Real time simulation of electric railway systems using RTDS

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ABSTRACT

Real-time simulation of electric system has been widely used in electric power system industries for more than 20 years. The uniqueness of the real-time simulation lies in the fact that the simulator can simulate the subject, an electric power system, in real time. Therefore, the simulation can be interconnected to an external device and provide the stimuli to the device in real time, which is vital to conduct the evaluation of the device. Currently, these simulation techniques are well established in the application areas such as protective relay testing of the electric power systems. With a very small size of time step in the range of 1-3uS, the simulation capability can address the issues associated with power electronics application in the electrified railway systems as well.

This paper presents the application of the real-time simulation in an electrified railway systems. A simple AC feeding system in conjunction with an electric traction system is a locomotive is modeled and simulated in real time. The simulation results present the effectiveness and possibility of the simulation technique in electric railway system studies.

INTRODUCTION

Since its inception in the late 1800's, electrification of railway systems has been expanding its reach in many different places in the world. It has been a major factor in making the system more precise in keeping in time and bringing more revenue to its operator. Moreover, as the concerns for the environment grows, the electrification of the system has been providing a good measure in dealing with the new government regulations regarding the environment. Furthermore, the friendliness of the system along with the environment resulting from the measure, not only regarding no emission but also regarding the generated noise, has been contributing to the higher level of acceptance of such systems by general public. Therefore, the electrified railway system is still expanding its reach to new areas such as the surface metro and downtown tram systems. Meanwhile, the higher power density of the electric traction systems has been enabled higher power rating tractors. Those higher power rating tractors brought in the increase of the single unit capacity, faster operating speed of a unit or both. Therefore the system operator can enjoy more convenience in scheduling and other benefits in operation.

However, the electrified railway system poses an entirely different set of issues for the people involved in the development and operation of such system. When the traction system was solely based on internal combustion engines, the major part of the issues associated with the system was mechanical. In the case of the Diesel-Electric locomotive, the part of the traction system is based on the electrical system, but the usual attention onto the system has been on the mechanical operation and maintenance, not on the electrical system. One completely new issue associated with the electrified railway system is the feeder protection. The issue was never heard of in the days when no electric feeder lines or Catenary lines ran with the railway on the ground [1]. Another issue coming with the electrification of the system is the characteristic of the traction cars. The tractive force-speed characteristics of electric motors in a traction cars are completely different from the one of internal combustion engine driven traction cars [2]. The different characteristics inevitably affect the dynamics of the cohesion between the traction wheels and the surface of the rails, eventually resulting in the difference in many different aspects of traction such as acceleration and braking. Therefore, a new set of tools is required to address those issues in the electrified railway systems.

Real-time simulation has been widely used in various areas in electric power systems [3]. One important aspect of the real time system in electric system is its real timeness. The definition of the word can vary according to the different applications. However, in electric power systems, the real timeness of simulation means that the result can produce from a simulator in a way that it can make no difference between the result from a real system and a simulated system in the view of an external system. Usually, the external system is the actual equipment to be deployed in the system, such as protective relays [4].

This paper introduces the application of the real-time simulator (RTDS) regarding the study of electric railway systems. The theory behind the simulation is to be introduced first. The explanation regarding the theory attempts to elucidate the fundamental simulation algorithm. More detailed introduction of the hardware utilized in the RTDS follows next. Then, a case study is presented and explained to address the effectiveness of the technique. The first experiment in case study is a real-time simulation case. The simulation case is based on an AC feeder system, composed of Scott transformer, AT feeder lines and electric traction system. Multiple (2) induction motors and a set of the drive system are modelled as the traction system in the simulation case. Then a simple HILS (Hardware In Loop Simulation) experiment and its results follows. Lastly, the conclusion attempts to recap the usefulness of the real time simulation.

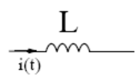
REAL TIME DIGITAL SIMULATOR (RTDS)

There are three categories of electric power system analysis. The first one is a load flow study. The fundamental purpose of the study is to figure out the static view of a given system. In other words, the study method, load flow study, offers the information regarding the steady state a given system, such as voltage magnitude, voltage angle, real power flow and reactive power flow. Then, the second category is what is usually referred to as transient stability analysis (TSA) method. The main focus of the study is to see if the synchronous machine in a given AC system can still maintain synchronism after a major disturbance, such as a fault. Thus, the method tries to capture and depict the mechanical dynamics of the synchronous machine(s) in the system. The engineers working with this method usually look for the machine angle transients, to tell the system is in good shape or not. Then, the third category is what people usually call as Electro-Magnetic Transient (EMT) method [5]. The fundamental assumption of the TSA method is a single phase equivalent representation of balanced 3-phase AC systems. Also, due to the focus of the study on the mechanical dynamics of the synchronous machine, the usual simulation time step is between 1/4 and 1/2 of the fundamental frequency period. However, such assumption underneath the TSA method doesn't hold in a DC network or single phase network, which are frequently found in electric railway systems. Then, the usual size of the time step is too large to account for the very fast dynamics of the power electronics based systems such as VVVF (Variable Voltage Variable Frequency) drive in a traction car. Unlike the TSA method, the EMT method doesn't have any of those assumptions or restrictions associated with TSA method. Any number of phase can be accommodated in an EMT method based simulation. Moreover, the time step side of an EMT method based simulation can be brought to a very small value, such as a couple of microseconds. Thus, the method allows to take the fast dynamics such as the one from power electronics based system into the larger picture of a simulation. Therefore, the method is a principle foundation of many power electronics simulation tools, such as MATLAB/SimpowerSystem blockset and PSCAD. The following table, Table 1, summarizes the three categories of electric power system study method:

Table 1 Electric power system study methods

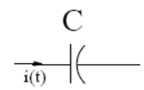
Type of Simulation	**Load Flow**	**Transient Stability Analysis (TSA)**	**Electromagnetic Transient (EMT)**
Typical timestep	Single solution	~ 8 ms	~ 2 - 50 µs
Output	Magnitude and angle	Magnitude and angle	Instantaneous values
Frequency range	Nominal frequency	Nominal and off-nominal frequency	0 – 3 kHz (>15 kHz with small time step)

The fundamental algorithm behind the EMT method is the combination of the ODE discretization and nodal analysis. One way of capturing the dynamic characteristics of any electrical system equipment such as transmission line or transformer is by using a set of algebraic and differential equations. Then, by applying a time domain numerical integration technique, the differential equations can be converted into a set of algebraic equations. The following figure, Figure 1, shows a simple example of an inductor and a capacitor. The resulting algebraic equations can be rearranged in a way that the output of the equation is current injection values and the admittance values. In the example depicted in Figure 1, the 'i(t)' at the left-hand side of the final equations are representing the current injection values, while the values in front of the voltage terms, $\Delta t/2L$ in the case of an inductor and $2C/\Delta t$ in the case of a capacitor, represent the admittance value.



$$v(t) = L * \frac{d\,i(t)}{dt}$$

$$i(t) = \frac{1}{L}\int v(t)\,dt$$



$$i(t) = C * \frac{d\,v(t)}{dt}$$

$$v(t) = \frac{1}{C}\int i(t)\,dt$$

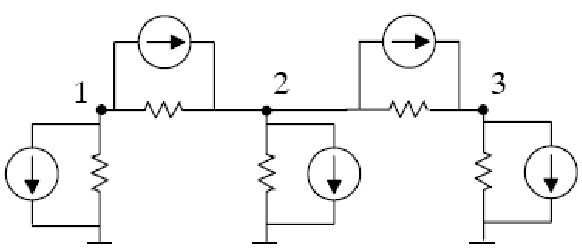
applying trapezoidal rule of integration

$$i(t) = \frac{\Delta t}{2L} v(t) + I_h(t-\Delta t)$$

$$i(t) = \frac{2C}{\Delta t} v(t) - I_h(t-\Delta t)$$

Figure 1 Discretization of dynamic elements

Once the discretization of all the differential equations representing electrical equipment in a simulation case based on EMT method becomes complete, then the network where those equipment are in can be described as a collection of the admittance values and current injection values from the discretization process. The following figure, Figure 2, shows an example of such network:



$$\begin{bmatrix} V1 \\ V2 \\ V3 \end{bmatrix} = \begin{bmatrix} G11 & G12 & G13 \\ G21 & G22 & G23 \\ G31 & G32 & G33 \end{bmatrix}^{-1} \begin{bmatrix} I1 \\ I2 \\ I3 \end{bmatrix}$$

Figure 2 Equivalent network

The left side of the figure above, Figure 2, shows the graphical representation of the network, while the matrix equation at the right side shows the mathematical representation. Once the network is constructed, then the equation at the right side of the figure, Figure 2, can be solved in order to produce the new set of node voltages. This process is usually referred to as a nodal analysis. Then, the new set of voltage values are used as input to the discretized dynamic equations. Then, the result of the step, solving the discretized equations is again becoming the input to the next step, which is the nodal analysis. By iterating these two steps, the simulation can proceed in an EMT method based simulation case.

Simply speaking, the RTDS is a computing machine where the abovementioned EMT method can be executed in hard real time. Usually, the meaning of real time can vary widely according to its application. However, when it comes to the application of the electric power system simulation, the real timeless of a simulation is bounded by two fundamental restrictions. The first restriction is the hard real-time characteristics. This first restriction tells that the time consumed by any simulation calculation cannot exceed the boundary of the time step. For example, if a given simulation time step size is 50µS, then the entire simulation is regarded as a failure once a single time step along with the entire simulation period violates the size. Then, the second restriction is the size of the time step. The size of time step determines the maximum bandwidth of dynamics which can be represented by the result from the simulation. For example, if the size of time step is half of the fundamental frequency period (8.3333ms in case of 60Hz), then the maximum frequency bandwidth expected from such simulation result is bounded up to the fundamental frequency. As mentioned previously, such low frequency is inadequate for representing very fast dynamics of certain devices in a railway system such as a VVVF (Variable Voltage Variable Frequency) drive system. If a VVVF system runs with a switching frequency of 1 KHz, then the necessary simulation time step needs to be less than 500 µS in order to cover the necessary bandwidth. However, when the simulation needs to come to fast dynamic systems such as VVVF, usual expectation is that the bandwidth needs to be more than 20 times higher than the switching frequency. The expectation brings down the time step size from 500 µS to 25 µS. The combination of the two restrictions explained hitherto makes the task of designing the necessary hardware and software tough.

Figure 3 An RTDS rack

RTDS successfully satisfies those restrictions above by utilizing parallel processing hardware architecture and efficient distribution of the calculation load onto multiple processing units. The fundamental idea regarding the hardware design originated from one of widely used multi-processor hardware architecture named VME [6]. As with the fundamental concept under VME, a backplane exists in a VME style 19'' rack. Then, the processing cards which are in charge of executing the necessary calculation for the real-time simulation are installed in the rack, and connected to the backplane. The backplane transfers the necessary data between those processing units participating in the real-time simulation. One card in the rack takes a different role in the simulation. It provides the interface between the simulation hardware and the simulation software through with a user can interact with the real time simulation. Then, another important role of the card is acting as a system master in the simulation hardware, another concept inherited from the VME system architecture. Figure 3 shows a RTDS rack.

Because of the modularity in design, the scale of the simulation hardware can be configured in many different ways. If the subject of the simulation is quite small, then one or two processing cards would be sufficient to execute the necessary simulation. When the size of the simulation subject grows very large, an entire electric railway network for example, then multiple racks can be connected together in order to provide the necessary simulation hardware.

Figure 4 Multiple RTDS racks

One paramount aspect of a real-time simulation is its interaction between the simulation itself and a real world. The fundamental purpose of the real timeness in the simulation is that it needs to go step by step with a real world equipment in perfect synchronism. Two different ways are possible for the necessary interaction. One is through physical signals such as analog voltage and the other is through communication. RTDS offers the necessary simulation hardware for the necessary interface, both the physical way and communication way. The physical signal I/O cards include the analog output card, analog input card, digital output card and digital input card. The analog output card (called as a 'GTAO' card) can convert digital simulation values into corresponding analog output voltages. In other words, it assumes the role of Digital to Analog (D/A) converter. Figure 5 shows the appearance of a 'GTAO' card. In addition, all the physical signal I/O cards are connected with the main hardware of RTDS through fiber optic cable, thus the connection offers high level of electric isolation and the necessary immunity to external noise. The analog input card can take in the real physical voltage values into the digital simulation, thus taking the role of Analog to Digital (A/D) converter. In similar ways, the binary signals such as on/off status of a switch can be easily exchanged between RTDS and a real world device by using the digital I/O cards.

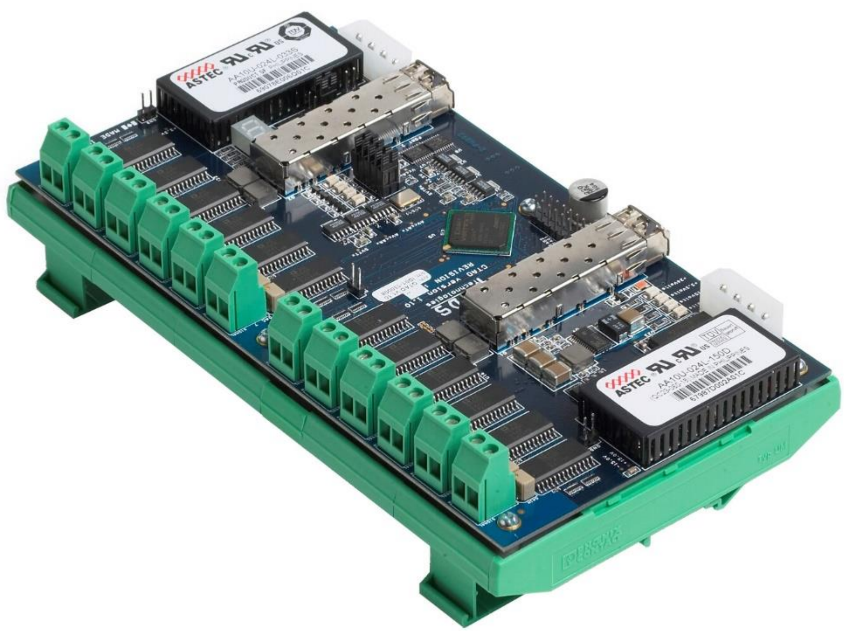


Figure 5 GTAO card

Meanwhile, the communication application in electric power system is gaining more momentum as the need for automation in such application grows. RTDS offers the necessary real-time communication interface, which allows real-time interaction between the simulation and a real world device in more convenient way [7]. One RTDS peripheral hardware named 'GTNETx2' offers the necessary real time communication capability. The appearance of the card is shown in Figure 6. The communication capability incorporates various industry standard communication protocols, such as DNP3.0 and IEC 61850 [8]. In particular, IEC 61850 is expanding its application into the electric railway systems. More IEDs (Intelligent Electronic Devices) equipped with the communication protocol are now being deployed in many different part of an electric railway systems. As such, the need for evaluating those IEDs in more realistic environment is becoming imperative. RTDS equipped with GTNETx2 card can accommodate such need, providing not only real time simulation results necessary for the IED's basic protective function testing but also it can provide the necessary communication interface where the test subject IED can interact with a real time simulation. One conspicuous example is the testing of protection function with IEC 61850 GOOSE protocol. Previously, a trip signal, the final output of a protective element in an IED, had to be carried over a hard wire to a target circuit breaker. With the IEC 61850

GOOSE protocol, such information can be carried on a communication network, then make the target circuit breaker trip in the same way as when the breaker is hard wired with the IED. In the same way, the trip decision from the IED can be brought back to a real time simulation in RTDS through the communication protocol, IEC 61850 GOOSE. Then, the trip information sent from the IED can control (turning on or off) a target circuit breaker in a simulation.

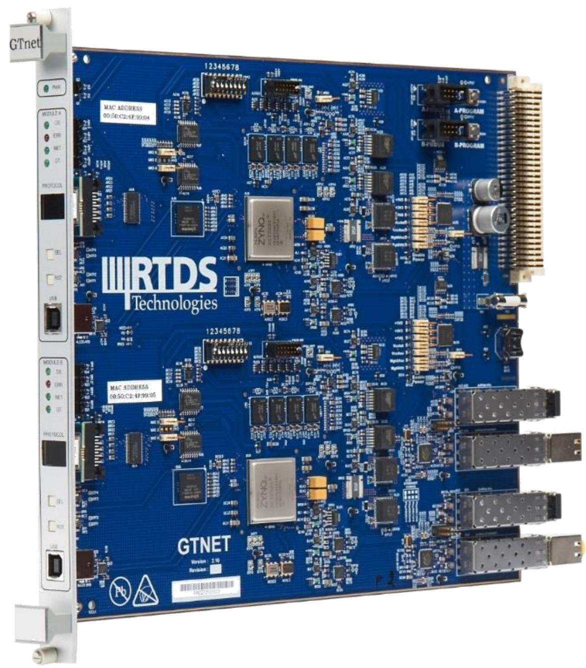


Figure 6 GTNETx2 card

CASE STUDY

A simple representative simulation case of an electric railway system was constructed in RTDS. The purpose of the simulation case is to demonstrate the capability of RTDS regarding the real time simulation of the electric railway system. The simulation case represents an AC electric railway. The AC feeder of the system is being provided from a Scott transformer. The nominal voltage of the AC feeder is 25 kV. The primary side of the Scott transformer is connected to a utility transmission system at the voltage level of 154 kV. Then, a realistic transmission line mode was added. The line model attempted to capture the feeding line, the clearance of a tower, grounding wire and catenary wire. Several different approaches in terms of transmission line modeling are available in RTDS. One such model is a model based on frequency dependent phase domain line model. The modeling technique is widely believed as the most advanced approach in terms of depicting the transient of a transmission line. Thus, electric power applications with higher level of technical complexity, such as HVDC (High Voltage Direct current) with a set of submarine cables, usually employ the line model for higher fidelity in the simulation results.

Before the feeding line modeling, there is an AT (Autotransformer), representing an AT feeder system which is frequently found in many different electric railway system. Then, a traction car was modeled. The traction system inside the traction car is composed of the following components: main transformer, 4-quadrant DC/DC converter, DC stage, a single VVVF drive and two induction motors. Therefore, the configuration of the VVVF is what is usually referred to as '1C2M' configuration[9]. The control of the VVVF is based on a simple scaler (V/F) control. Due to the power reversal capability, the 4-quadrant DC/DC converter can inject the regenerative braking power coming from the VVVF into the AC feeder. A quasi-DQ two axis control based upon the SOGI (Second Order Generalized Integrator) was implemented as control of the DC/DC converter[10].

The following figure, Figure 7, shows the overview of the entire simulation case:

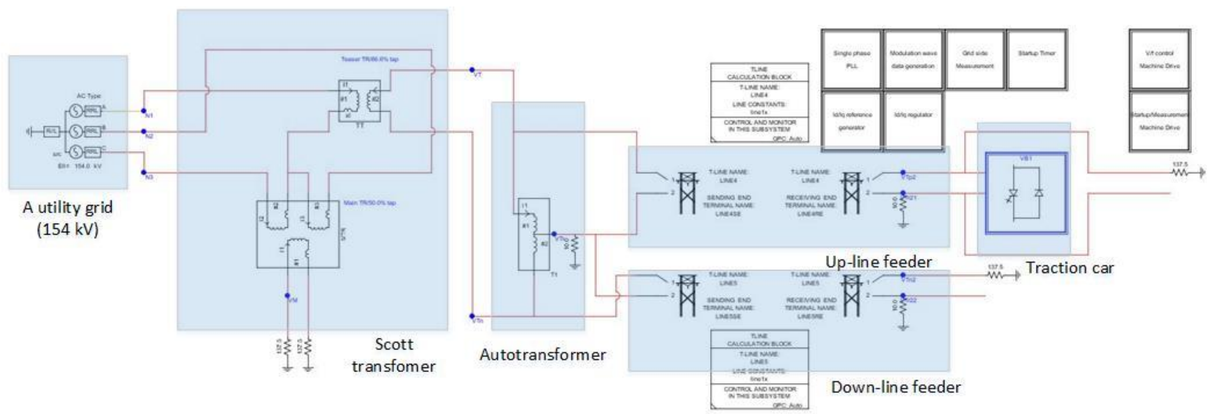


Figure 7 Electric railway RTDS simulation case

Then, the following figure, Figure 8, shows the composition of the electric traction car model in the simulation case above:

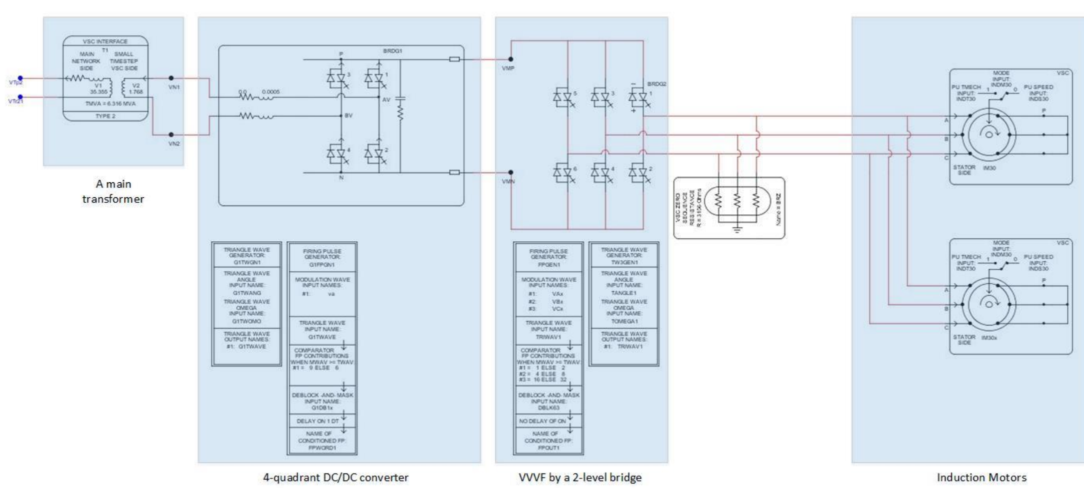


Figure 8 Traction car model in RTDS simulation

The system in Figure 7 and Figure 8 has two different time scales. The AC feeder system is operating on a fundamental frequency, 60 Hz in this simulation case, while the traction system runs with switching frequencies which are much higher than the fundamental frequency at the feeder side. Thus, in order to accommodate two different time scale in the whole electric railway systems, the simulation case was made in a multi-rate simulation case. The AC feeder part of the simulation case, depicted in Figure 7, runs with the simulation time step size of 50 µS. On the other hand, the traction car system, depicted in Figure 8, runs with much smaller time step. The size of the time step is 2.0 µS. The switching frequency of the 4-quadrant DC/DC converter is 2000Hz, while the switching frequency of the 2-level VVVF is 1200 Hz. Therefore, the given size of time step, 2.0 µS, for the traction car modeling is small enough to accommodate the fast transients from the power electronics based systems inside the traction car, namely 4-quadrant DC/DC converter and the 2-level VVVF system. At the same time, the induction motors connected to the VVVF converters are running with the same time step as the converter, which allows generation of higher fidelity dynamic response from those motor models in the simulation. The following table, Table 2, presents the parameters given to the induction motor models [11]:

Table 2 Induction motor parameters

Power (kW)	1676
U_N (V)	2300
R_S (%)	0.82
R_R (%)	0.62
L_m (pu)	4.5
$L_{s\lambda}$ (pu)	0.077
$L_{r\lambda}$ (pu)	0.077
F_N (Hz)	60
p	2
J (kgm2)	31.9
S_N	0.008

The following plots in Figure 9 show the initial transients from the simulation observed from the scalar motor control output as well as the electrical torque output from the induction motors when the unit with the traction car accelerates from a low speed to a higher speed. The first plot in the Figure 9 shows the accelerating frequency modulation output from the scalar controller, while the second and third plots show the electrical torque values from the induction motors.

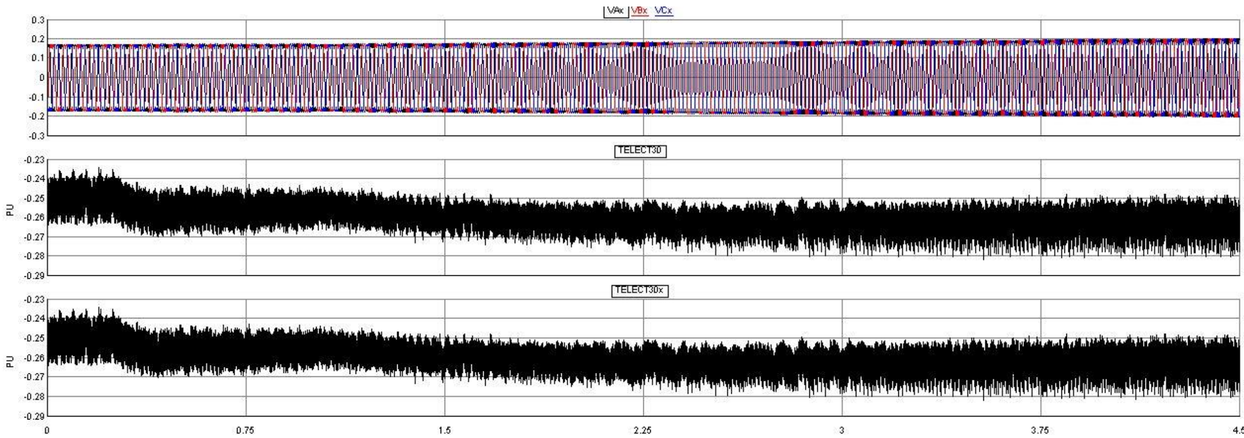


Figure 9 Acceleration transients

When the unit tries to apply break by using regenerative braking, the power direction reverses. In other words, the kinetic energy stored in the moving mass, both cars in t e unit as well as the rotating mass of the motors are extracted, resulting in speed reduction. The following figure, Figure 10, shows the DC stage and the VVVF active power output transients when the regenerative braking was attempted by reducing the speed order to the VVVF drive control:

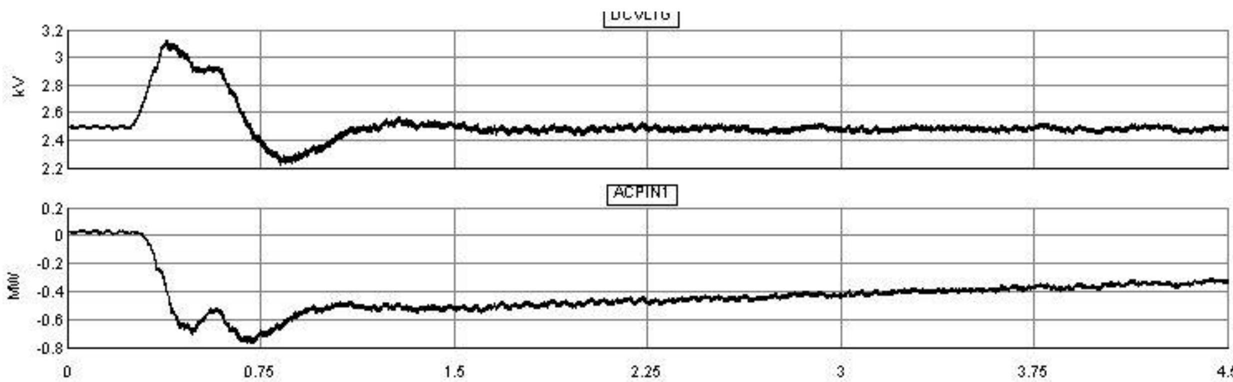


Figure 10 Regenerative braking transients

The first plot in Figure 10 shows the DC stage voltage when the regenerative braking was attempted. The nominal value of the DC voltage is 2.5 kV. Once the braking starts, the energy from the moving mass begins to flow into the stage, contributing to the increase of the voltage. Then, because of the successful 4-quadrant DC/DC converter operation, the excessive energy in the stage begin to be injected back to the AC system through the main transformer. Meanwhile, the second plot in Figure 10 clearly shows that the direction of the power (+ is into the motors) reversed, presenting the reversal of the direction during the regenerative braking.

In order to evaluate the capability of real time simulation using RTDS further, an external controller was interfaced with RTDS and tested with a real time simulation. The simulation used for the evaluation was a modification from the one in the previous experiment. The scalar control of the motors was removed from the simulation. Instead, it was programmed into an external controller. The external controller is based on a micro-controller. The micro-controller is one of DSP based MCUs from Texas Instruments, TMS320F28377s[12]. The micro-controller is able to perform single precision based control calculation[13]. In addition, it has various types of internal peripherals, including high precision PWM (Pulse Width Modulation) signal generation modules. Thus, it is ideally suited to the purpose like the one attempted in this experiment. The simple scalar control (V/f) control is not a full closed loop control in a usual sense with more complex closed loop control such as FOC (Field Oriented Control). However, an analog voltage signal, which is representing the DC stage voltage, was brought out from the real time simulation and used as an input signal to the modulation wave generation. Thus, the experiment introduced here carries a certain aspect of a closed loop HILS (Hardware in Loop Simulation) testing. The following figure, Figure 11, presents the experimental setup:

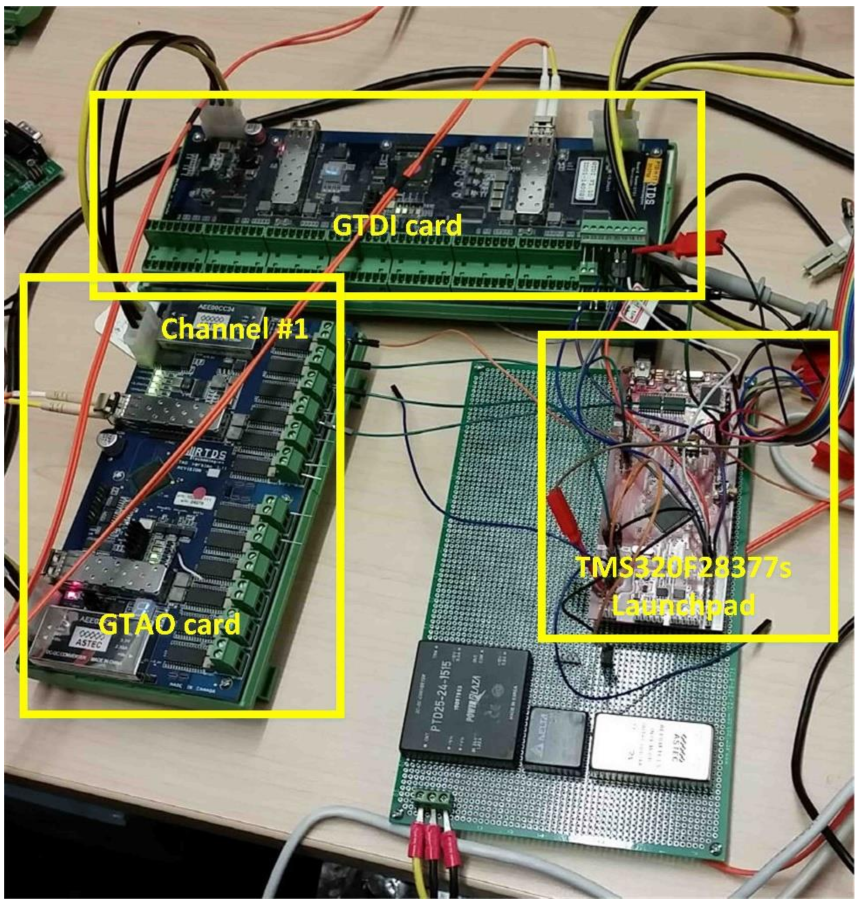


Figure 11 HILS testing with RTDS and an external controller

The card named 'GTAO card' in Figure 11 produces the necessary analog voltage signal to the external controller. The channel named 'Channel #1' in Figure 11 is the channel where the analog voltage representing the DC stage voltage is produced. Because of the external controller has a limited range (0~Vcc, Vcc is 3.3V) in terms of the A/D converter input, the signal was preprocessed in the real time simulation in order to make sure that the output analog voltage from the GTAO card channel does not exceed the limit. Then, the external controller in the Figure 11, in a box labeled as 'TMS320F28377s Launchpad' takes in the DC stage voltage through an internal A/D converter inside the processor. The resolution of the A/D converter is 12 bit and its sampling rate is 3.5M SPS (Sample Per Second). The, the same control algorithm as the one in the previous experiment, namely scalar(V/f) control is performed with the information of the DC stage voltage coming from the A/D conversion. The final output of the control is modulation index. The index goes into the PWM modules in the micro-controller. In this experiment, three out of twelve modules participated in the PWM output signal generation. Those modules are ePWM2, ePWM6 and ePWM8. Those modules are not in consecutive manner, due to the hardware restriction in the external hardware controller ('TMS320F28377s Launchpad' [14]). Finally, the PWM gating signals generated from the external controller is brought back to the real time simulation in RTDS through a digital interface card, which is labeled as 'GTDI card' in Figure 11. The gating signals are driving a 2-level bridge labeled as 'VVVF by a 2-level bridge' in Figure 8. The output of the VVVF drives the two induction motor which compose the vital part of the traction system. The first plot in the following figure, Figure 12, shows the PWM gating signal from the external controller to the GTDI card of RTDS.

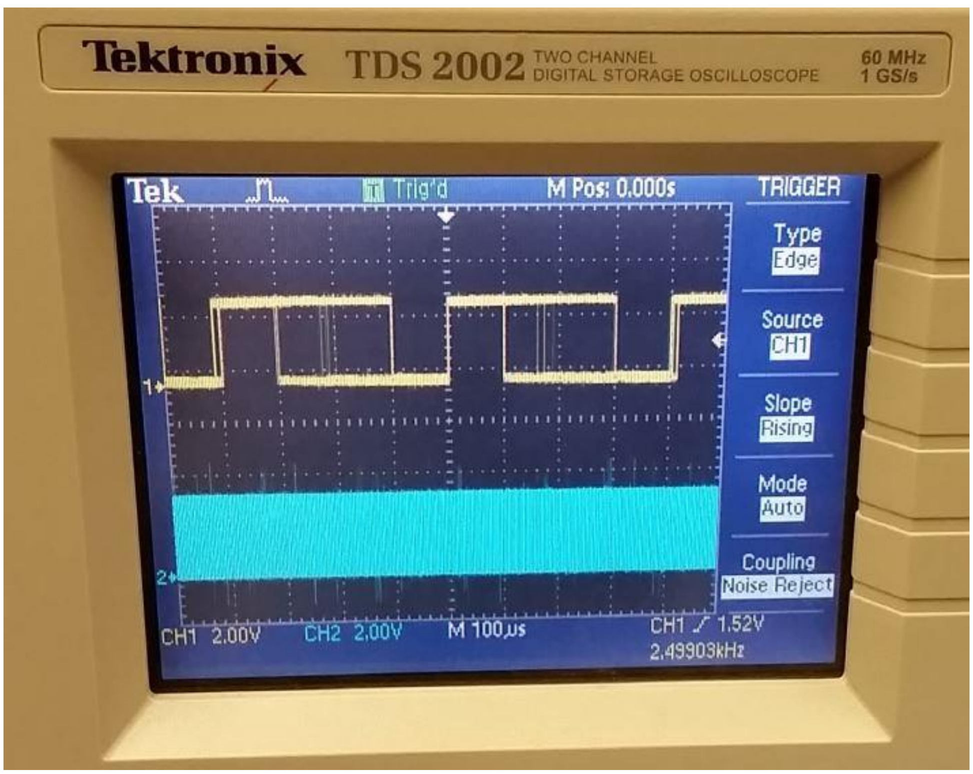


Figure 12 PWM gating signals on an oscilloscope screen

The statistics information at bottom of the oscilloscope screen capture in Figure 12 tells the switching frequency of the PWM signal. It is 2.5 kHz. Finally, the screen capture in the Figure 13 presents that the external controller was able to control the VVVF drive and the induction motors connected to the VVVF drive in the real time simulation. The values of the meters in the box labeled as 'Meters' at the left side of Figure 13 show the rotational speed of two induction machines in the simulation case, in the unit of rad/s, while the six sets of the pulse trains in another box labeled as 'Gating signals' in the same figure shows the incoming gating signals, coming from the external controller.

Figure 13 HILS experiment result

CONCLUSION

With the ongoing trend of railway system electrification, there is corresponding demand for proper understanding of such systems. A good set of study tools is critical for achieving the purpose. Moreover, the testing and evaluation of a real electrical equipment in the electrified railway systems calls for a real-time simulation which is capable of interacting such real world equipment. This paper introduced one such tool, RTDS (Real Time Digital Simulator). The case study in this paper presented that the tool not only offers the adequate capability of off-line type study for electrified railway systems including traction cars, but also it can cover the need of HILS testing with external equipment such as the controller of the drive system in a traction car.

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