International Journal of Control and Automation
Vol.8, No.11 (2015), pp.421-432
http://dx.doi.org/10.14257/ijca.2015.8.11.39

Regenerative Energy Control of DC Electric Railway Based on Solid State Transformer

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Abstract

Regenerative energies are generated by regenerative braking of train. Regenerative energies might cause the problem of power quality such as the voltage drop and malfunction of the power conversion device in the electric railway system. For these reasons, many researches have studied to solve these problems. In this paper, we modeled DC electric railway system based on the solid state transformer that is composed of voltage source converter (VSC) and bi-directional DC-DC converter for controlling the regenerative energy. In order to verify the performance of the proposed electric railway system, electric railway system is modeled by using real time simulator OP5600. In addition, the controller of solid state transformer is implemented by using DSP, TMS320F28335.

Keywords: *Electric railway, Voltage source converter (VSC), Regenerative Energy Control, Modeling, Hardware-in-the-loop simulation system (HILS)*

1. Introduction

Regenerative energy in DC electric railway is either generated from the deceleration intervals or from the braking intervals of the train. The regenerative energy results in the rise of catenary voltage of DC line. This rise causes various problems such as malfunction of system and/or damage of rectifiers [1-2].

In order to solve these problems, in existing DC electric railway systems 70~80% of the regenerative energy is used within the electric vehicle or for accelerating other electric vehicles in vicinity. Surplus of regenerative energy is wasted either by using a resistive load or is used for air braking [3]. Recently, in order to improve the energy efficiency, a lot of research has been carried out regarding regenerative energy storage in electric double layer capacitor (EDLC), storage in battery and transmitting it to an AC power system [4].

However, most of the domestic DC electric railway systems use diode rectifier method for supplying power to the electric vehicles. With this method, it is difficult to send the regenerative energy to the AC power system. Thus, many studies have investigated about the installation of the regenerative inverter to improve the regenerative energy efficiency [5-6]. Also, other studies have been carried out with EDLC which is installed on DC electric railway systems [7-9]. EDLC stores regenerative energy generated from the deceleration intervals of the train and uses the stored regenerative energy when the train departs or accelerates.

But, the usage of regenerative energies with EDLC or battery is limited by the capacity of the respective element and remaining energy can no longer be stored. So, the remaining energy is still wasted through a resistor.

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ISSN: 2005-4297 IJCA

Meanwhile, an AC/DC rectifier along with a transformer was used for adjusting the AC voltage level to a desirable DC voltage level in accordance to the user requirements. However, due to the recent advancements in semiconductor and power electronics instead of conventional transformers semiconductor devices similar to AC/DC inverters and DC/DC converters are used. Various researches have been carried out to use these device for making a solid state transformer in order to convert the AC voltage to a desired DC voltage level. These devices comes with a compact size and are light weighted as compared to the conventional devices. These devices are also advantageous in reducing the fault currents and supplying high power quality [10-11].

In this paper, we modeled an electric railway system based on the solid state transformer for controlling the regenerative energy. The solid state transformer is composed of a voltage source converter (VSC) and a bi-directional DC-DC converter. In this model separate installation of regenerative inverters or EDLC is not required. When regenerative energy is generated, it can be given back to the AC power system. The proposed model is also capable of maintaining the level of catenary voltage in DC electric railway system due to the usage of converter for controlling the voltage. In order to test the performance of the proposed DC electric railway system, proposed DC electric railway system is modeled in real time simulator OP5600 and the controller of solid state transformer is designed by using DSP, TMS320F28335.

The introduction portion is followed by the background information of the DC electric railway system. Section 3 explains the DC electric railway system controllers and the implemented HILS system and the TMS320F28335 based DC electric railway system controllers for this study are explained Section 4. The TMS320F28335 based converter controllers of the proposed DC electric railway system are tested in the HILS system and the performance of the controllers is analyzed in Section 4 which is followed by conclusions.

2. DC Electric Railway System

Most of the domestic DC electric railway systems receive the required power for electric vehicle by converting the three-phase AC 22.9[kV] (received from KEPCO substations) through rectifiers to desired DC levels (750[V] or 1500[V]).

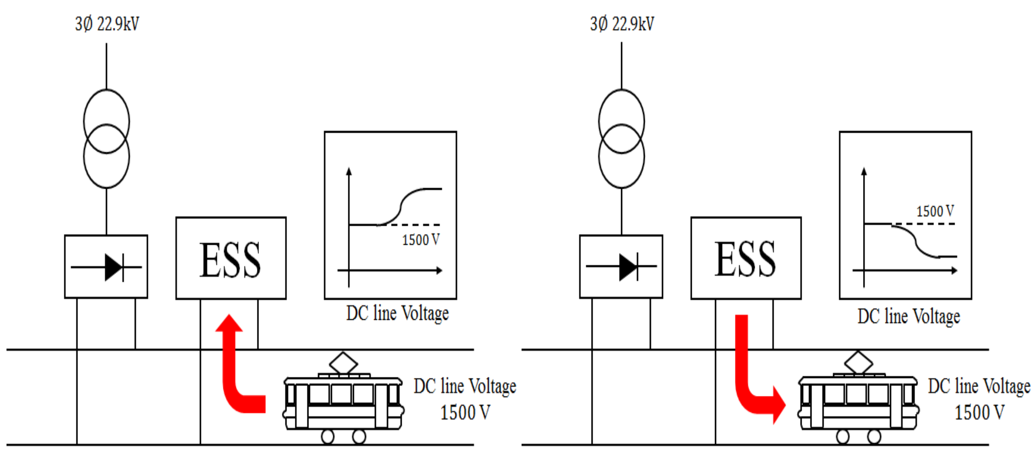


Figure 1. Energy Flow of Energy Storage System

A lot of research has been observed regarding the energy storage systems (ESSs) and regenerative inverters in DC electric railway system to use the regenerative energy efficiently. Deployment of ESS in the DC electric railway systems can be seen in Figure 1. Different researches have been carried out regarding the installation location and type of storage system for ESS in railway systems [12].

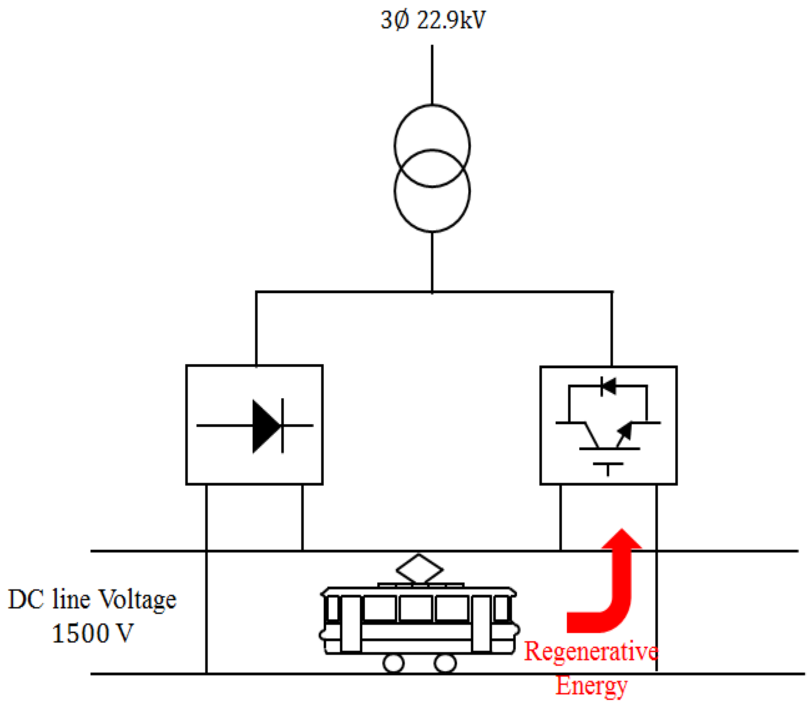


Figure 2. DC Electric Railway System by Using Regenerative Inverter

Also, in order to give back the regenerative energy to the main AC power system, DC electric railway system uses a thyristor or an insulated-gate bipolar transistor (IGBT) as shown Figure 2 [13].

3. Proposed DC Electric Railway System

In this paper, we proposed DC electric railway system based on the solid state transformer which is composed of a VSC and a bi-directional DC/DC converter. The VSC is capable of bi-directional AC/DC power conversion and the bi-directional DC/DC converter can control the DC voltage level.

3.1. Voltage Source Converter

VSC is used to convert an AC voltage to a DC voltage of the power system. The VSC is capable of bi-directional AC/DC power conversion. Figure 3 shows the structure and control system of the VSC [14].

The VSC voltage equations can be represented in rotating dq-frame. The rotating dq-frame representation is given by equation (1) [15].

$$L\frac{d}{dt}i_d = U_d(t) - Ri_d(t) + j\omega Li_q(t) - V_d(t) \quad (1)$$

$$L\frac{d}{dt}i_q = U_q(t) - Ri_q(t) - j\omega Li_d(t) - V_q(t)$$

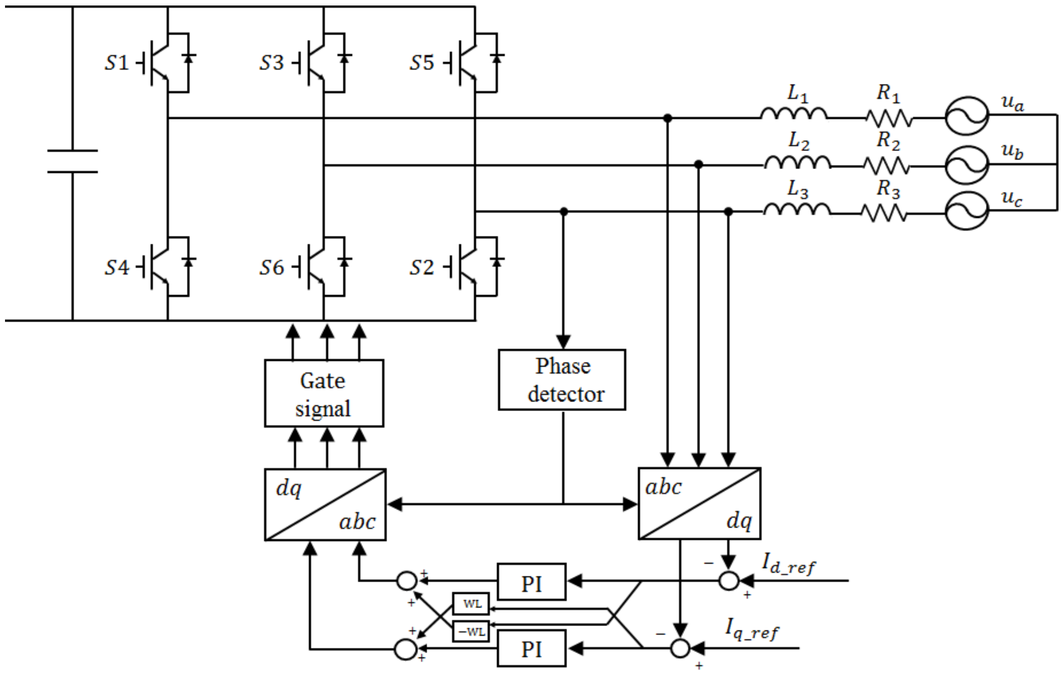
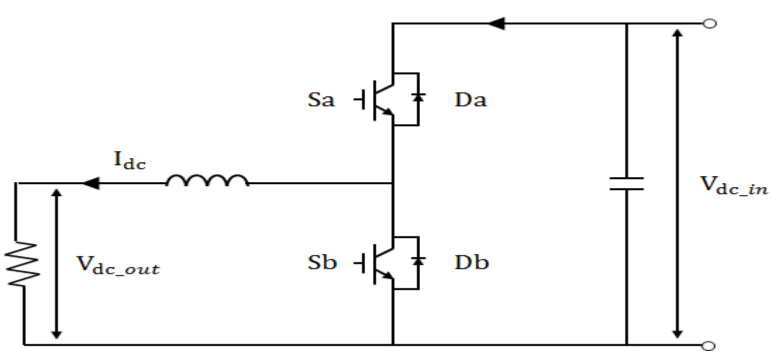


Figure 3. Structure and Control System of Voltage Source Converter (VSC)

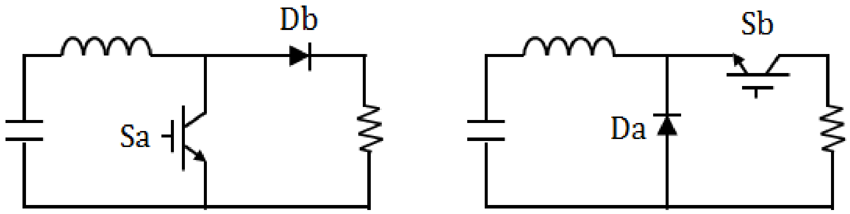
Using equation (1), it is possible to design the voltage controller of VSC. In order to improve the dynamic characteristics and to eliminate the coupling effect, decoupling control and feed-forward control is applied.

3.2. Voltage Source Converter

The VSC used in the proposed DC electric railway system has a characteristic of boost converter. Thus, the VSC alone can't control the 1500[V] by receiving 22.9[kV] from the main AC system. Therefore, bi-directional DC/DC converter is used to control the 1500[V] voltage and is depicted by Figure 4 (a). This controlled voltage can be supplied to the electrical vehicles. Figure 4 (b) shows a boost mode to operate in the discharging mode; energy consumed by the load. Figure 4 (c) shows a buck mode to operate in the charging mode and in this mode energy flows into the capacitor from the DC side [16].



(a) Structure of Bi-directional DC-DC Converter



(b) Boost (Discharge) Mode **(c) Buck (Charge) Mode**

Figure 4. Bi-directional DC-DC Converter

The input/output voltage relation of the bi-directional DC/DC converter can be expressed with equation (2).

$$V_{dc\_out} = \frac{D}{1-D} V_{dc\_out} \quad (2)$$

, Where V_{dc_out} = Voltage of output
V_{DC_in} = Voltage of input
D = Duty ratio

3.3. Proposed DC Electric Railway System

In order to control the regenerative energy, a solid state transformer is used for the proposed DC electric railway power system. The regenerated energy by electric vehicle is given back to the main AC power system to improve the energy efficiency of the system. Figure 5 shows the system diagram of the proposed DC electric railway power system. It comprises of a railway power load and a solid state transformer. The solid state transformer is made up of a VSC and a bi-directional DC/DC converter.

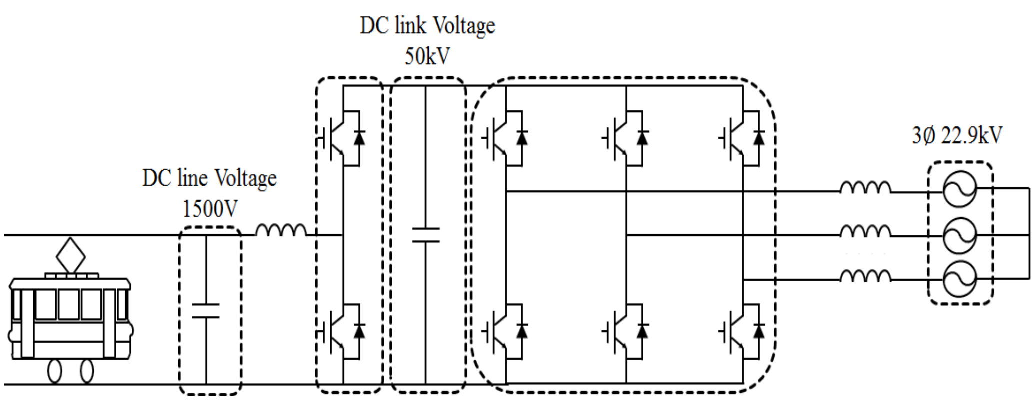


Figure 5. Modeling of Proposed DC Railway Power System

(a) Load Power Consumption Case

During departure or acceleration of electrical vehicles, due to the consumption of power, an instantaneous voltage drop in DC line voltage is occurred. During such cases, solid state transformer is used to control the catenary voltage of the DC line. The deficit power is received from the main AC power system to maintain the level of catenary voltage to 1500[V].

(b) Regenerative energy generation case

The regenerative energy is either generated from the deceleration intervals of the train or from the braking intervals of the train. Due to these effects, catenary voltage of DC line is higher than the 1500[V]. During such cases, solid state transformer is used to control the catenary voltage of DC line. The regenerative energy is given back to the main AC power system to maintain the level of catenary voltage to 1500[V].

4. Simulation by Using HILS

4.1. Implementing HILS System based on Real Time Simulator OP5600

In this paper, the solid-state transformer which is composed of a VSC and a bi-directional DC/DC converter is developed in DSP, TMS320F28335 and the proposed DC electric railway system is modeled in real time simulator OP5600. The HILS system has been realized with the above mentioned two components.

Figure 6 shows the input/output signals of the realized HILS system for this study. The real time simulator OP5600 interfaces with the TMS320F28335 based controllers through the data shield cables. The controller of VSC acquires the data for the three-phase current (I_{abc}), the three-phase voltage (V_{abc}) and the voltage of DC link (V_{DC_link}). The controller of bi-directional DC/DC converter acquires the data for the single-phase current (I_{dc}) and voltage of the DC line (V_{DC_line}). Then, the 3-phase PWM signals ($S_1, S_2, S_3, S_4, S_5, S_6$) of VSC and single phase switch signals (S_a, S_b) of bi-directional DC/DC converter are transmitted to the real time simulator OP5600.

Figure 7 shows the simulation environment of the implemented HILS system for the proposed DC electric railway system based on real time simulator OP5600 and DSP, TMS320F28335.

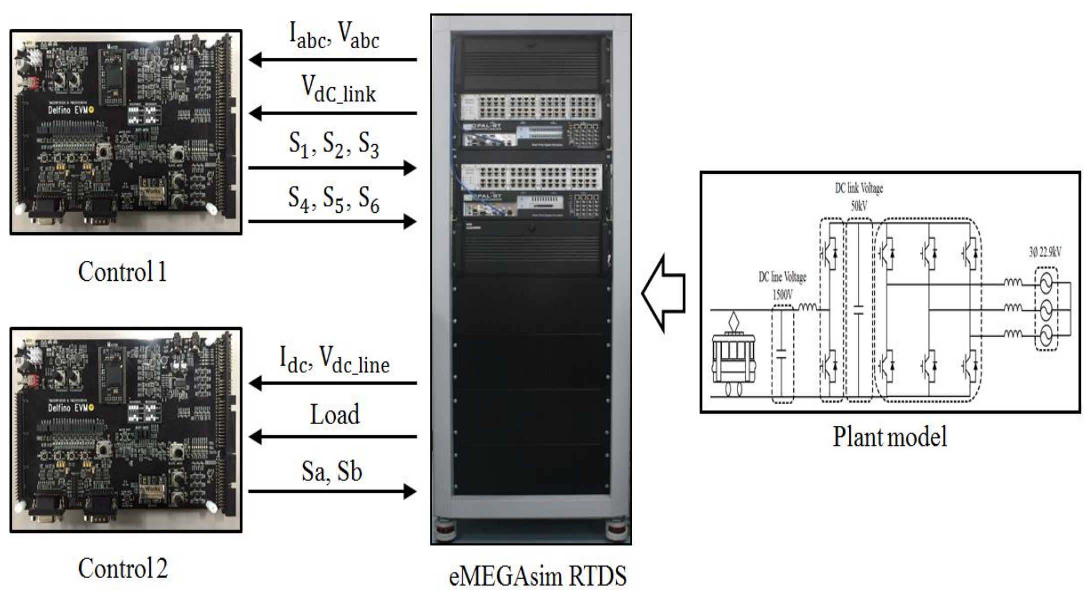


Figure 6. Input and Output Signal of HILS System

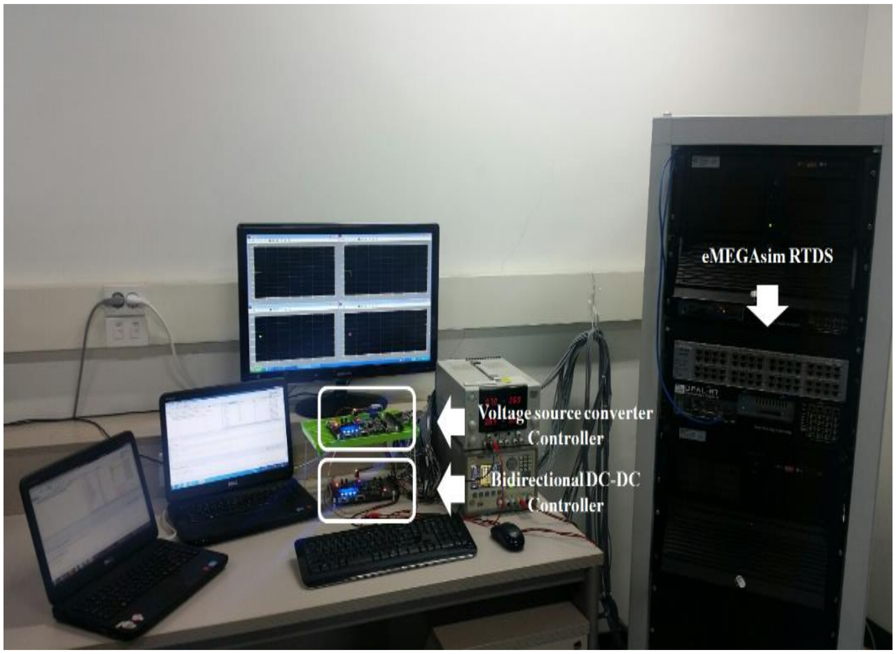


Figure 7. Constructed HILS System in LAB

4.2. Simulation Results

In order to test the performance of the proposed DC electric railway power system following two scenarios as shown in Figure 8 are considered.

· Case 1: Load Power Consumption Case
· Case 2: Regenerative Energy Generation Case

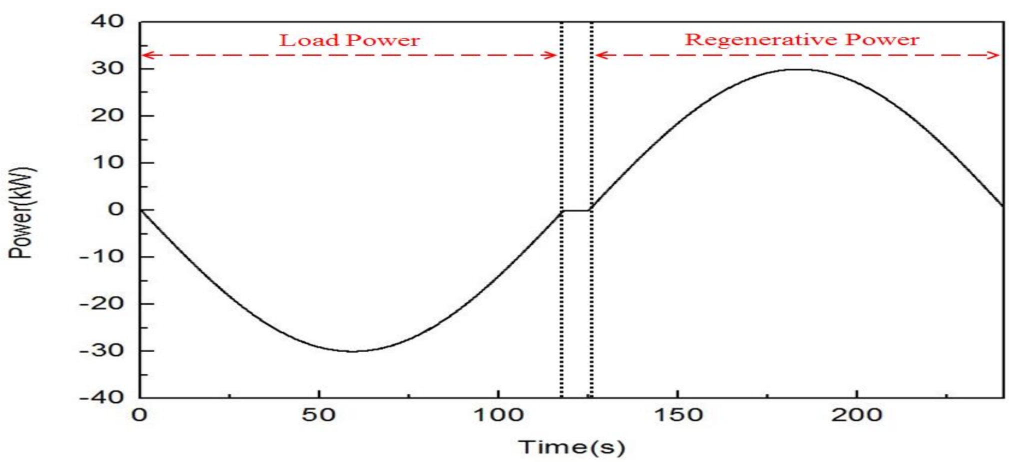


Figure 8. Load of DC Railway

4.2.2. Case 1: Load Power Consumption Case: In case 1, the power consumption of train during starting or accelerating is considered.

The load variation of DC railways from 0 to 117 seconds interval is considered and is depicted by Figure 8. Figure 9 shows the load power flow through converter in the load consumption interval. Due to the voltage control by bi-directional DC/DC converter, power is received from the AC power system in accordance to the load variation. That is, when the power is consumed by the electric vehicles, the DC voltage drop occurred in the electric railway power system due to this consumption is compensated by the main AC power system.

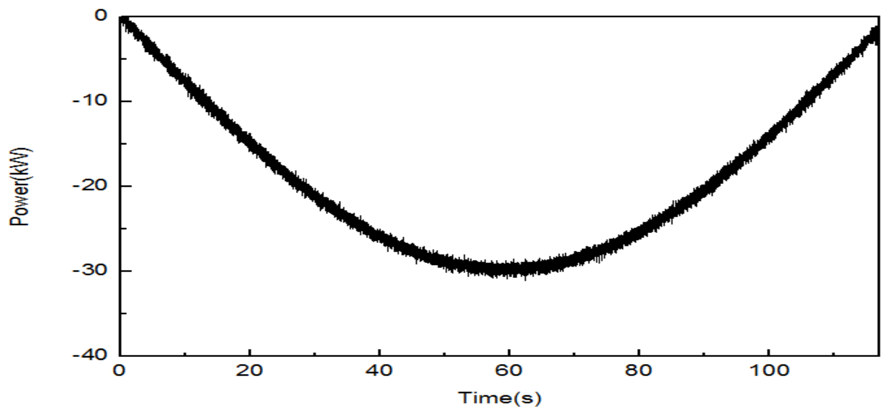


Figure 9. Load Power

Figure 10 shows the catenary voltage of a DC line. The catenary voltage (1500[V]) is maintained in the allowable range even after the consumption of power by electrical vehicles due to the electric power supplied to the load by main AC system in accordance to Figure 9. This effect can be observed from Figure 10.

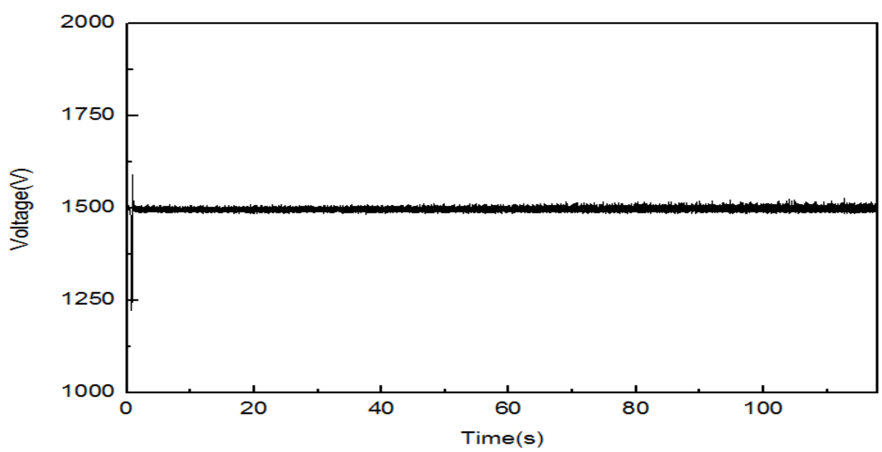


Figure 10. Catenary Voltage of DC line

4.2.2. Case 2: Regenerative Energy Generation Case: In case 2, the regenerative energy is either generated from deceleration interval or from the braking interval of the train. The load variation of DC railways from 125 to 242 seconds interval is considered and is depicted by Figure 8.

Figure 11 shows the power flow through converter in the regenerative energy generation interval.

The regenerative energy generated by the electric vehicle is sent to the main AC power supply through VSC and DC/DC bi-directional converter. The amount of energy sent is equal to the amount of regenerated energy by the electric vehicle as shown in Figure 11. When the regenerative energy is generated by the electric vehicles, the DC voltage rises in the electric railway power system. In order to prevent this rise, regenerative energy is sent to the main AC power system. Figure 12 shows the catenary voltage of a DC line. The catenary voltage (1500[V]) is maintained in the allowable range even after the generation of power by electrical vehicles.

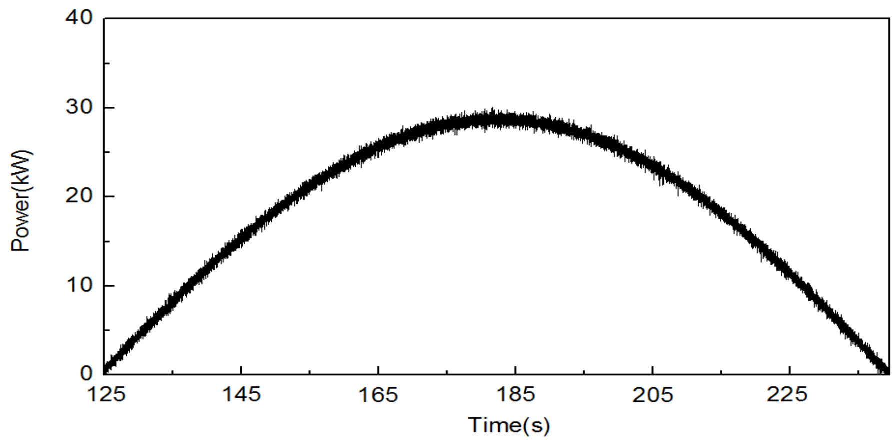


Figure 11. Regenerative Energy

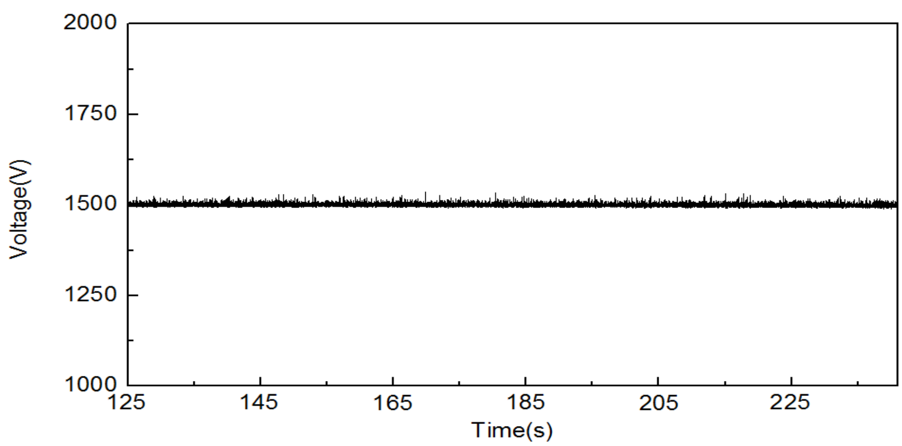


Figure 12. Catenary Voltage of DC line

5. Conclusion

In this paper, we proposed a DC electric railway system based on the solid state transformer in order to control the regenerative energy. The solid state transformer is composed of a VSC and a bi-directional DC/DC converter. In order to verify the performance of the proposed DC electric railway system, proposed DC electric railway system has been modeled by using the real time digital simulator OP5600. The VSC controller and the bi-directional DC/DC converter controller have been designed by using DSP, TMS320F28335. The converter controllers have been tested using the HILS system. It has been observed from the simulation results that, when the regenerative energy is generated or consumed by the load, the catenary voltage of DC line has been maintained at 1500[V] by using the solid state transformer controller.

Acknowledgements

This work was supported by the Incheon National University Research Grant in 2014.

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