Design of Wireless Electric Power Transfer Technology: Shaped Magnetic Field in Resonance (SMFIR)

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Abstract

Major advances in the development of electric vehicles (EV) – buses, cars, high speed trains, etc. – have been made using a new wireless power transfer technology named the "Shaped Magnetic Field in Resonance" (SMFIR) that can send electric power over a significant distance. SMFIR is a basic technology that can be used in many applications where electric power has to be supplied remotely without using conductive wires. The "On-Line Electric Vehicle" (OLEV) is a SMFIR-based electric vehicle, which was chosen as one of the 50 Best Inventions of 2010 by the TIME magazine. In this paper, the underlying design for SMFIR is presented, which was done applying the Independence Axiom of Axiomatic Design Theory.

Keywords:
Axiomatic Design, electric vehicles, OLEV, SMFIR

1 INTRODUCTION

Historically a series of major innovations have sustained the economic growth of the world since the Industrial Revolution. Most important steps involved in major innovations are: (1) problem identification, (2) definition of functional requirements (FRs) that a solution for the identified problem must satisfy, (3) design of the product to satisfy the FRs by through the identification of the design parameters (DPs), (4) actual implementation of DPs in the final system using chosen process variables (PVs), and (5) commercialization of the product. Creative design and implementation are the basis for successful innovations that can spur economic growth [1-2]. This paper presents one such innovation.

Since 2009, KAIST has been involved in the invention and innovation of two new green transportation technologies: Mobile Harbor (MH) and On-Line Electric Vehicle (OLEV). These basic inventions were possible because of the "Axiomatic Thinking" process, i.e., application of the Independence and the Information Axioms. Furthermore, the rapid conversion of these inventions to innovations was possible, because the detailed design and implementation of these large complex systems followed a systematic and logical process prescribed by Axiomatic Design and because of the hard work of competent researchers and engineers. Also the importance of the large funding provided by the Korean government cannot be over-emphasized. Now a group of investors has formed "OLEV Technologies, Inc." in the United States and the "OLEV Korea Company" is being established in Korea by another group of investors. If they succeed, the last step of the conversion process – from invention to innovation – would be completed.

This paper deals with the On-Line Electric Vehicle (OLEV). The basic concept of OLEV was presented as a keynote paper in the 2010 CIRP Design Conference in Nantes, France [3]. At the time, the details of the basic technology of wireless transfer of a large amount of electric power over a significant distance were not described because of the issues related to intellectual property rights (IPR). In this paper, the design of the basic wireless electric power transfer technology -- the "Shaped Magnetic Field in Resonance" (SMFIR) -- is described. KAIST has filed over 180 patents on this and related technologies. The purpose of this paper is to describe the basic design process and concept of SMFIR.

The goal of OLEV is to reduce the CO2 level in atmosphere by replacing cars with internal combustion (IC) engines with electric cars (EV). The interest in EVs has intensified in recent years in order to meet the regulations on the emission of CO2 and other harmful gases from IC engines. The need to reduce CO2 has been articulated by the International Panel for Climate Control [4].

Most commercially introduced EVs and vehicles with IC engines share one common concept: both carry the energy required to propel the vehicle on board of the vehicle: EVs use large batteries and cars with IC engines use a liquid fuel tank. Although R&D has been done to reduce the size, weight, and cost of the batteries (especially, lithium polymer batteries and lithium ion batteries) they will continue to be heavy, large, and costly. Today, the battery almost doubles the cost of an EV over typical cars with IC-engines. The basic idea behind the OLEV is to minimize the size of the battery and the distances that must be travelled using the battery by supplying energy to moving vehicles from an external source (an underground power supply system).

The OLEV project was initiated in 2009 under the sponsorship of the Korean government. This was a major research project for KAIST with an annual budget of about $25 million during the first year and $15 million during the second year. A commercial scale OLEV was developed, installed, and ready to take passengers within a year after the project was initiated. KAIST is in the process of transferring the OLEV technology to industry, in addition to continuing research on OLEV and other "green" transportation technologies that uses the SMFIR technology.

2 DESIGN OF OLEV

2.1 OLEV FRs, DPs, and Constraints at the First Level

The highest-level functional requirements (FRs) of OLEV are as follows [3]:

FR1 = Propel the vehicle with electric power

FR2 = Transfer electricity from underground electric cable to the vehicle

FR3 = Steer the vehicle

FR4 = Brake the vehicle

FR5 = Reverse the direction of motion

FR6 = Change the vehicle speed

FR7 = Provide the electric power when there is no external electric power supply

FR8 = Supply electric power to the underground cable

Constraints are as follows:

C1 = Safety regulations governing electric systems

C2 = Price of OLEV (should be competitive with cars with IC engines)

C3 = No emission of greenhouse gases

C4 = Long-term durability and reliability of the system

C5 = Vehicle regulations for space clearance between the road and the bottom of the vehicle

The design parameters (DPs) of OLEV may be chosen as follows:

DP1 = Electric motor

DP2 = Power transfer device from the underground coil to the vehicle

DP3 = Conventional steering system

DP4 = Conventional braking system

DP5 = Electric polarity

DP6 = Motor drive

DP7 = Re-chargeable battery

DP8 = Electric power supply system (Inverter, etc)

2.2 Design Matrix (DM) for the First Level FRs and DPs

The Design Matrix (DM) for the first level FRs and DPs is given in figure 1:

	$DP1$	$DP2$	$DP3$	$DP4$	$DP5$	$DP6$	$DP7$	$DP8$
$FR1$	X	X	0	0	0	0	0	0
$FR2$	0	X	0	0	0	0	0	0
$FR3$	0	0	X	0	0	0	0	0
$FR4$	0	0	0	X	0	0	0	0
$FR5$	X	0	0	0	X	0	0	0
$FR6$	X	0	0	0	0	X	0	0
$FR7$	0	0	0	0	0	0	X	0
$FR8$	0	0	0	0	0	0	0	0

Figure 1: First level design matrix for OLEVs

The first level design is a decoupled design. The design of FR2/DP2 is the critical phase of the design task.

3 DESIGN OF SMFIR (THE SECOND LEVEL FR2X, AND DP2X OF OLEV)

The first-level FRs and DPs given in the preceding section must be decomposed until the design is completed with all of the details required for full implementation. The second-level FRs are the FRs for the highest–level DPs and at the same time, the children FRs of the first-level FRs [1,5]. The basic core technologies have been created at this second level of FRs and DPs. In this section, only FR2 and DP2 are decomposed. The design that satisfies FR2 is known as the Shaped Magnetic Field in Resonance (SMFIR). It may be defined as a disruptive technology that can be applied to many fields replacing existing products [6].

The SMFIR technology that made OLEV possible transmits a large amount of electrical energy across empty space wirelessly and captures it at the other end. To develop SMFIR, we started out with the FRs for OLEV. In this paper, only FR2 and DP2 of OLEV are decomposed and designed.

3.1 FRs and DPs for SMFIR

FR2 and DP2 are restated below:

FR2 = Transfer electric power from underground power supply system to vehicle

DP2 = Power transfer device from the underground coil to the vehicle

Since FR2 cannot be implemented without further detailed design, FR2 must be decomposed.

The second level FRs are obtained by decomposition of FR2 are as follows:

FR21 = Create a magnetic field above the ground

FR22 = Control the shape of the magnetic field

FR23 = Control power level of the magnetic field

FR24 = Pick-up the energy of the magnetic field from the vehicle

FR25 = Minimize the radiation of electromagnetic field, i.e., EMF

Figure 1 shows the conceptual design that satisfies the FR2s. The lower-level DP2 are as follows:

DP21 = Electromagnet design (ferrite core inside electric field)

DP22 = Magnetic pole design (L)

DP23 = Power level (strength) of the magnetic field

DP24 = Magnetic energy pick-up unit on the vehicle that is in resonance with the magnetic field

DP25 = Shield for stray electromagnetic field, i.e., EMF

The constraints that the design must not violate are the following:

C21 = Maximum allowable EMF level of 62.5 mG

C22 = Maximum weight of the pick-up unit

C23 = Electric shock resistance of the system

C24 = Temperature rise should not exceed 20C

C25 = High magnetic permeability of the core material

C26 = Minimize the power loss

Some of these FRs and DPs such as FR25 and DP25 have been further decomposed but are not presented in this paper.

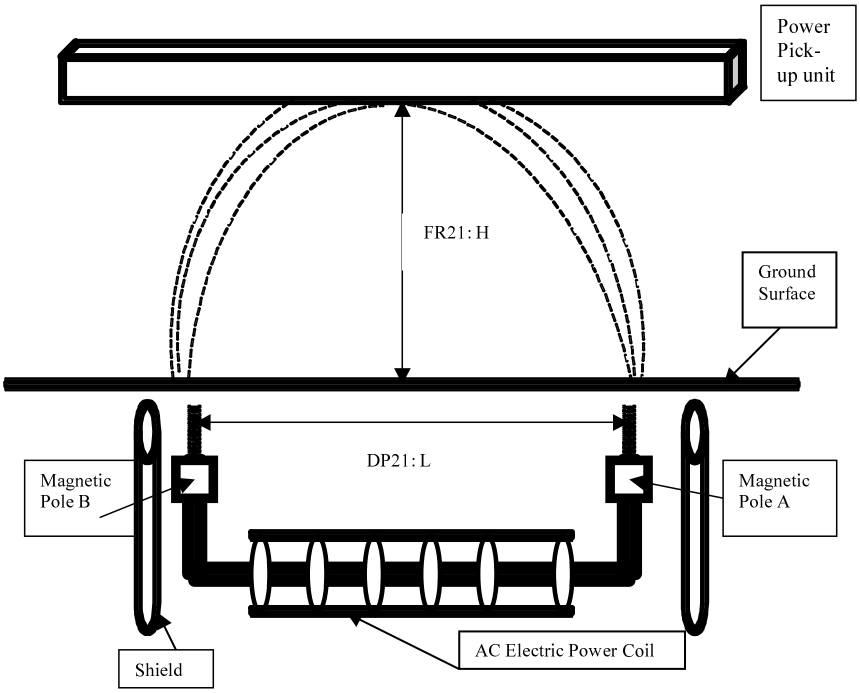

Figure 2: Schematic drawing that shows the principle behind SMFIR

As shown in Figure 2, the magnetic field above ground is controlled by the underground power supply. The shape of the magnetic field is controlled to change the distance between the ground and the pick-up unit attached to the vehicle, H. The DP that controls H is the distance between the two magnetic poles, L. The alternating magnetic field is picked up by the pick-up unit mounted on the vehicle at the frequency of the magnetic field. The shield imbedded in the ground and the active and passive cancellation system mounted on the vehicle minimize the radiation of the magnetic field (EMF). This is the essence of Shaped Magnetic Field in Resonance technology.

The design matrix for the FR2s/DP2s is given by Equation (1):

$$\begin{Bmatrix} FR21 \\ FR22 \\ FR23 \\ FR24 \\ FR25 \end{Bmatrix} = \begin{bmatrix} X0000 \\ XX000 \\ XXX00 \\ 000X0 \\ XXX0X \end{bmatrix} \begin{Bmatrix} DP21 \\ DP22 \\ DP23 \\ DP24 \\ DP25 \end{Bmatrix} \qquad (1)$$

The design is a decoupled design. According to Equation (2), all DPs, except DP24, affect the shielding of radiation. DP25 was designed to cancel the radiation due to other DPs.

The frequency chosen through simulation for optimum power transmission was 20 KHz, which minimizes the loss while maximizing the power transfer. The simulation was performed by Professor J. H. Kim and his research group [7]. The current supplied to the under ground cable to generate the magnetic field was in the range of 200 amps at a voltage of around 400 volts. The actual implementation of the design was done under the direction of Professor D. H. Cho, the director of the OLEV program, Professors C. T. Rim, and In-Soo Suh.

The OLEV system installed in Seoul Grand Park in December 2009 is shown in Figure 3. It replaced the noisy and smelly diesel system. The length of the circular path around the Park is about 2.2 km. The total length of the four-segments of the underground power supply system is 372.5 m. OLEV has a small battery on board to propel the vehicle even on roads without the imbedded power system. The battery is recharged when the vehicle is on top of the underground power system. The system was designed so that the charge on the battery remains about the same after completing each round.

Figure 3: OLEV Tram installed in Seoul Grand Park

The input power to the underground system is 200 amps at 440 volts and 20KHz. This creates a magnetic field above the ground, which is shaped to reach the vehicle, using the magnetic poles in the ground. The maximum height of the magnetic field, H, increases when L is increased. To maximize the power pick-up, the pick-up unit mounted under the vehicle is tuned to the frequency of the magnetic field. The power that is picked up is supplied to the electric motor that drives the wheels of the OLEV at 60 Hz and to the battery in DC to recharge it. Two kinds of shielding for EMFs are deployed: one imbedded in the underground and also a passive cancellation system mounted on the vehicle. Sometimes an active shielding system is also mounted on the vehicle. The EMF radiation from OLEV is well below the internationally specified level of 62.5 mG at 20kHz. The power supply is segmented so that only the segment right below the vehicle is activated.

An integration team of the OLEV project constructed the design matrix for the OLEV system to identify and eliminate coupling between the FRs at several levels. The final design concepts were either uncoupled or decoupled designs. When there was coupling, its effect was minimized by making the magnitude of the element of the design matrix that caused coupling much smaller than other elements through design changes.

A given FR may have several different DPs. In this case, the final DPs were selected through modelling and simulation of the design using different DPs. The final values of DPs were also determined through modelling and simulations before the hardware was actually built.

4 APPLICATION OF SMFIR

SMFIR can be applied to many fields. We are trying to apply the SMFIR technology to bus systems first, since it is more readily adopted with a minimum investment in the infrastructure. As notedin the paper given at the 20th CIRP Design Conference, the overall economy of the OLEV system is attractive. At KAIST, we are conducting research to apply this technology to buses, passenger cars, high-speed trains, subways, appliances, and even to airplanes.

5 SUMMARY

The design of the Shaped Magnetic Field in Resonance (SMFIR) was achieved by applying the Independence Axiom. This technology, which enables the wireless transmission of a large amount of energy, has many important applications, including the On-Line Electric Vehicle (OLEV). This technology is being explored for other applications where wireless power transmission is required, ranging from low to very high kilowatts. This technology has been implemented in the OLEV systems deployed in the Seoul Grand Park and at KAIST.

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