

Dynamic Model of an FC- and UC-based IPT system for railway vehicle

Kyung-Hee Han ^{1,2*}, Byung-Song Lee ², Hyun-Jun, Park ², Sam-Young, Kwon ², Soo-Hyun, Baek¹

¹ Dongguk University/ Department of Electrical Engineering, Seoul, 100-715, Korea

² Korea Railroad Research Institute/ Department of Electricity & Signaling, Uiwang, Kyonggi, 437-757, Korea
E-mail:khhan33@krri.re.kr

Abstract- A fuel cell powered system is regarded as a high current and low voltage source. Effects of electric loads on the power source are of importance to design an optimal integrated system. In particular, dynamics of the system should be considered to determine a configuration and the size of the components. In this paper, we present an IPT system that operates in parallel with FC and UC bank, because the available power generated from a FC power plant may not be sufficient to meet sustained load demands, especially during peak demand or transient events encountered in railway vehicle applications. A new dynamic model and design methodology for an FC- and UC-based IPT system for railway vehicle applications has been developed. Simulation results are presented using MATLAB, Simulink, and Ansoft EM environments based on the mathematical and dynamic electrical/magnetical models developed for the proposed system.

I. INTRODUCTION

As the studies with reference to system having environmental affinity are increased, studies for transit systems such as electrical/hybrid vehicle are in active progress.

Recently, electrical/hybrid vehicles are given as the alternative plan but have residual problems, such as short traveling distance per once charge. In case of light electrical railroad, the existing power supply equipment has some disadvantages, such as high management expenses, low environmental affinity and accident due to minor collision. [7-11]

This paper proposes the concept of inductive power collection used for the light railway and road transportation system to improve these problems. And also, we will study the characteristic of power transfer system with the variation of mutual inductance for the structure of power collector. This is the system for transportation therefore, large output power is required. There is a wide difference of this system from general product in the industrial world, which is the large air-gap between inductive power collector and primary power line laid under the ground to secure enough distance for transportation.

The large air-gap makes a leakage inductance to increase. So, the system must be compensated by using resonant circuit.

The characteristic of power delivery in compensated circuit applying primary resonant circuit is presented by simulation and examination of the model.

The power source of fuel cell (FC) hybrid railway vehicles consists of both FC power generation and energy storage devices (i.e. ultra-capacitor (UC) bank or battery system). The available power generated from a FC power plant may not be sufficient to meet sustained load demands, especially during peak demand or transient events encountered in railway vehicle applications.

The combined use of FC and UC is pertinent to the system. An UC bank can supply a large burst of power, but it cannot store a sufficient amount of energy in railway vehicle systems without sufficiently frequent charging.

So, the vehicle system using inductive power transformer (IPT) is feasible in FC hybrid railway vehicle. IPT means a contact-less battery charging device with the frequent charging chance. This system can easily give many chances charging battery.

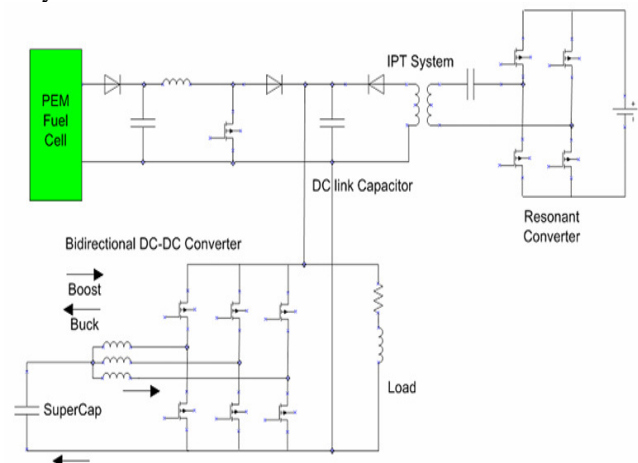


Fig 1 The FC- and UC- based IPT system

II. FUEL CELL SYSTEM

The combined use of FC and UC is pertinent to the system. An UC bank can supply a large burst of power, but it cannot store a sufficient amount of energy in railway vehicle systems without sufficiently frequent charging.

Fuel cell is constructed with different layers composed of bipolar plates, gas diffusion layers, catalyst and membrane. A single cell has approximately 1.2V ideal voltage and it supplies DC power. When the load current increases, the output voltage drops rapidly because of increased over-potentials at the electrodes, so a fuel cell stack is regarded as a voltage source.

The balance-of-plant is the part of the power system necessary for secure and reliable operations, by delivering fuels, keeping the humidity properly, and removing heat and control actuators. Representing major components are hydrogen tank, air compressor, humidifier and supply manifolds for fuel including dynamics of fuel cells, pressure and temperature distribution of fuel cell stacks, control strategies for fuel flow including pressure and humidity, thermal and power management.

A fuel cell system is a generator that can supply electric power and produce heat as a byproduct. However, the heat can be captured and used for heating up water or air needed for households or buildings. The combined heat and power generation (CHPG) can be configured with a reformer, a fuel cell system, the DC/DC converter, and the DC/AC converter with an energy storage device [1] shown in Fig.2. The grid as a load can be a single phase or a three phase line. Due to the characteristics of the PEM fuel cell system as a high current and low voltage source, the output voltage of the fuel cell should be stepped up to a level of the DC bus voltage that is higher than the given grid nominated voltage. A converter that in principle stores energy in an inductor or a capacitor makes it possible to electronically boost the fuel cell output voltage by means of controlling switching periods and follow the required power [2, 3, 4].

Hence, DC link capacitor connected in parallel to the DC bus plays a role to decouple the load with the fuel cell. In fact, the fuel cell system cannot absorb any energy. The storage device can be either battery or super capacitor.

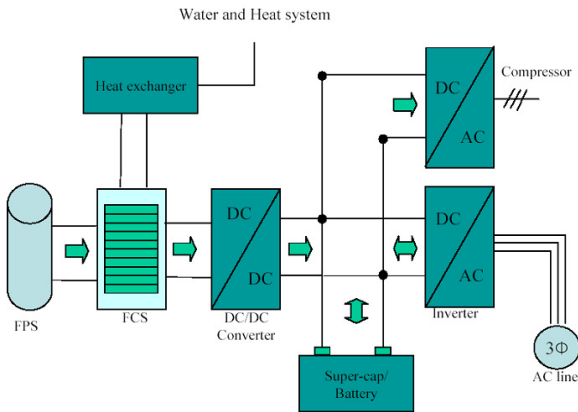


Fig 2 The Structure of fuel cell powered system

A. DC/DC Converter

A typical configuration of a fuel cell powered system configuration with a DC/DC converter is shown in Fig. 6, where the fuel cell output is supplemented by a capacitor (C_{in}) that should serve as a buffer to deliver any instant current peaks during operations. The diode (D_1) at the output of the fuel cell stack is used to prevent currents from flowing into the stack. The reverse current can cause a high reverse blocking voltage across membrane, which consequent effects have not been clarified yet. In addition, the diode also blocks any ripple currents from flowing to the stack and vibrate the double layers of the catalysts. Both are very crucial issues in securing the reliable and safe operation of the fuel cell stack.

B. Modeling of DC/DC Converter

The DC/DC converter taking into account is a typical PWM one that employs two IGBTs and diodes with a capacitor and an inductor. Since the output voltage of the converter should be higher than the PEM fuel cell voltage, a boost converter is inevitable. The converter circuit can be described by (1) and (2) for a conduction mode, if no losses occur at the power conversion and the current in the inductor continuously flows.

$$\frac{dv_{DC}}{dt} = \frac{1}{C} i_{cap} = \frac{1}{C} (1-D)i_{FC} - \frac{v_{DC}}{CR_{load}} \quad (1)$$

$$\frac{di_{FC}}{dt} = \frac{1}{L} (v_{FC} - (1-D)v_{DC}) = \frac{1}{L} (v_{FC} - v_1) \quad (2)$$

v_1 denotes the average voltage at the lower IGBT during Pulse Width Modulation (PWM) period and D does the switching on-duty period. v_{FC} is the voltage supplied by the fuel cell system and v_{DC} is the output voltage of the converter. Under assumptions made, the input power of the converter, $P_{FC} = v_{FC} i_{FC}$, must be equal to the output power of the converter, $P_{con} = v_{DC} i_{con}$. Then, the currents at the output and the capacitor result in as follows.

$$i_{con} = \frac{P_{FC}}{v_{DC}} = \frac{v_{FC} i_{FC}}{v_{DC}} \quad (3)$$

$$i_{cap} = i_{con} - i_{load} \quad (4)$$

$$i_{con} = \frac{v_{FC} i_{FC}}{v_{DC}} - i_{load} \quad (5)$$

Hence, the load current i_{load} can be regarded as a measurable disturbance. The state equations above present a second order system with two state variables, the DC link voltage and the fuel cell current i_{FC} .

C. Control of the Converter

If the amplitude of the current ripple should be less than 30A, the minimum inductance required amounts to 240 μ H, which corresponds to around 16% of the input average current.

The capacitance at the output makes a resonant circuit with the inductance, so that the resonant frequency is enough low to

suppress the voltage ripples. At the same time, the electric loads effects are considered. In this investigation, 1500 μ F is taken as an example.

Other challenging issues are controllability of the output voltage. Generally, simple controllers have been employed to control the inductor current and the voltage at the capacitor. In fact, the load current can be measured, which allows for designing a feed-forward control strategy in order to compensate slow dynamics. In addition, proportional and integrator (PI) controller is employed for the current loop. The control diagram for the DC/DC converter is illustrated as Fig. 3.

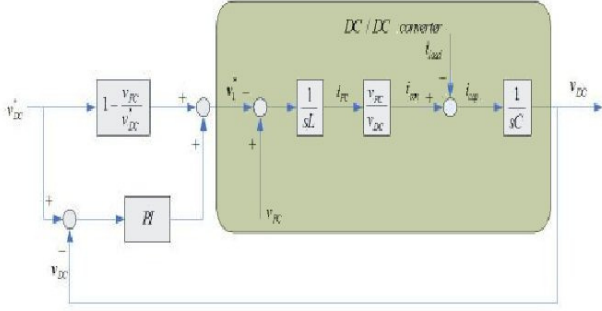


Fig 3 Feed-forward control of the DC-DC converter

Moreover, if the DC link voltage is disturbed, an error between the reference and the actual value occurs, which should be corrected by a controller that manipulates the duty ratio of the PWM. However, the dynamic response of this method is pretty slow at a sudden change of the output voltage. The slowness can be improved, if the duty ratio could be directly adjusted by accommodating the change in advance. Then, the DC-DC converter output voltage would remain unchanged. This idea can be realized by directly feeding the input voltage level to the modulation part of the DC-DC converter.

III. IPT SYSTEM

The system of inductive power collection (shown in fig 4.) has two compensation circuits in primary and secondary part. It consists of two inductively coupled independent electrical systems. The constant current in the track inductance L_1 through a suitable resonant power supply is produced by the primary power line of the inductive power collection system. In secondary inductive power collector, compensation capacitor is also required. The switched mode controller is used to control power flow for control of motor.

The charging battery requires limited voltage and large current. But the current supplied from primary power line is restricted by cost, capacity and method of power delivery.

The maximum output current of inductive power collector is short circuit current of secondary winding. It can be presented by limited inductance of secondary winding.

Fig. 5 shows the mutual inductance both by measurement and by simulation of inductive power collector. By increase of air-gap length, the mutual inductance was decreased. The range

is 13-28 μ H. It was known that self inductance is the sum of leakage inductance and mutual inductance, in which leakage inductance is increased and mutual inductance is decreased with the variation of air-gap length.

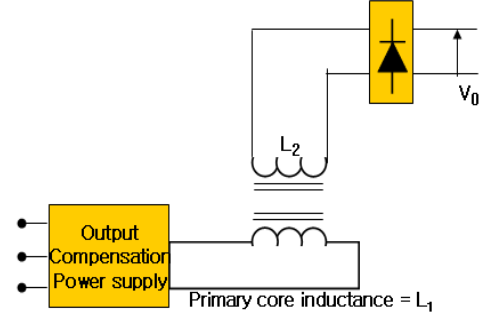


Fig. 4. The system of inductive power collection

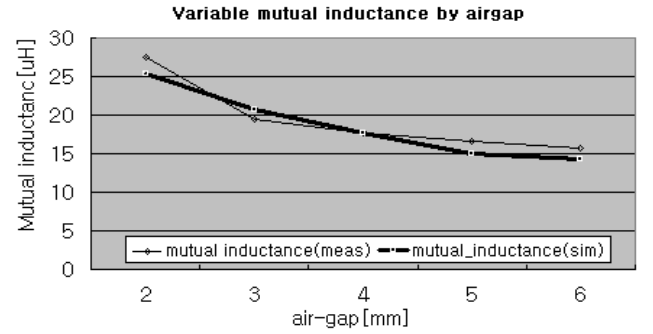


Fig. 5. The mutual inductance with various air-gap length

As the length of air-gap is increased, the leakage flux is increased. And then, M_{ip}/L_2 can't be maintained but be declined by the $L_2 = L_{lk} (\frac{N_2}{N_1}) M_{ip}$ equation, $L_{lk} \gg M_{ip}$.

Consequently, if we assume a certain output power of the system, it is expected that reactive power is increased in primary part of inductive power collector by equation (7).

Open circuit voltage (V_{po}) of secondary winding including tuning capacitor (C_c) and the output power is given by

$$V_{po} = j\omega M_{ip} I_{L1} \quad (6)$$

$$I_{psc} = \frac{V_{po}}{j\omega L_2} = \frac{M_{ip}}{L_2} I_{L1} \quad (7)$$

$$P_{max} = |V_{po} I_{psc}| = \frac{\omega I_{L1}^2 M_{ip}^2 Q_c}{L_2} \quad (8)$$

Where,

V_{po} : Open circuit voltage of secondary winding of inductive power collector

M_{ip} : Mutual inductance

I_{L1} : Primary current of inductive power collector

I_{psc} : Short circuit current of secondary winding of inductive power collector

L_2 : Self inductance of secondary winding of inductive power collector

ω : Operating frequency of primary part of inductive power collector

IV. RESULTS OF SIMULATION

The fuel cell system has higher efficiency than Carnot cycle (40%). The system can be driven farther than the other system with the same amount fuel. The hydrogen oxidizes in anode and the oxygen is reduced in cathode.

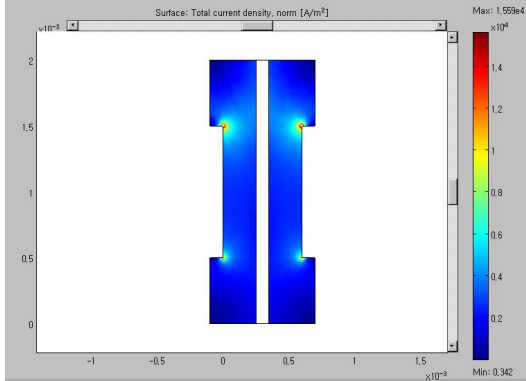


Fig. 6. Current density (surface plot) and current vector field in fuel cell

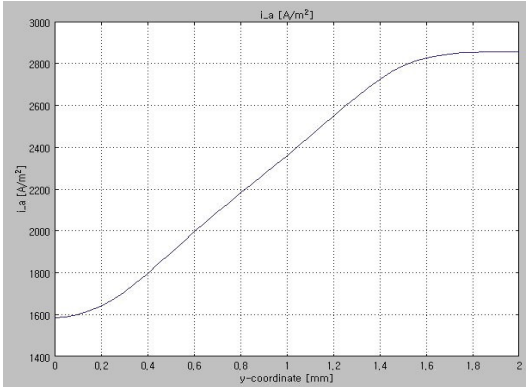


Fig. 7. Current density distribution at the active layer at the anode

The PEM fuel cell electrodes are of the gas diffusion type. They consist of a supporting carbon structure with gas-filled pores (denoted gas backing) and a porous active layer that also contains the polymer electrolyte. The electrochemical reactions take place in the active layer, which contains a platinum catalyst. The gas diffusion electrodes are designed to maximize the specific area available for the reaction. Maximize the distribution of reactant (that is, achieve a low gas-transport resistance), and minimize the resistance for the proton transport to and from the active sites at the electrodes.

TABLE I: SIMULATION PARAMETERS

DC/DC CONVERTER			
PARAMETER	VALUE	PARAMETER	VALUE
Switching frequency	20 KHz	V_{DC}	400 V
C_m	350 μ F	C	1500 μ F
L	240 μ H	R_{load}	50 Ω
IGBT forward voltage	1 V	IGBT turn off current tail time	4×10^{-6} sec
IGBT ON resistance	0.017 Ω	Diode ON resistance	0.015 Ω
Diode forward voltage	0.8 V	Calculation step size	1×10^{-6} sec

Fig 6 shows the current distribution in the PEM fuel cell. There are significant current spices present at the corners of the current collectors. To further analyze the cell's behavior, plot the current density at the active layer as a function of cell height(y) as in fig 7.

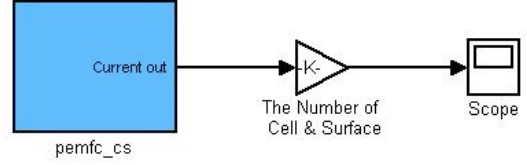


Fig. 8. Simulink model of PEM fuel cell stack

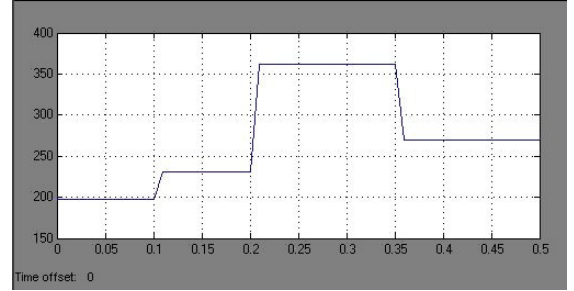


Fig. 9. Simulation result of PEM fuel cell stack model

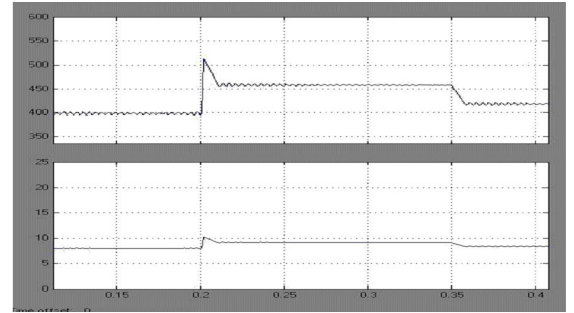


Fig. 10. Output of DC/DC converter (Voltage/Current)

V. CONCLUSION

In the presented work, a PEM fuel cell powered system including a DC/DC converter is fully simulated. In particular, a typical PWM DC/DC converter is used to step up the output voltage of the stack and a control strategy with a feed forward is proposed to effectively keep the DC link voltage constant.

A new dynamic model and design methodology for an FC- and UC-based IPT system for railway vehicle applications has been developed. Simulation results are presented using MATLAB, Simulink, and Ansoft EM environments based on the mathematical and dynamic electrical/magnetical models developed for the proposed system.

The future research will focus on improvement of the stack model considering temperature effects and the associated management of the temperature and water. In addition, models

for a three phase load will be developed to understand the system dynamics in an application as a multi-purpose uninterruptible power supply that can deliver not only active power but also reactive power.

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