototype magnetic cable for experiments with 1.5 *m* long was constructed, as shown in Fig. 6. Two square-type aluminum shields with 1cm isolation gaps were installed between the cores.

For maximum power delivery, compensation capacitors were connected in series with the source and load transformers; then, the source and load powers were measured by a digital power meter and volt meters. It is verified from experiments that the magnetic cable with the aluminum shield can transfer 154 *W* power with 67 % efficiency, while the magnetic cable without any magnetic shields can transfer only 2.1 W power with merely 8.5 % efficiency. Since a constant current source was used for the experiments, the phase of the load current led the source current by $\pi / 2$ [3], as shown in Fig. 6 (b).

The load voltage induced by way of the proposed magnetic cable was measured for several gaps *d* as shown in Fig. 7 (a), where considerable voltage increase was observed for the magnetic shield case compared to the core only case. Theoretically calculated values of (5) were verified by MAXWELL simulation results and experimental results. From Fig. 7 (a) and (5), $\Re_p$ can be calculated; it is identified that $\Re_p$ is kept a constantly high value for the magnetic shield case regardless of the gap *d*.

3. Conclusion

A new magnetic cable with two parallel core lines and a magnetic shield preventing leakage flux is proposed and verified by simulations and experiments. By increasing the magnetic leakage resistance, the load power and efficiency could be improved considerably. The magnetic cable is inherently safe and robust to vulnerable environments; hence, it can cover a wide range of power transfer applications, i.e. from micro watt implant chips to Mega Watt Power Systems such as electric trains, industrial equipments, and others.

Reference

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