Experiments of In-Vehicle Inductive High-Voltage Power Line Communication

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Abstract— In electric vehicles (EVs), high-voltage batteries supply power to power distribution units (PDUs) that drive motors, generators, blowers, and air conditioners through high-power cables. In the future, as the number of electronic devices in a vehicle increases, communication lines must be added for controlling the electronic devices. In this study, we proposed the application of inductive power line communication (PLC) to simplify EV wiring. An inductive coupler consisting of nano-crystalline cores was fabricated and applied to high voltage power lines of EVs to measure the performance of in-vehicle inductive PLC. As a result of the experiments, the high-voltage cable guarantees the data rate of 35Mbps. The real-time video transmission between the engine room and the trunk was successfully carried out. We expect that the inductive PLC in EVs will contribute to the simplification of communication lines and reduction of vehicle weight.

Keywords—Inductive coupling; in-vehicle power line communication; High-voltage powerline communication; nano-crystalline

I. INTRODUCTION

Information systems such as autonomous navigation and digital multimedia become part of the automobile. High-speed data links must be built to ensure interconnectivity between smart electronic components. Typically, this task is performed through a dedicated wired data bus. However, wiring infrastructure is the third contributor to vehicle weight. We need a way to build the in-vehicle network while reducing the weight of the car. [1].

In-vehicle power line communication (PLC) is one of the key issues that lighten the vehicle. The scope of this study includes new channels such as medium and high-voltage power lines inside EVs. Typically, that cable connects high-voltage batteries to power distribution units (PDUs) and provide power to operate the EVs. So far, some research has been done to maximize the benefits of EV-PLC [2, 3]. A key advantage is to reduce the weight and cost of wiring devices by using existing wiring infrastructure to simplify the design of in-vehicle networks.

There are two types of coupling in PLC: capacitive and inductive. The former shows the required high-pass filtering characteristics. The signal power is coupled through the displacement current by the capacitor. Conventional narrow-band PLCs are two-wire systems that inject signals between wires using capacitive couplers. The capacitive type is simple in construction, but there is a restriction that the coupler must come into direct contact with the electrical outlet or wire. In the latter method, the signal power is coupled to the power line in a noncontact manner by electromagnetic induction. The main advantage is that the coupling circuit provides an isolated voltage to the signal source and is easy to install in the cable without electrical contact. Until recently, this has been achieved by using soft ferrite magnetic materials [4]. However, in high frequency applications of electronic devices, soft ferrites and amorphous materials are being replaced by nano-crystalline alloys. Inductive couplers for PLCs could also be fabricated from nano-crystalline alloys.

In this study, the PLC coupler was made of a toroidal core wrapped with nano-crystalline ribbon. We confirmed 35Mbps bandwidth and real time video transmission through PLC experiment using EV high voltage line..

II. INDUCTIVE HIGH-VOLTAGE POWERLINE COMMUNICATION

Nano-crystalline alloys are the result of manufacturing crystal grains of tens of nano-meters by applying amorphous manufacturing technology. The amorphous state means that the atoms inside the material do not have a regular arrangement. When the metal is dissolved, the internal atoms are activated and when the temperature is lowered, the atom returns to its original, regular crystal state. [5]. Figure 1 shows the BH curve of a crystalline core used in this study. A magnetic field (H) of 40 At/m creates a magnetic induction (B) of 0.92 T. The maximum permeability is defined as the maximum slope of the line starting at the origin (B = H = 0) and ending at a point on the initial curve. The calculated maximum permeability was 39,470.

Figure 2 shows the configuration of the inductive coupling unit. It is made up of two wire coils placed close to each other such that current running in one coil can induce a voltage in the other coil without the coils touching. The signal power of PLC can be transferred without a metal connection with the inductive coupling unit. Additionally, these units make a good buffer to isolate one signal from another. When a time-varying current flows in primary wire placed nearby the second one then the flux produced by the primary wire may also link the secondary one. This varying flux linkage from the primary wire will also induce electromotive force (emf) across the secondary wire. If the primary coil is connected to the time varying signal source, the net emf of the secondary coil (e_2) is the result of mutually induced emf.

$$e_2[\mathrm{V}] = -\mathrm{M}\frac{\Delta I_1}{\Delta t} = -N_2\frac{\Delta \emptyset_2}{\Delta I} \quad (1)$$

Mutual inductance (M) is given by Eq. (2).

$$\mathrm{M} = \mu\frac{A}{l}N_1 N_2 \quad (2)$$

Here $\emptyset$ is magnetic flux, N_1, and N_2 is turns ratio of primary and secondary wires, A is a cross-sectional area, and l is an effective circumference of the core.

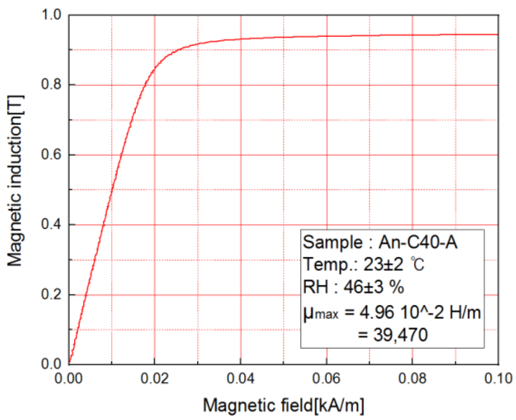


Fig. 1. B-H curve of nano-crystalline core measured.

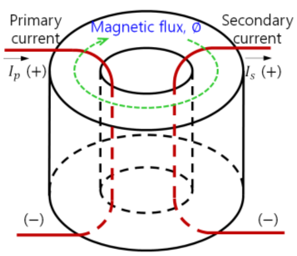
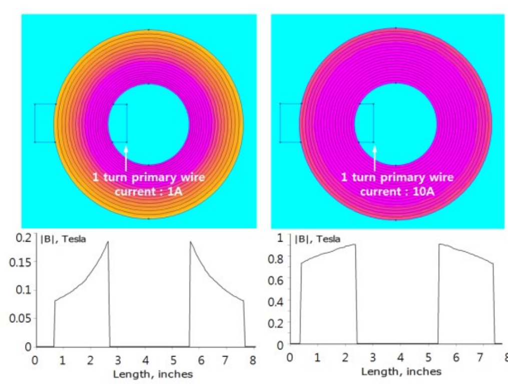


Fig. 2. Schematic of the inductive coupling unit



(a) (b)

Fig. 3. Magnetic flux density distribution. (a) 1 A and (b) 10 A primary current.

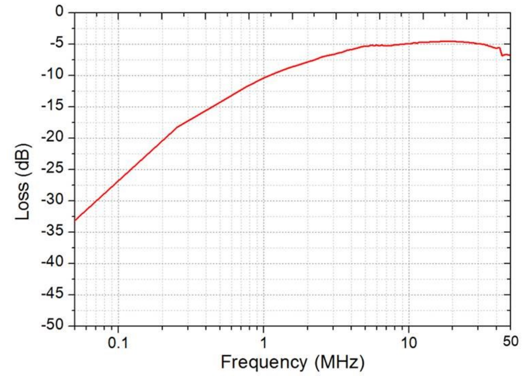


Fig. 4. Magnetic flux density distribution. (a) 1 A and (b) 10 A primary current.

Numerical methods provide a better understanding of the electromagnetic behavior of magnetic cores. Figure 3 shows the magnetic flux density distribution of the core at the primary current of 1 A and 10 A, respectively. The simulation results show that the nano-crystalline core is suitable for induction coupling because the variation of the magnetic flux density with respect to the primary current change induces the electromotive force of the secondary wire as shown in equation (1). However, since the magnetic flux density is saturated around the primary current of 10 A as shown in Fig. 3 (b), the dynamic range of the current fluctuation of the coupling unit will be limited.

Figure 4 shows the coupling loss of the nano-crystalline inductive coupling unit as a function of frequency. Signal coupling efficiency drops sharply in the frequency range below 5 MHz, but shows a flat insertion loss of -5 dB in the 5-40 MHz frequency range that belongs to the broadband PLC bandwidth.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 5 shows the EV PLC experimental configuration. A coupler was fastened to the high-voltage power line between high voltage battery and power distribution unit (PDU). Another coupler was installed on the power line passing the LDC (Low DC-DC converter). Here, PDU supports function converting and power distribution to every systematic unit such as motor control unit, battery management system, charging system, DC to DC system, air condition system, electric steering auxiliary system, and brake system. PDU can also provide short circuit protection, current leaking protection and IP protection [6].

The powerline modem that provides up to 200 Mbps bandwidth is connected to the coupling unit. If the PLC signal passes through the PDU, it shows a power loss of -10 dB or more, and if it passes through the LDC, it also shows an additional loss. The bandwidth measured by Jperf, which is a widely used tool for network performance measurement and tuning, was around 35 Mbps as shown in Fig. 6.

Many cars are equipped with cameras for various purposes such as surveillance, lane departure monitoring, and autonomous driving. If the interconnections of these systems

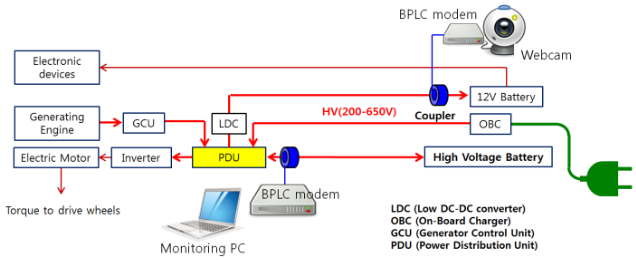


Fig. 5. Experimental configuration of EV PLC

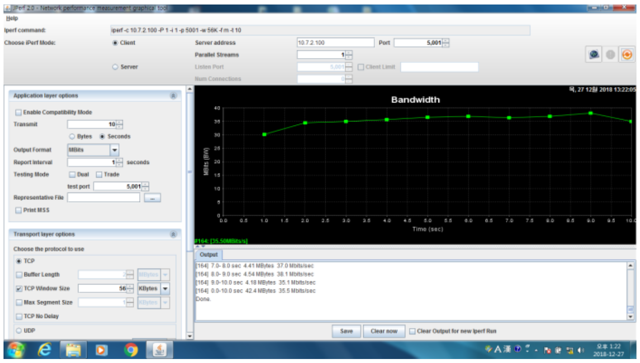


Fig. 6. Screenshot of iperf PC monitoring program showing channel bandwidth.

(a) (b)

Fig. 7. Webcam image transmission using high-voltage powerline of EV.

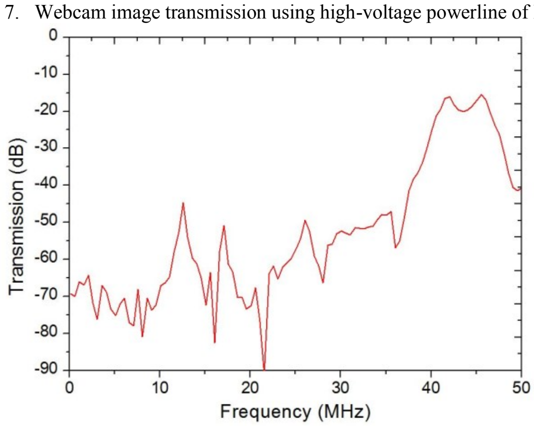


Fig. 8. Transmission channel characteristic between webcam and monitoring PLC system

can be applied to the vehicle's electrical cables, it can contribute to the weight reduction of the vehicle and the simplification of the wire harness. Figure 7 shows a webcam video transmission testbed using a high-voltage PLC system installed on the prototype EV. There is no dedicated line for communication. The camera PLC system was mounted on the LDC cable located in the trunk and the monitoring PLC system was installed on the PDU power cable assembled in the bonnet.

Figure 8 shows the transmission channel characteristics between two couplers respectively connected to the PDU and LDC. Although most of the broadband PLC bandwidth shows insertion loss of -50 dB or more, it shows insertion loss of -20 dB or less in the 40 MHz regions. In video transmission, we confirmed that real-time communication was achieved at a rate of 30 frames per second.

IV. Conclusion

In this study, we demonstrated the performance of an inductive PLC system using a prototype electric vehicle. We have also confirmed that noncontact couplers using nano-crystalline cores are suitable for high voltage PLC systems. In addition, the high voltage power cable inside the EV showed sufficient transmission characteristics to be used in the inductive PLC. PLC signal attenuation occurred largely when passing through PDU and LDC, but there was no problem with video transmission. We hope that the inductive PLC system proposed in this study can contribute to the weight reduction of electric vehicles and the simplification of the wire harness.

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