Analysis of Switching Surge Transients in Express Traction Vehicle

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Abstract

This paper presents an overvoltage analysis of the DC catenary in the DC powered railway system. The main objective is to study the sources of damages of on-board equipment and cause service interruption by the occurrence of the surge transients in rail passenger vehicles in the DC express traction system during the operation stage. During the testing phase, vehicle manufacturers must demonstrate the performance of the vehicles under the specified transients, but testing generally not available during design. Certain engineering analysis must be performed to ensure that the design will meet the transient requirements by using matlab. Meanwhile, the designer will meet the transient conditions such as the over voltages and over current protection devices which is coordinated at the system level. In response to these design challenges, detailed time-domain simulation models of a switching surge transient generator and the vehicle equipment is developed and compared with the experimental results. These models are used to evaluate vehicle system parameter sensitivity as well as to provide design guidelines like increased vehicle power system safety, reliability and availability. A maiden attempt is made for analyzing switching surge in express traction vehicles. Furthermore, this analysis can be extended to the Indian railway traction system.

Keywords: *DC Power System, Power System Protection, Railway Safety, Surge Protection.*

1. Introduction

Express traction systems are widely used in all over the world for high volume passenger transportation. They are composed of rail passenger vehicles operating as trains on a local DC traction power system [1]. Substations are equipped with 6 and 12-pulse diode rectifiers. The power from the traction system substations is delivered to the moving trains by an overhead catenary system [2, 3] at voltage between 600 and 1500V. During this operation, the rail passenger vehicles are facing surge transient events [4-7] that can seriously damage the on-board equipment and cause major service interruption. These surges [8] can be predictable or unpredictable. In DC traction systems, surge transients are mainly the consequence of vehicle regenerative braking action [5], lightning strikes [6], [9-11] rectifier AC-side capacitor bank switching [12], and stored magnetic energy release [13] at fault clearing. The waveform and the energy level of the surge depend on the nature of the surge transient.

High energy switching surge results from the release of magnetic energy stored into the DC traction system track at fault clearing. Evaluation of the magnetic energy stored as a function of the fault distance from a typical Montreal subway system substation (750V, 2.5MW, 12-pulse rectifier). This curve is obtained using the developed substation model in. At fault clearing, if the DC traction system is not receptive, the energy needs to be dissipated by both the wayside and the vehicle on-board equipment. The maximum energy condition typically occurs at a close distance from the substation. Surge transient specifications for rail vehicles are generally based on standardized waveforms, but traction authorities may specify their own requirements based on the knowledge of their local traction system. During the testing phase, vehicle manufacturers must demonstrate the performance of the vehicles under the specified transients [14]. Experiences have shown that the investigation of protection solutions during the testing phase is costly [15]. Complete analysis, considering the behavior of the on-board equipment, should be performed during the design phase to reduce the risk of protection issues and enhance the system operational performance, such as safety, reliability, and availability.

This paper contributes to the knowledge in modeling DC express traction vehicles for simulation and analysis of high energy switching surge transients. The section 2 deals with the detailed modeling of vehicle equipment's and protective devices. Section 3, the developed simulation model is used to evaluate the influence of the main system parameters on the overall vehicle operational performance under switching surge transients. The design guidelines are provided based on the simulation results and conclusion and future scope.

2. Express Traction Vehicles

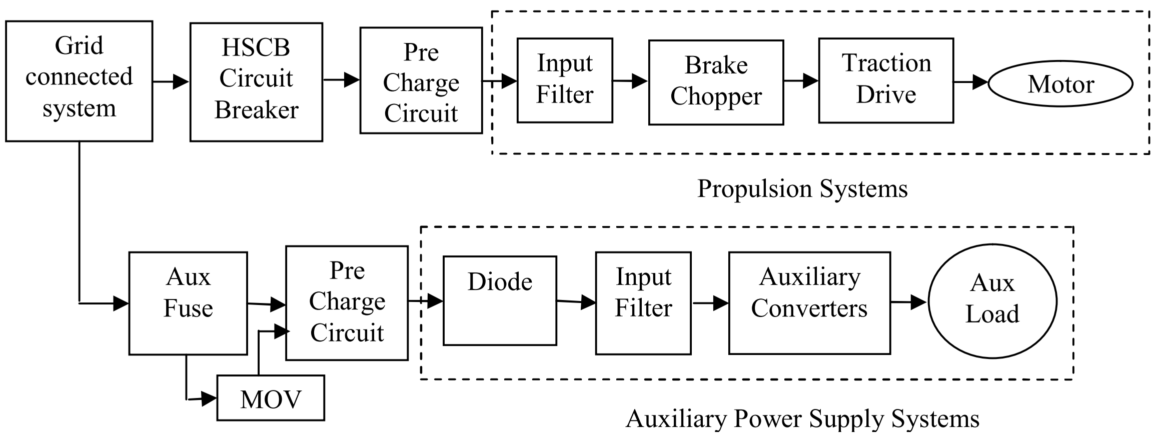

Figure 1. Block diagram of DC Express traction vehicle

The Figure1. represents the block diagram of express traction vehicle under the following, the propulsion system of modern vehicles is composed of one or two traction inverters, each connected to one or two three phase traction motors. A brake chopper system is dissipate extra braking energy in case of non-receptivity of the DC traction system during dynamic braking operation and it can also act as an overvoltage protective device upon detection of overvoltage conditions. A High-Speed Circuit Breaker (HSCB) is also generally used to protect the propulsion system against internal faults. The train auxiliary subsystems are supplied by an Auxiliary Power Supply (APS). The APS converts the DC traction power system high voltage supply into lower galvanically isolated DC and AC supplies. The auxiliary fuse is used to protect the APS against internal faults, while surge arrester or crowbar circuit may be used for overvoltage protection inside the APS. Input diode can be protecting against negative voltage events during regenerative braking operation. Both the propulsion system and the APS are also equipped with input LC-filter to meet the railway electromagnetic compatibility requirements when both air and iron-core inductors are used and also used to reduce harmonics when the surge transients are occurred.

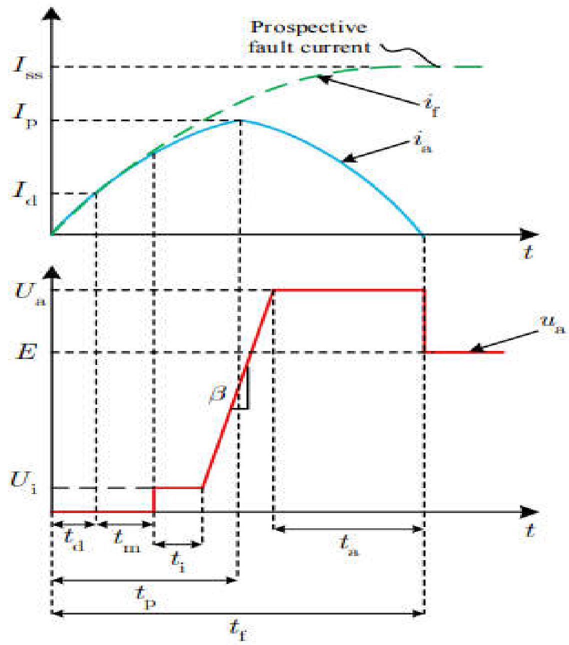

Figure 2. High-speed circuit breaker timing diagram

In Figure 2, when the circuit breaker current if exceeds the current setting I_d, a trip signal is sent to the HSCB trip coil by its internal detection circuit. As seen in Figure 2, the detection time t_d decreases with the prospective current I_{ss} and increases with the circuit time-constant (L/R). An opening delay t_m is present before the breaker contacts start to open.

2.1 Equipment Modeling

2.1.1 High-speed circuit breaker:

High-Speed Circuit Breaker is also generally used to protect the propulsion system against internal faults. HSCB are located inside the community leading as much as the control devices from the pantographs, and they both feature safety devices that permit and allow cut off electricity to the essential circuitry as shown in Figure 2.

In particular, must a large quantity of electrical current reversals along the primary circuitry due to a failure of a devices, the HSCB is right now cut off the power to shield the control devices (along with the Variable Voltage Variable Frequency (VVVF) inverters) from capacity damage that could arise if exposed to such electric power surges. When the one’s breakers cut off the power, in addition they internally deal with arcing to reduce the hazard of electrocution for a maintenance employee.

2.1.2 Precharge Circuit:

Both systems need a precharge circuit to reduce the inrush current at the regenerated period of the converter or after going through a rail gap. This circuit can be modeled as two ideal switches and a precharge resistance.

2.1.3 Propulsion Systems:

The propulsion system of modern vehicles is composed of one or two traction inverters, each connected to one or two three phase traction motors.

2.1.3.1 LC Filter:

Both the propulsion system and the APS are also equipped with input LC-filter to meet the railway electromagnetic compatibility requirements when both air and iron-core inductors are used.

2.1.3.2 Brake chopper:

The Brake chopper system is also used to dissipate extra braking energy in case of non-receptivity of the DC traction system during dynamic braking operation. The brake chopper can also act as an overvoltage protective device upon detection of overvoltage conditions because this system is voltage controlled it may be very beneficial by the usage of preventing oscillations with the aid of use up the power of the oscillation. Calculation of the energy absorbed through the brake chopper inside the path of surge transient is approximated with the resource of integrating the energy dissipated by the braking resistor is given below

$$E_{br}(t) = \int v_{br}(t)\, i_{br}(t)\, dt \tag{1}$$

2.1.3.3 Traction Drive:

The traction drive uses the electric power for moving forward. One of the major applications of an electric drive is to transport men and materials from one place to another. The traction drives are mainly classified into two types, i.e., the single phase AC and DC traction drive. Electric trains are main-line trains in such type of train the electricity substances to the motor in approaches, i.e., either from an overhead line in an electric powered locomotive or through diesel generator set in a diesel locomotive.

Suburban trains are used for travelling at small distances. In traction purpose used motor is a synchronous motor.

2.1.3.4 Brushless DC Motor:

It is used as a load to improve Efficiency for a Brushless DC Motor (BLDC) motor of up to 96.5%, at the same time as DC automobiles with brush equipment are commonly 75–80% efficiency and Increase the reliability, power continuity, more efficient and cheap.

2.1.4. Current Limiting Fuse (Auxiliary Fuse):

The Fuse is used to protect the internal in the Auxiliary power system means on board equipment to be protected. The selection of the fuse ratings based on the VI-characteristics as shown in Figure 2. Fuse should be avoided to break during the surge transient. The surge energy should be absorbed Metal Oxide Varistor (MOV) by the without breaking the fuse to allow the system to quickly recover after the event. For transient analysis by simulation, the melting energy calculation is performed using both the fuse Time-Current Curve (TCC) and the pre-arc i^2t data.

The total melting time

$$T_{mr}(t)=\int\frac{1}{t_{mf}(t)}dt \tag{2}$$

The pre-arc i2t energy

$$i^2t_{mes}(t)=\int\left(i_{mes}(t)\right)^2dt \tag{3}$$

2.1.5. Metal Oxide Varistor:

Metal Oxide Varistor is mostly used in protection of DC applications during over voltages. Based on the nominal voltage, select the Maximum Continuous Operating Voltage (MCOV) of the MOV in the available not permanent overvoltage in the system as well as the permissible leakage current. Once the MCOV is selected, it is important to calculate the required clamping voltage by the selection of a MOV with a near value of VI-characteristics. It is also necessary to select a MOV with the energy-handling capacity for the surge environment. Modeling the MOV VI-characteristic is necessary for insulation coordination and to calculate the necessary energy-handling capacity. Minimum and maximum VI-characteristic tolerances should be considered.

$$E_{mov}(t)=\int v_{mov}(t)\cdot i_{mov}(t)dt \tag{4}$$

The MOV energy is calculated using eqn.(4) and compared to the energy capability provided by the MOV manufacturers. Once again, it is important to carefully analyze manufacturer’s data because the energy rating depends on the testing conditions, which can differ from different manufacturers.

2.1.6 Auxiliary power supply systems:

The train auxiliary subsystems are supplied by an APS. The APS converts the DC traction power system high voltage supply into lower galvanically isolated DC and AC supplies. While surge arrester or crowbar circuit may be used for overvoltage protection inside the APS.

2.1.6.1 Input Diode:

The diode is also used in many applications to protect against negative voltage events.

2.1.6.2 Auxiliary Converters:

These converters converts variable DC to variable AC with PWM controllers and eliminates some harmonics, Pulse-Width Modulation (PWM) or Pulse-Period Modulation (PPM), is a modulation approach used to encode a message into a pulsating signal. Although this modulation approach can be used to encode information for transmission, its most important use is to allow the manager of the energy furnished to electric devices, in particular for inertial hundreds which includes vehicles. In addition, PWM is one of the two principal algorithms utilized in photovoltaic sun battery chargers, the opposite being most power point monitoring.

RC circuit is used as an auxiliary load to take AC voltage from the auxiliary converters. This is used to supply power internally.

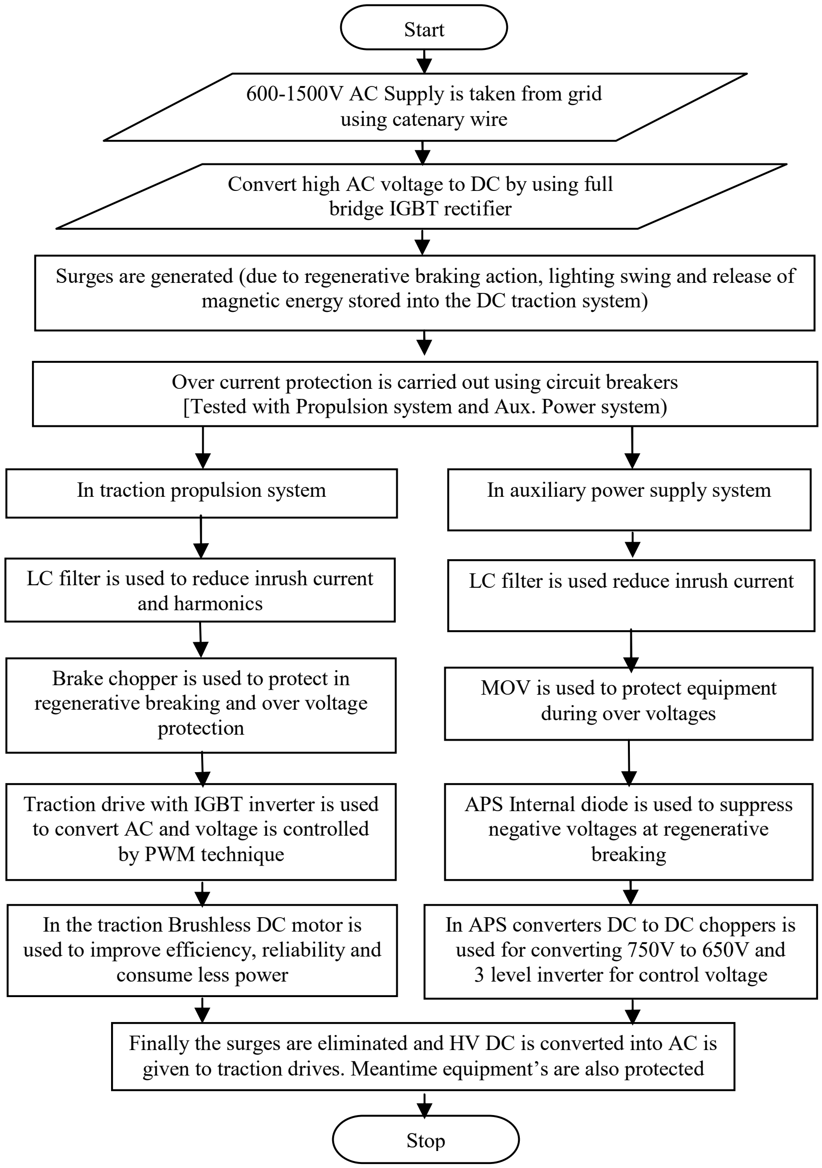

Figure 3. Flow diagram for Complete Analysis of Switching Surge Transients in Express Traction Vehicle

The flow diagram for complete analysis of switching surge transients in express traction vehicle is shown in Figure 3 for easy understanding.

3. Result and Discussions

The model of the propulsion system includes the HSCB and rheostatic brake chopper. The chopper is first validated experimentally which is shown in Figure 4. A surge of approximately $+3kV$ and $60kJ$ is applied to the propulsion system while running at full power 700kW. The propulsion system has an air-core inductor. The HSCB over current trip setting is set at $2.2\,p.u.$

The model of the APS is also validated experimentally is shown in Figure 4. The specific APS under test does not have an input diode but do have a saturable-core inductor. A surge of $+3KV$, $60KJ$ is still injected into the APS while it is lightly loaded.

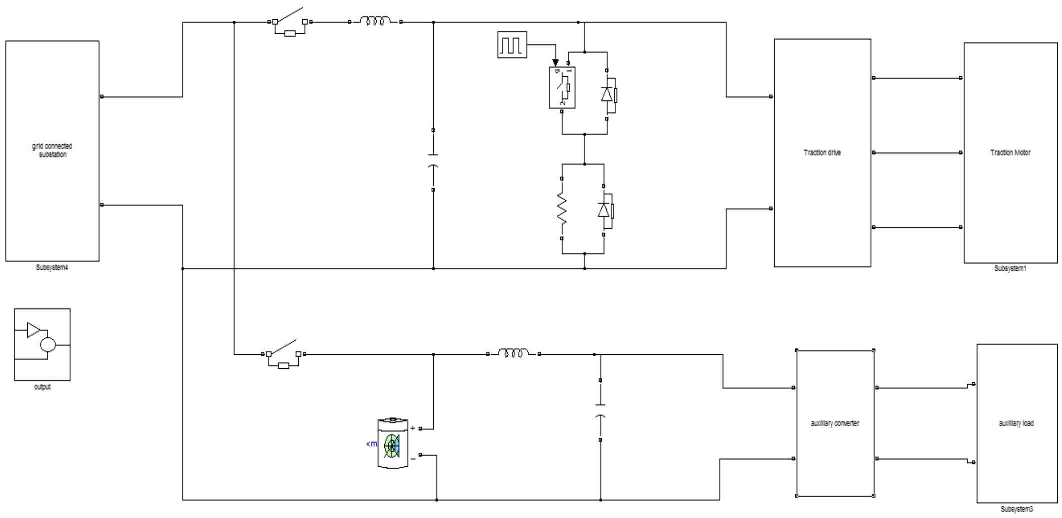

Figure 4. Simulation Diagram of Express traction Vechicle

For the validation of the vehicle model, a custom surge transient generator has been used in Figure 5.

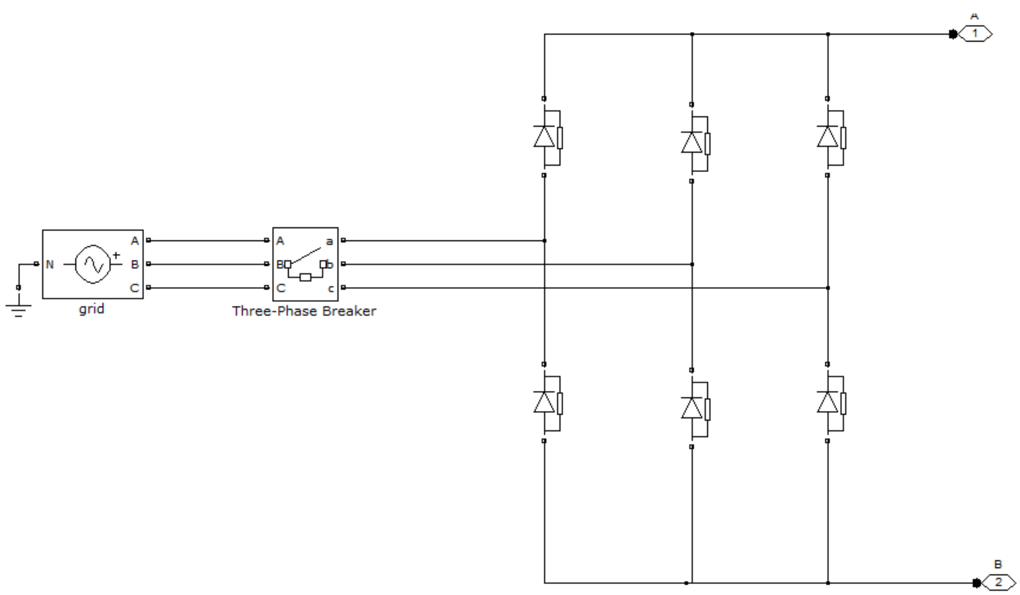

Figure 5. Sub System of Grid Connected 600V-1500V System

The parameters of the whole system model are given in Table1. It is composed of a nonreceptive substation rectifier and a series injection surge transient source. It allows performing $\pm 3KV$, $60KJ$ surge transient tests. The surge transient generator power components and the control circuitry are replicated in the simulation model for increased precision.

Table 1. Main Simulation Parameters for express traction vehicle system

Model	Description	Symbol	Value
Traction systems	Nominal voltage Maximum voltage	– –	750 900
Propulsion system (2 units)	Power Set-Point Input Filter Inductor Filter Capacitor	– L_f C_f	No-load 2.5 mH 8.2 mF
Brake Chopper (2 units)	Turn-on Voltage Turn-off Brake Resistor	– – R_{br}	1010 V 975 V 0.3 Ω
HSCB	Detection Arc Voltage	I_d U_i U_a t_m t_i β	2 kA 50 V 1500V 4 ms 2 ms 480 V/ms
Auxiliary Fuse	Melting Energy	–	140 KA^2s
APS	Power Set Point Input Filter Inductor Input Filter Capacitor	– L_f C_f	No-load 6.4 mH 5.6 mF

Figure 6 is the inverter model it is used to voltage control in traction motor. Discrete PWM technique is used for triggering the switches in inverter.

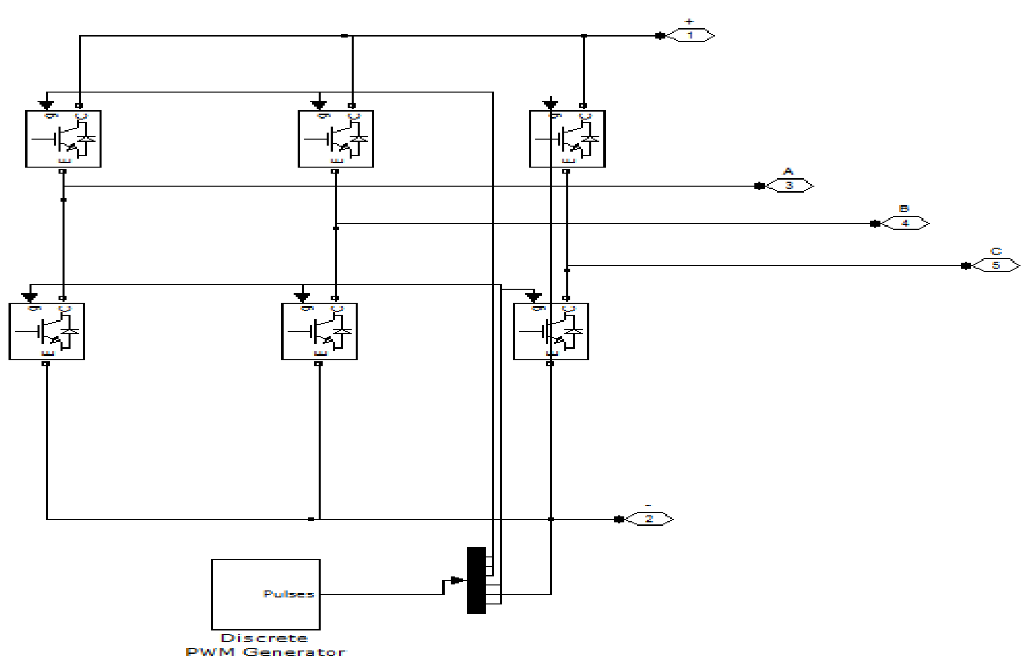

Figure 6. Sub system of switching logic circuit for traction Drive

The model shown in Figure 7 is DC-DC chopper and it is used to control internal DC voltage followed by inverter is used to convert DC to AC with PWM technique.

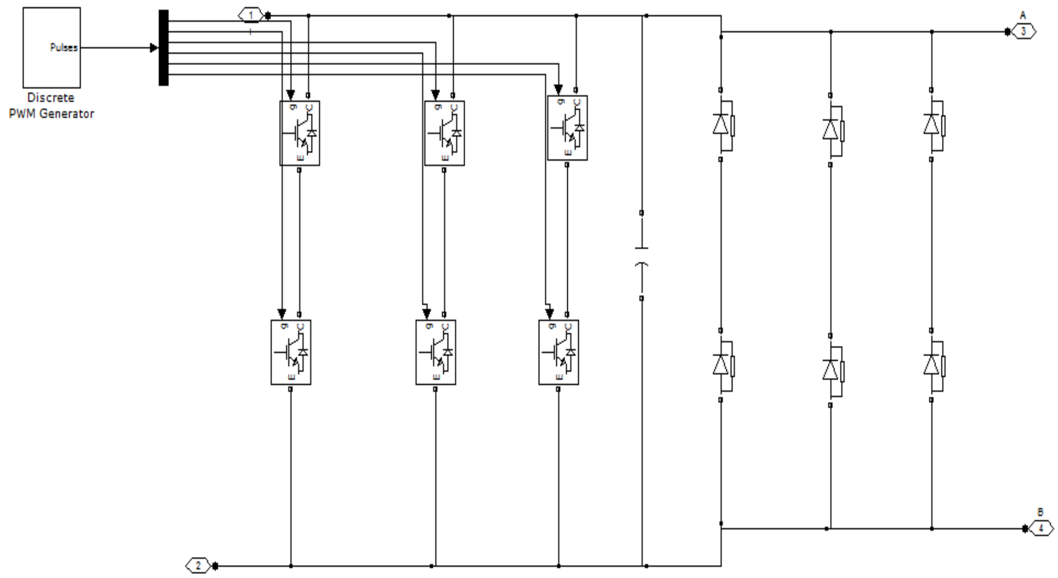

Figure 7. Subcircuit for auxiliary converters in APS system

In railway systems, second-order input LC-filters are used. Typically, at frequencies higher than 50/60 Hz, Cut-off frequencies in the range of 15-35 Hz are generally selected, the input filter must be inductive. and the values of the capacitor and inductor are selected accordingly.

Input diode cannot be used in the propulsion system because regenerative braking requires the power to flow in both directions at the converter terminals shown in Figure 4. However for APS, the input diode can enhance the converter's ability to deal with negative voltage surges.

The figure shown in 8 is the load circuit which consists of brushless DC motor to incresase the effiency.

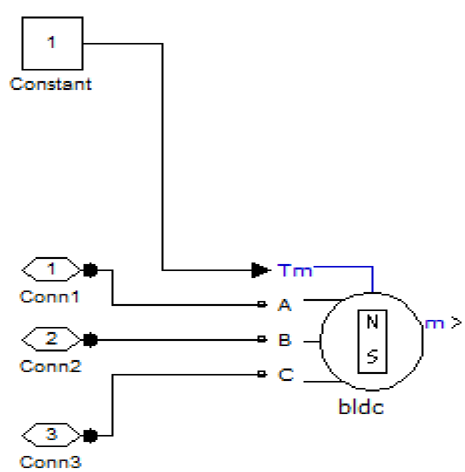

Figure 8. Simulation of subcircuit for Brushless DC Motor

The figure 9 shown below indicates the auxiliary load in APS System.

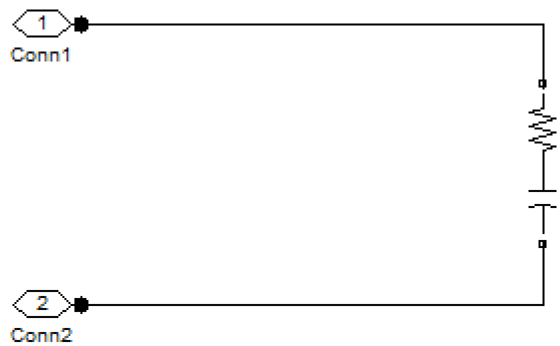

Figure 9. Sub System for Auxiliary load in APS System

Coordinating current-limiting fuse with MOV is important as shown in Figure 4. Historically, surge arresters have been placed on the load side of the protection fuse for maintainability reasons associated with the localization of the equipment boxes.

The disadvantage of this configuration is that the MOV acts as a low resistance during the surge transient and may lead to malfunctioning of the fuse. A fuse should be avoided to break the circuit during the surge transient. To overcome this disadvantage, the surge energy should be absorbed by the MOV without breaking the fuse to allow the system to recover quickly after the event.

The HSCB can reduce the level of trapped charge at the filter capacitor. These trapped charges are due to limitations with simple hysteresis band control of the brake chopper. Under running condition, these trapped charges are dissipated by the traction motors. Under the no-load condition, these trapped charges may take time to discharge. This is important to be considered when selecting the brake chopper turn-on and turn-off thresholds.

A surge of approximately $+3kV$ and $60kJ$ is applied to the propulsion system while running at full power (700kW) as shown in figure 10. The propulsion system has an air-core inductor. The HSCB over current trip setting is set at 2.2p.u.

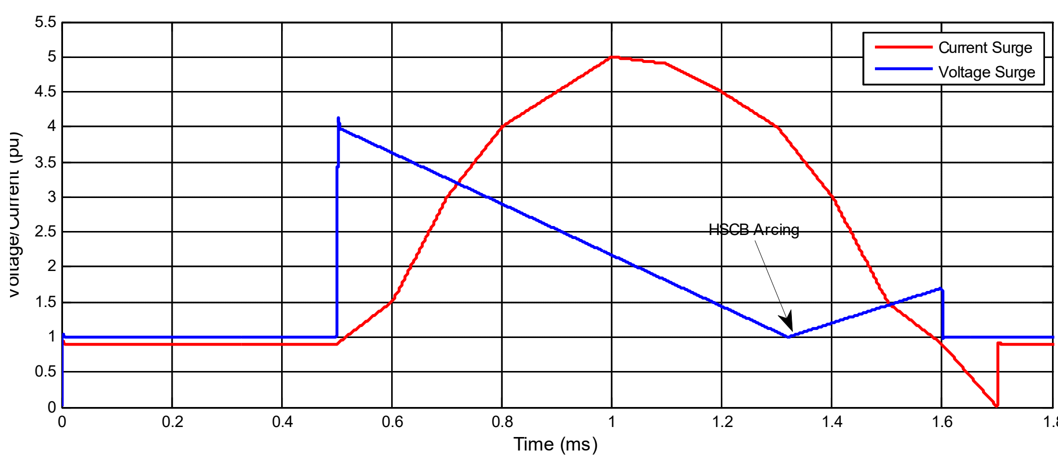

Figure 10. Validation of the propulsion system and HSCB models (+3 p.u test)

In the simulation results of Figure 11, since the HSCB current exceeds its trip setting, the HSCB trips and part of the surge energy is dissipated into the HSCB arc.

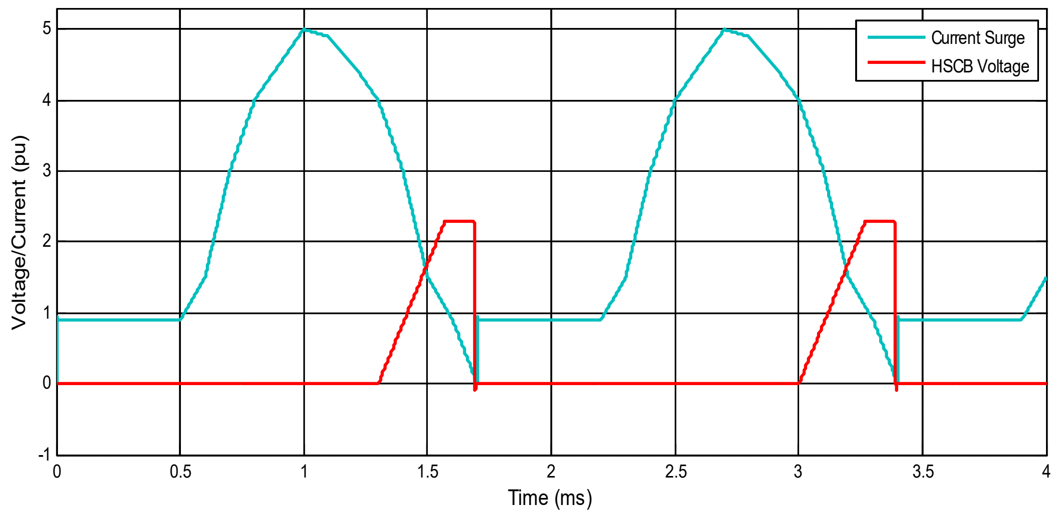

Figure 11. HSCB arcing (+3 p.u test)

The brake chopper is also dissipating part of the surge energy to control the capacitor voltage between its hysteresis bands (1.30 - 1.35 p.u) is shown in Figure 12. The remaining energy is absorbed by the traction motors and the filter capacitor.

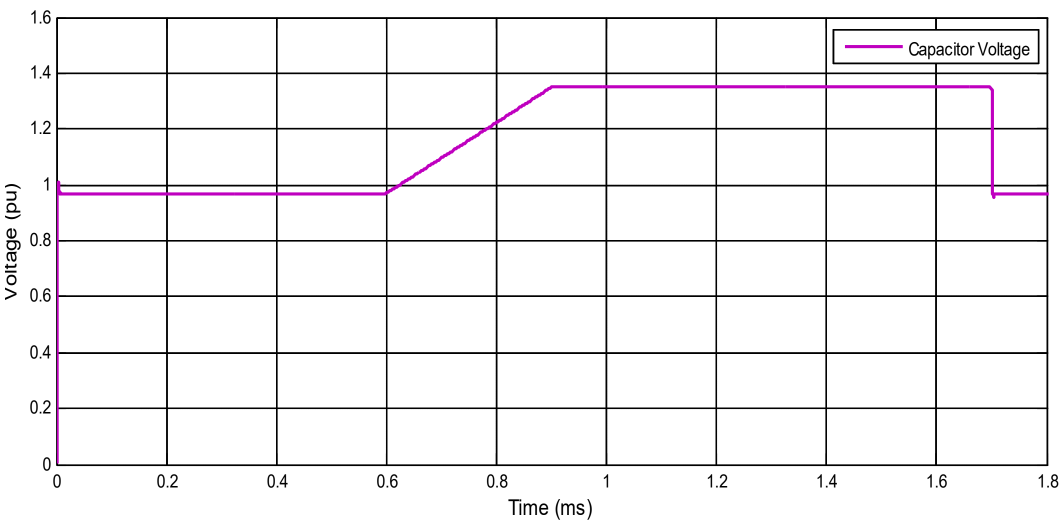

Figure 12. Brake chopper clamping action (+3 p.u test)

A surge transient of $+3kV$, $60KJ$ is applied into the APS system and the melting energy (in p.u.) calculated with the fuse TCC is illustrated. A surge of $+3p.u$ is still injected into the APS while it is lightly loaded. The test results are also successfully compared with the simulation results in Fig 13. From this figure, it is concluded that the filter inductor saturation is an important contributing factor because the rate-of-rise of the surge current increases drastically once the inductor saturates.

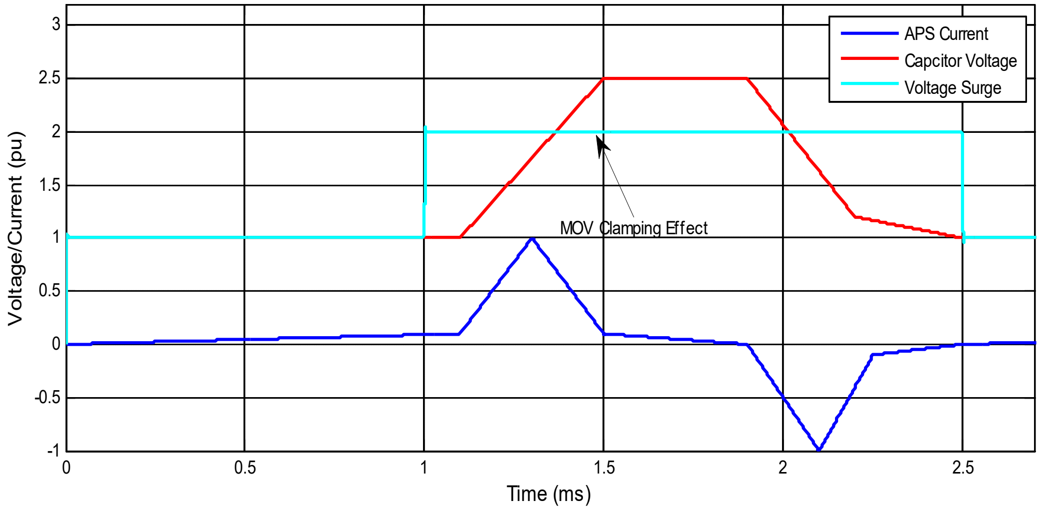

Figure 13. Validation of the APS model (+3 p.u test)

As below Figure 14 shown, the HSCB can reduce the level of trapped charge at the filter capacitor. These trapped charges are due to limitations with simple hysteresis band control of the brake chopper. Under running condition, these trapped charges are dissipated by the traction motors. Under the no-load condition, these trapped charges may take time to discharge. This is important to be considered when selecting the brake chopper turn-on and turn-off thresholds.

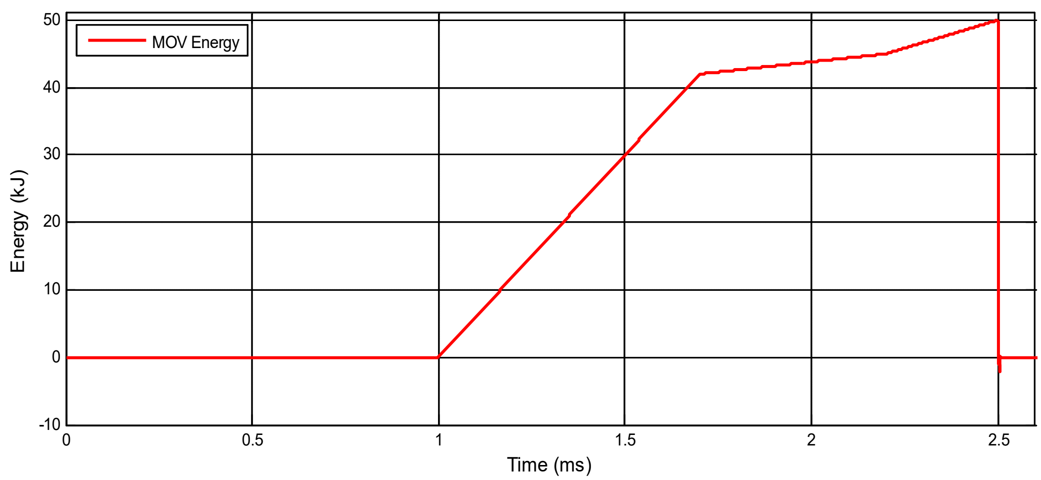

Figure 14. Calculation of the energy absorbed by the MOV (+3 p.u test)

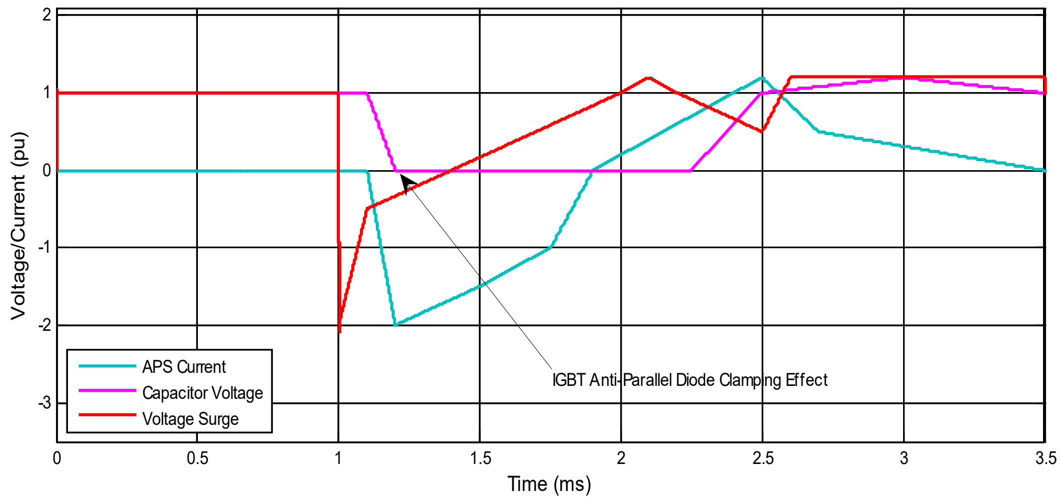

Figure 15. Validation of the APS model (-3 p.u. test)

The result in Figure 15 shows that the filter capacitor voltage is clamped to zero between 1-1.5ms. This is because the IGBT anti parallel diodes are conducting, when there is a polarity reversal at the capacitor terminals. A large amount of energy may pass through these diodes and evaluation of their energy is mandatory to ensure that they will not be damaged. It must also be mentioned that, in both cases, the melting energy of the fuse, which is not high enough to break the fuse.

4. Conclusion

This paper contributes to the modeling of DC express traction vehicles analysis for excessive power switching surge transients. A detailed model of a surge transient setup along with the vehicle equipments underneath test and the protective devices is advanced and verified experimentally using the evolved and confirmed vehicle model. Moreover, it identifies essential modeling considerations for accurate analysis of surge transients in DC fast traction motors. Through specific case study, it offers important design tips which can also be extended for any converter designed for running in a similar surge environment. One important end of these modeling is that vehicles need not be excluded of surge transient evaluation in DC fast traction structures. This modeling includes problem and the solutions, i.e. fault inside a vehicle can generate surge conditions, but the on-board protective devices are also a mean of absorbing surge energy circulating in the DC traction system. The model practices show that the development of accurate models is a crucial step to reduce design iterations. The models are validated and the analysis of the system behavior is tranquil using simulations than by high-power laboratory testing. A candid understanding of the system behavior is obligatory to enhance system safety, reliability and availability. With the use of brushless DC motors losses are reduced, performance and efficiency is enhanced. Besides, the developed model can be utilized for analyzing the surge transients in the Indian DC Traction system.

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