

Development of AC/DC Hybrid Simulation for Operator Training Simulator in Railway System

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Abstract – Operator training simulator, within a training environment designed to understand the principles and behavior of the railway system with respect to operator's entries and predefined scenario, can provide a very strong benefit in facilitating operators' handling undesired operations. This simulator consists of computer system and applications, and the purpose of applications is to generate the power and voltage and analyze the AC substation and DC railway, respectively. This paper describes a novel approach to the new techniques for AC/DC hybrid simulation for the operator training simulator in the railway system. We first propose the structure the database of railway system. Then, topology processing and power flow using a linked-list method based on the proposed database, full or decoupled newton-rapshon methods are presented. Finally, the interface between the analysis for AC substation using a newton-rapshon method and the analysis for DC railway system using a time-interval power flow method is described. We have verified and tested the developed algorithm through the extensive testing for the proposed test system. To demonstrate the validity of the developed algorithm, comparative simulations between the proposed algorithm and PSS/E for the test system were conducted.

Keywords: Electric railway system, Operator training simulator, AC/DC hybrid simulation, Topology processing, Power flow analysis

1. Introduction

The manufacturing technology of railway system and the power monitor and control technology have made rapid progress due to the development of railway industry. Since the railway systems have been integrated with IT technology, there is a growing need for operational control center (OCC) in particular which manages and controls the entire system including railway traffic and all systems [1-2]. OCC operated in the Korea is comprised of total traffic control, supervisory control and data acquisition (SCADA), communication control system, and automatic control system for machine. Monitoring in the railway system through SCADA is a very important factor. Human errors caused by operator who operates the energy management system (EMS) in the power system and the OCC in the railway system can lead to significant social problems. Therefore, a systematic training for operators is required to operate secure these systems, and repeated training is also required in readiness for action in the event of fault and recovery operation as well as normal operation.

In terms of the planning and operation of railway

systems, it is one of the most important works for operators to improve an ability to deal with an emergency situation promptly by constructing an operator training system for railway (OTS/R) which has identical features of real railway system. To simulate the railway system composed of AC and DC systems, the power and voltage acquired from Korean Electric Power Corporation (KEPCO) system are required. Topological changes according to the failure in railway systems, the configuration of railway systems composed of redundancy of system, and the event at incoming point from KEPCO system should be considered to develop the OTS/R. In addition, a comprehensive approach, which performs the interface between the AC substation and the DC railway system, is should be considered.

Much research has been carried out on this topic and various systems have been proposed, as documented in the literature [3-7]. These research efforts can be categorized into two techniques. One is the analysis for railway system except for AC substation, which derives the solutions from either loop equations or nodal equations. In [3], after calculating the Norton equivalent parameters for each railway substation, the solution is determined using nodal equations and iterative calculations. The other method is the analysis for AC substation, which derives the solutions from either Newton-Rapshon (N-R) method or Guess-Seidel method. In [5], an approach to evaluate the overall impact of the electric traction demands of a high-speed railroad on a power system is described based on N-R

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power flow method. However, a robust and precise methodology is required in order to develop the OTS for simulation and control of railway system. In [7], new technique for enhancing the accuracy of hybrid simulation is proposed.

This paper describes the design, implementation and validation of the OTS/R based on database, topology processing, N-R power flow, and hybrid simulation. First, a database model which can connect different network components of the railway systems in common was constructed. Then an robust methodology, which converts physical nodes composed of AC and DC to the electrical buses and analyze the railway system using full and decoupled N-R power flow method, was proposed based on the database of the strong hierarchy structure. The contingency analysis applying the topology processing and iterative power flow method on the railway system was also introduced. Finally, a study of the interface between the AC substation and the DC railway system is described. The OTS/R adopting the proposed algorithms and database has been tested and verified using various test scenarios for a test system. Input/output files are generated in the form of CSV file. The availability of the proposed methodology was verified through comparison with PSS/E [9].

2. Structure of Operator Training Simulator

As mentioned above, the OTS/R provides the training of ordinary operation procedure of railway system to operators, and helps improve the ability to deal with actual operating situations depending on the different emergency scenarios such as fault, equipment malfunction and a rapid change in power or load [8].

2.1 Overview of electric railway system

The DC electric railway system transforms the voltage of 22.9 kV or 154 kV received from the KEPCO system to AC 1,200 V which is an appropriate voltage at the railway substation, and transforms it to DC 1,500 V using rectifier to supply to the feeder. AC substation is consisted of redundancy of system, and vacuum circuit breaker (VCB) is installed at a critical point and the initial condition of VCB is open. When event occurred, the status of VCB would be changed and then configuration of the railway system would be changed by topological path. Fig. 1 shows the electric railway system which comprise the configuration of AC substation and the DC railway system.

2.2 Design of database for operator training simulator

Modeling for railway system means that the physical equipment in railway system is converted into the mathematical model to perform the railway system simulation. Circuit breaker, switch, transformer, line, shunt

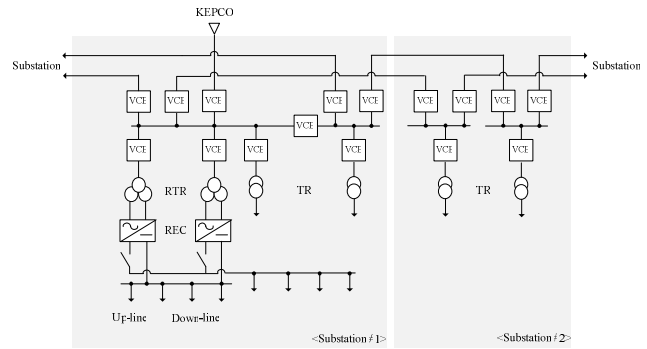


Fig. 1. Configuration of a DC railway system

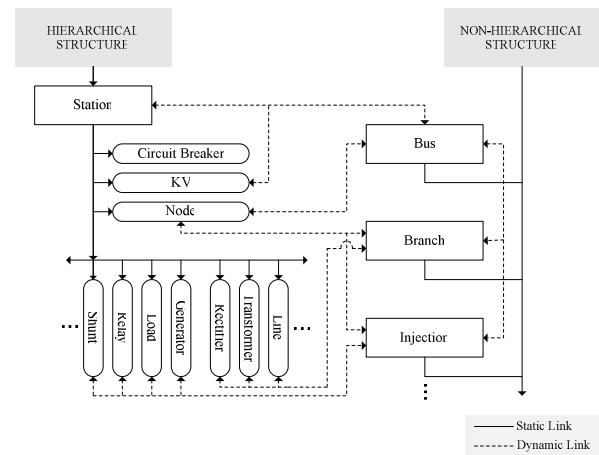


Fig. 2. Major part of the database regarding simulator

device, and rectifier are considered as major components among the all equipment consisting of electric railway system shown in Fig. 1. And the incoming point through the KEPCO system is done modeling by generator, while vehicle can be done modeling by load.

Fig. 2 shows the structure of database built for the simulator. The database model is classified into two, hierarchy model and non-hierarchy model. Hierarchy model is a common model which various applications share, while non-hierarchy database model is composed of user input data, setting parameters, dynamic data such as the connection among bus, branch and injection tables. Such database is helpful in analyzing rapidly and conveniently developing a program.

2.3 Methodology for enhancing the performance of electric railway system

The analysis for electric railway system is divided into two domains, AC substation and DC railway system. In order to calculate the flow from the incoming point through the KEPCO system to the supply point of the feeder of the DC railway system, an accurate power flow analysis is required. In addition, this analysis might be considered for the topology processing because substation consists of redundancy of system based on circuit-breaker. The detail

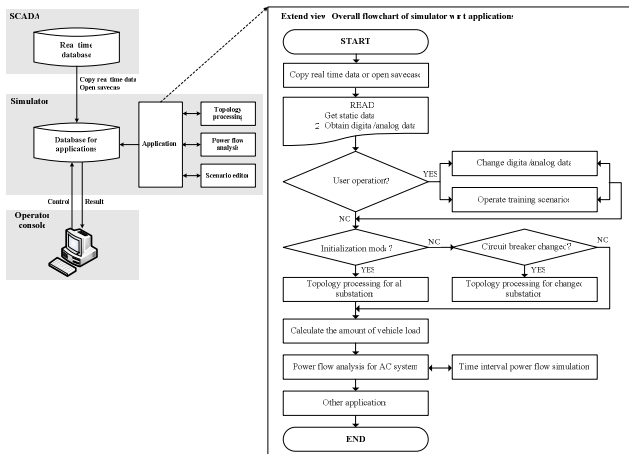


Fig. 3. Configuration of operator training simulator

modeling of vehicle is required to simulate many vehicles connected to the feeder consisting of DC railway system. In this paper, two methodologies for the interface between the AC substation and the DC railway system are investigated. First, the vehicle load was calculated considering the amount of power consumed by vehicle and topology in the DC railroad. And then the vehicle load calculated in DC railway system was converted to the load of AC system. Second, the vehicle load was calculated through the interface between the boundary bus of AC system and the vehicle load. If the operation curve of vehicle such as the actual track data, curvature and gradient and position and velocity limit for each curve section was prepared, the latter could be applied to simulate the railway system.

As shown in Fig. 3, the simulator which was designed to robust and accurate simulation has features as follows.

- The simulator allows training in using railway system simulation program, scenario editor program, and user control display, based on the on-line data.
- The simulator is equipped with database composed of AC and DC system, and the results of simulator should be similar with those of the railway system operating in practice.
- Input data of the simulator, which includes the amount of power consumed by vehicle and feeder voltage, is based on the cases obtained from SCADA system, saved cases or user input. Saved cases mean that the outputs of the power flow analysis were saved.
- FEP function which acquires real-time data from SCADA is substituted for power flow analysis, which generates power, voltage and current. The generated data is used to input data of other applications.
- Power flow analysis consists of 2 functions such as topology processing and power flow method. It analyzes on AC and DC systems. AC system is calculated using full or decoupled N-R method.
- The vehicle itself has variable characteristics such as variations in the location of vehicle, variations in the

amount of vehicle load, reverse supply of regenerative power generated from the vehicle. In order to respond the characteristics of vehicle, the vehicle load is calculated using two methodologies mentioned above.

- In order to give a clearer feature of the applications for analyzing the railway system in a simulator, the overall flowchart to simulate the power system using data processing, topology processing, power flow analysis, contingency analysis, and short circuit analysis are shown in Fig. 3.

3. The Proposed AC/DC Hybrid Simulation

Robust database and applications are the critical factors that affect the performance of the OTS/R. Topology processing, N-R power flow method and time-interval power flow method should be considered for hybrid simulation regarding the railway system with AC substation and DC railway system.

3.1 Topology processing

In topology processing, real-time data is duplicated in the database for applications once acquired from SCADA. The equipment' structure based on physical node is converted into those based on electrical bus using analog and digital data. In addition, it is checked whether isolated system or not using the created buses, and the equipment are decided whether the energized or not.

As shown in Fig. 1, DC railway system was not installed in every substation, so analysis for DC system is only required on certain substation. Load consumed by vehicles on DC railway system is calculated and converted into the load of AC system. Fig. 4 shows the topological configuration of vehicle load at single line diagram illustrating DC system. As shown in Fig. 4, it is the most important factor to calculate the load on the DC system composed through rectifier. The loads #1 to #4 are the load of normal vehicles, while the load #5 indicates regenerative power. Regenerative power is calculated by the negative

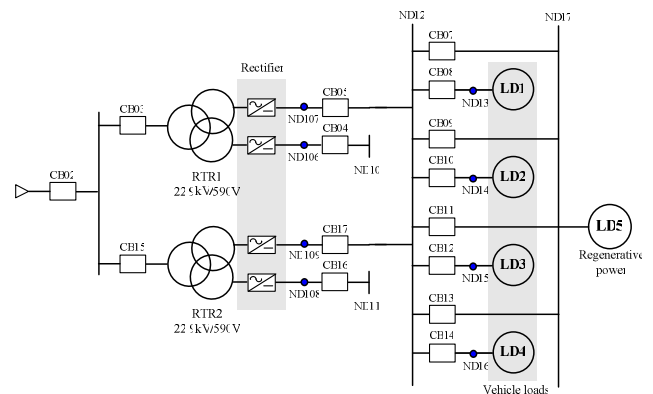


Fig. 4. Method of topology processing for DC system

load. In general the actual value of loads is measured by devices installed CB associated with load. The procedure to calculate the connectivity and vehicle load of AC and DC systems is described as follows.

Step 1) Create the electrical bus using closed circuit breaker for all substations. Especially, topology processing in DC system creates the number of 4 buses regarding 106 to 109 which are nodes at the bottom of rectifier shown in Fig. 4.

Step 2) Assign the electrical bus to the equipment terminal.

Step 3) Validate the electrical island using buses generated in Step 1). The state of the railway system is checked to be decided whether it is normal or not using the created island.

Step 4) Check whether the vehicle load is connected to the generated bus or not for DC system.

Step 5) Check whether the bus including the vehicle load is regenerative power or not. The amounts of load and regenerative power connected to rectifier are considered as total load.

In the OTS/R, the various events such as fault and a rapid change in power or load were generated by the opening of CB or the changing of individual generator and load. Topology processing was prepared to input data to calculate the actual state at normal and contingency conditions.

3.2 Power flow analysis

Two methods of full and decoupled N-R methods were applied in this work. As the data acquired directly from SCADA is used in power flow, initial value is critical factor. Decoupled N-R method is less sensitive to initial value compared to full N-R method. However, Decoupled N-R method would be inappropriate to line with the bigger R/X rate, while full N-R method would be appropriate to obtain more accurate solution. As shown in Fig. 5, this work proposes a procedure of power flow analysis as follows.

Step 1) Perform the pre-processing for input data acquired from SCADA, topology processing, model value, and pseudo measurement. Operator can input the incoming amount and the load of a vehicle when measurements are not acquired from SCADA. Model value saved in the database can be used when measurement is not acquired nor input by operator.

Step 2) Calculate the amount of vehicle load at the boundary bus of the AC system. The amount of vehicle load connected to each rectifier at DC system is transferred to AC system using the formula as follows (1).

$$Q = P_{dc} \times \tan \theta \quad (1)$$

Phase angle should be calculated when various data

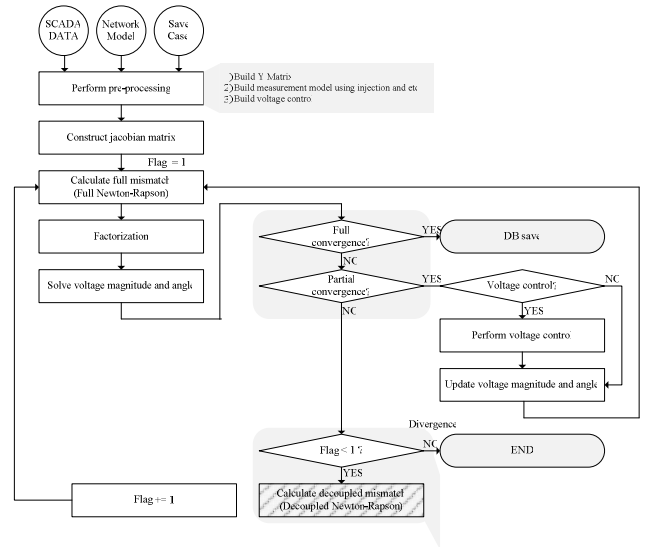


Fig. 5. Overall flowchart of the proposed power flow

regarding rectifier are acquired from SCADA. In general, 0.65 for $\tan \theta$ is used in this work.

Step 3) Perform the full N-R power flow analysis and check the quality of the result of it. If the solution of this step has diverged, go to Step 4).

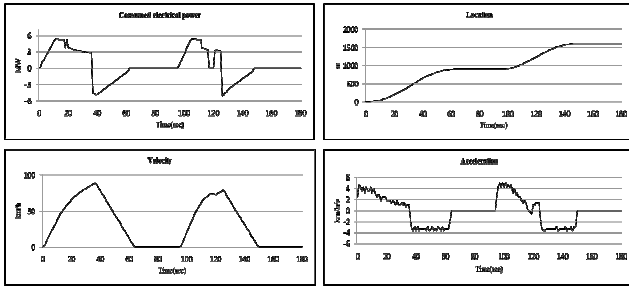
Step 4) Perform the decoupled N-R power flow analysis.

As mentioned before, the power flow algorithm in the OTS/R calculates the actual state at various conditions. The generated voltage, current and power were used to other applications such as contingency analysis, short-circuit analysis and protective coordination. If the quality of the values of load and generation obtained from SCADA system was poor, the solution of power flow analysis should be diverged. In order to overcome this problem, state estimation technique was applied to railway system.

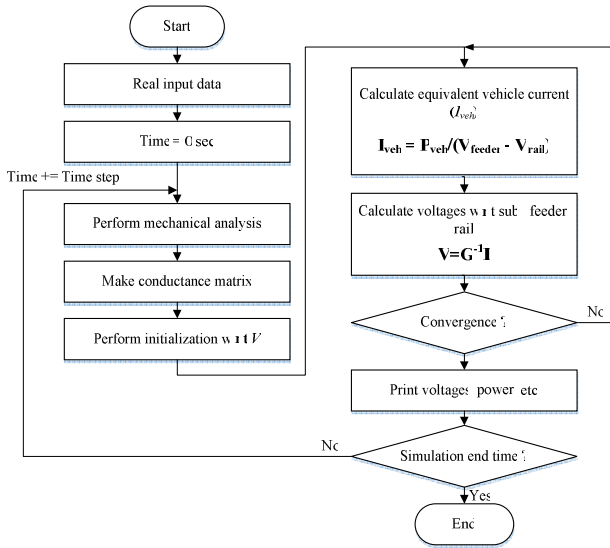
3.3 Hybrid simulation

A new hybrid approach, which integrates the time-interval simulation for DC railroad into the power flow analysis for the rest of railway systems, is proposed for enhancing the accuracy of simulation in railway system. The time-interval power flow method determines the location and power of each vehicle in railroad through mechanical analysis, and then calculates the each state of snapshot using through electrical analysis. The simplified railway system should be represented as the Norton equivalent circuit, and the system formulation with respect to voltages of substation, feeder and rail is given by [3]

$$\begin{bmatrix} g_{sub1} + g_{fd1} & 0 & -g_{fd1} & 0 \\ 0 & g_{sub2} + g_{fd2} & -g_{fd2} & 0 \\ -g_{fd1} & -g_{fd2} & g_{fd1} + g_{fd2} & 0 \\ 0 & 0 & 0 & g_{ra1} + g_{ra2} \end{bmatrix} \begin{bmatrix} V_{sub1} \\ V_{sub2} \\ V_{feeder} \\ V_{rail} \end{bmatrix} = \begin{bmatrix} I_{sub1} \\ I_{sub2} \\ -I_{veh} \\ I_{veh} \end{bmatrix} \quad (2)$$



(a) Results of mechanical analysis



(b) Overall flowchart of the time-interval power flow

Fig. 6. Methodology of the time-interval simulation

$$I_{veh} = \frac{P_{veh}}{(V_{feeder} - V_{rail})} \quad (3)$$

where g_{fd} , g_{sub} and g_{ra} represent the impedances of feeder, substation and rail, respectively. I_{veh} and I_{sub} denote an equivalent vehicle current and an equivalent source current, respectively. Fig. 6(a) shows the results of mechanical analysis based on the standard operation curve between the two stations, and Fig. 6(b) shows the overall flowchart of the time-interval power flow method [3]. As shown in Fig. 6(b), initial current was calculated by using Eq. (3) and was updated by using Eq. (4). This simulation calculates the time-interval power flow analysis during one headway time since it is impossible to perform the power flow analysis at the moment with the load.

As mentioned before, in order to build the interface between power flow analysis for the boundary bus of AC substation and time-interval simulation for the vehicle of DC railroad, the initial values determined by topology processing and N-R power flow method were used to input of time-interval simulation. Then it was performed during specific time duration, and the power consumed by vehicle is transferred to the boundary bus of the AC system. These

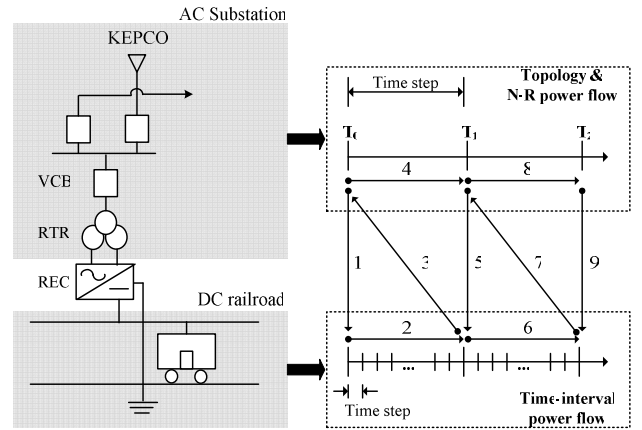


Fig. 7. Methodology of the AC/DC hybrid simulation

processes are repeated until the simulation end time. The simple methodology of the AC/DC hybrid simulation is shown in Fig. 7 [7]. In the OTS/R, hybrid simulation was applied to the accurate behavior of the railway system with AC substation and DC railway system. As shown in Fig. 7, this work proposes a procedure of AC/DC hybrid simulation as follows.

Step 1) Calculate the initial values for the boundary bus of AC substation using topology processing and N-R power flow method.

Step 2) Perform the time-interval power flow method for the DC railway system using mechanical analysis and electrical analysis. Initial values determined by Step 1) were used to input of time-interval simulation. It was performed during specific time duration.

Step 3) Transfer the power consumed by vehicle to the amount of load at the boundary bus of the AC system.

Step 4) Perform the power flow analysis for the AC substation.

Step 5) Repeat from Step 2) to Step 4).

4. Case Studies

In this work, test system based on the electric railway system was used to verify the availability of the proposed methodology. First of all, the developed algorithm was verified through the extensive simulation based on the database. Then the reliability of the developed algorithm through the comparison with PSS/E simulation was verified.

As shown in Fig. 8, test system consists of 5 substations, and the substation #1 incoming from the KEPCO system and the opposite substation #5 were constructed as a generator of 22.9kV. Test system forms two islands through the normal open switch. The initial status of CB #42 and CB #84 is open, and the status of the above CB will be changed in case of events. Test system consists of total 109 nodes, 2 generators, 22 loads, 8 shunts, 10 two-winding

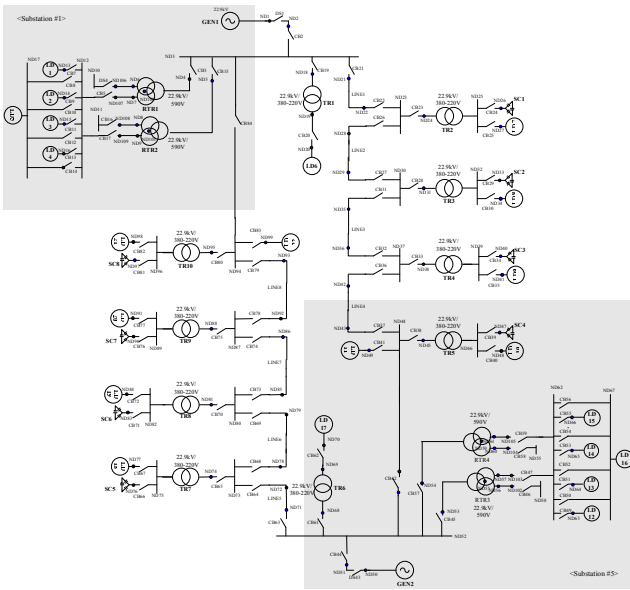


Fig. 8. Configuration of test system

Table 1. The caption must be followed by the table

Id	Test item	Description	Validation
4.1	Topology processing	Create the buses using closed circuit-breaker	Theoretical result
		Determine the electrical island	
		Analyze the DC railway	
4.2	Power flow analysis	Calculate bus voltage and power flow	PSS/E
4.3	Contingency Analysis	Rectifier fault	PSS/E
		Incoming point fault	
4.4	AC/DC Simulation	Interface between two systems	-

transformers, 4 three-winding transformers, and 8 rectifiers. All the shunt devices are currently put. Performance of the developed algorithm which is supposed to be loaded in the simulator was evaluated using the test scenario. Table 1 shows the summary of scenarios for test system.

4.1 Test cases: Topology processing

This scenario illustrates the node-bus mapping and the calculation of vehicle load of the topology processing. As shown in Fig. 8, the status of circuit breakers #42 and #84 of the test system is open. Table 2 shows the result of topology processing. 36 buses are generated from topology processing, and 4 out of 36 become outaged. Valid 32 buses are classified into two independent islands. In other words, slack bus exists in each island. In topology processing, the link between bus and equipment is also assigned. The state of individual rectifier, the sum of the amount of loads connected buses, and the number of relative rectifier are presented followed by an analysis on the DC system through topology processing. Table 3 is the result of the DC system analysis of the substation #1. It is

Table 2. Result of topology processing for test system

Id/ Type*	Island id	Link between bus and equipment			
		Station [†]	Volt. [†]	Node [†]	Injection [†]
1/3	1	1	1	21	1
2/1	1	1	3	6	0
...
15/1	2	2	5	92	0
16/1	2	2	6	91	30
...
35/4	0	5	13	67	26
36/1	2	5	14	70	27

* Type of bus, 1: Load, 2: generator, 3:slack, 4: dead

[†] Pointer number of database between bus and equipment

Table 3. Result of topology processing for DC system

Rectifier id. (Node name)	State of rectifier	Opposite rectifier id	Amount of load
#1 (nd#109)	In-service	#2	0.4 MW
#2 (nd#108)	Out-of-service	0	0
#3 (nd#107)	In-service	#4	0.4 MW
#4 (nd#106)	Out-of-service	0	0

Table 4. Result of power flow for test system

Bus id	Isl./S t. [†]	Voltage magnitude (p.u.)			Voltage angle (degree)	
		PF*	PSS/E	Diff.	PF*	PSS/E
1	1/1	1.0000	1.0000	.0000	0.00	0.00
9	2/1	1.0118	1.0118	.0000	-0.05	-0.05
13	1/2	1.0032	1.0032	.0000	-0.01	-0.01
15	2/2	1.0116	1.0116	.0000	-0.05	-0.05
17	1/3	1.0069	1.0069	.0000	-0.03	-0.03
19	2/3	1.0103	1.0103	.0000	-0.04	-0.04
21	1/4	1.0110	1.0109	.0001	-0.04	-0.04
23	2/5	1.0056	1.0056	.0000	-0.02	-0.02
25	1/6	1.0119	1.0118	.0001	-0.05	-0.05
27	2/7	1.0000	1.0000	.0000	0.00	0.00

[†] Id of island and station

* The proposed power flow method

confirmed that 2 rectifiers are normal and share 0.8 MW.

4.2 Test cases: Power flow analysis

In order to validate the reliability of the power flow method which generates the power and voltage used in OTS/R, a comparative simulation between the developed algorithm and PSS/E was performed at flat condition. Table 4 is the results of power flow analysis of the developed algorithm and PSS/E. Among 32 activated buses, only the results that meet the 22.9kV of bus voltage were printed. The system consisted of two independent islands was analyzed according to the results. It was also identified that the results between the developed algorithm and PSS/E are very similar.

4.3 Test cases: Contingency analysis

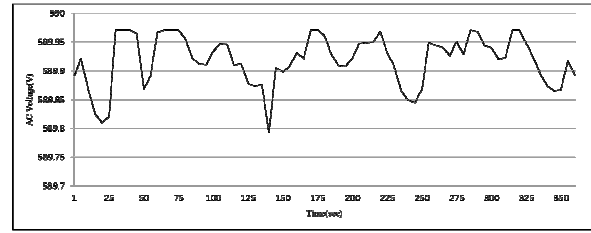
This scenario aims to verify the performance of contingency analysis in the event of the fault in rectifier

supplying the power to the DC railway system. Simulation conditions are to generate the fault in rectifier by opening the circuit breaker #17 in the test system. In other words, DC vehicle load in the substation #1 is operated by 1 rectifier. Other simulation conditions are identical to power flow analysis mentioned above. The features of the contingency analysis are as follows. When the status of the circuit breaker #17 is open, the developed algorithm identifies that vehicle load is connected to the rectifier #3 in accordance with the topology processing on DC system. Then operation conditions of the rectifiers #1, #2, and #4 are outaged regarding the substation #1. Only the Rectifier #3 is operating, and the amount of vehicle load is 0.8 MW.

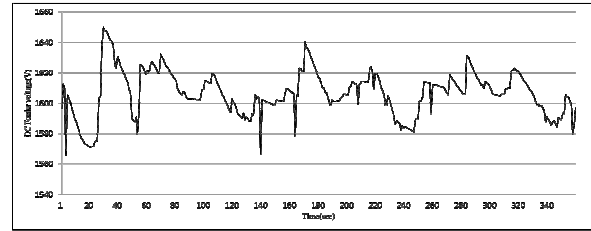
Next, this scenario aims to verify the performance of contingency analysis when the status of VCB in the substations #1 and #5 is changed because of the fault at one point incoming from the KEOC system. Simulation conditions are to generate the fault in substation by opening the circuit breaker #2 in the test system, and also generate merge operation by inputting the circuit breakers #42 and #84. Other simulation conditions are identical with power flow analysis mentioned above. As shown in Fig. 8, one island is formed, and the generator #1 is classified into the outaged equipment as the circuit breaker #2 connected to the generator #1 is open. Table 5 is the results of contingency analysis based on the results of topology processing.

4.4 Test cases: Hybrid simulation

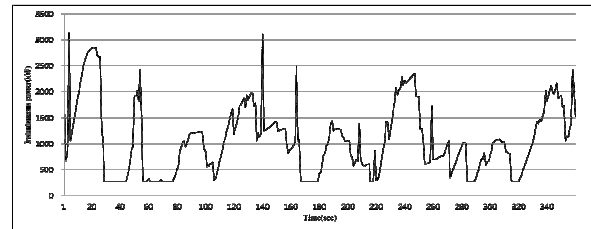
The proposed methodology for AC/DC hybrid simulation was tested to ensure that the interface between AC substation and DC railway system can enhance the accuracy of AC/DC simulation in the railway system. The configuration of test system is identical to Fig. 8 except for DC railway system. DC railway system uses some parts of the Seoul Metro. The track conditions used in the time-interval power flow analysis are described in [3]. The rated voltage of DC railway system is 1500 V, and unit resistance per 1 km of the equivalent conductors for the feeder and rail are 0.0203 and 0.000464 Ω /km, respectively. As shown in Fig. 7, the period of data exchange between two methods is 5 seconds. Fig. 9(a) and 9(b) show the AC



(a) AC voltage of substation #1



(b) DC feeder voltage of substation #1



(c) Instantaneous power consumed by DC system of substation #1

Fig. 9. Results of hybrid simulation

voltage of boundary bus and DC feeder voltage in substation #1, respectively. Fig. 9(c) shows the instantaneous power consumed by vehicle. As shown in Fig. 9, the responses of AC voltage and DC feeder voltage with respect to the change of the power consumed by vehicle are well considered. The results of the hybrid simulation showed that the AC boundary bus can calculate actual values exactly from DC railway system and can be correctly operated during simulation. Hybrid simulation has the advantages that the comprehensive analysis for the railway system with AC substation and DC railway system was performed. In addition, it determines the accurate velocity in the next state through mechanical analysis.

Table 5. Result of contingency analysis for test system

Comparative item	Equipment name	Split operation	Merge operation
Generation	#G1	2 MW	0 MW
	#G1	2 MW	4 MW
Bus voltage of substation #1	#Busbar 1	1.0000 [†]	1.0116
	#Busbar 2	1.0118	
Bus voltage of substation #5	#Busbar 1	1.0119	1.0000 [†]
	#Busbar 2	1.0000 [†]	
Maximum difference*	-	0.0001	0.0001

* Maximum difference between the proposed N-R power flow and PSS/E for bus voltage

[†] Slack bus

5. Conclusion

This paper describes the simple technique of AC/DC hybrid simulation for the operator training simulator in railway system. Database was constructed to allow operators to do convenient and various simulations on railway system. In order to simulate the railway system composed of AC substation and DC railway system, two methodologies are proposed. First, the combined methodology of topology processing and N-R power flow was introduced based on

the database. Topology processing determined the connectivity of railway system and the amount of power consumed by vehicle, and power flow analysis performed to minimize divergence in the simulation by developing full and decoupled N-R power flow methods. Second, the AC/DC hybrid simulation between the AC substation using a newton-rapshon method and the DC railway system using a time-interval power flow method is investigated. To demonstrate the validity of the proposed methodology, comparative simulations for the test system were conducted.

Further work on enhancing the accuracy of hybrid simulation through detail modeling of rectifier, state estimation and incorporating distributed generation such as energy storage and photovoltaic will be conducted.

Acknowledgements

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