RT Box

DEMO MODEL

Railway Traction Application Demo

Multi-core simulation of traction system for railway application on RT Box 2 or 3

Last updated in RT Box Target Support Package 3.0.1

1 Overview

This demo showcases the computational power of the RT Box in case of a real-time simulation of a large PLECS model with many complex components. The chosen model includes converters, machines, transformers, and, as an example of a non-ideal component - a vacuum circuit breaker (VCB). Such large and complex models are challenging to simulate in real-time due to limitations of the computational power per CPU core. The proposed solution is to split the model into three parts, using Task Frame for easy configuration. Each part is deployed on one of the CPU cores of an RT Box 2 or 3. The chosen discretization step size and average execution time for the multi-core application are shown in Tab. 1.

The model used for this demo comprises the traction system of a moving rail car fed by a catenary. The focus of the simulation lies on the moment after a short blackout due to the train transferring from one power supply line to another. During the blackout, the VCB activates. The simulation will show the effect of the non-ideal oscillations on the operation of the system in the moments after the blackout.

Table 1: Discretization step size and average execution time of the demo model on RT Box 2

	Discretization step size	Average Execution Time
Core 0 (Input stage)	$5.5\,\mu$s	$5.4\,\mu$s
Core 1 (Auxiliary stage)	$5.5\,\mu$s	$3.0\,\mu$s
Core 2 (Motor stage)	$16.5\,\mu$s	$14.0\,\mu$s

1.1 Requirements

To run this demo model, the following items are needed (available at `www.plexim.com`):

- One PLECS RT Box 2 or 3 and one PLECS Coder license
- One 37 pin Sub-D cable to connect the digital I/Os of the box front-to-front
- The RT Box Target Support Package
- Follow the step-by-step instructions on configuring PLECS and the RT Box in the Quick Start guide of the RT Box User Manual.

Note This model contains model initialization commands that are accessible from:

PLECS Standalone: The menu **Simulation + Simulation Parameters... + Initializations**

PLECS Blockset: Right click in the **Simulink model window + Model Properties + Callbacks + InitFcn***

1.2 Limitations

The focus of this model is to showcase the RT Box capabilities. There is no intention of providing an actual, real-world implementation. Therefore, the model comprises only the main components of a railway traction system. The values chosen are also unverified and may differ from actual implementations.

Further, the split of the model into three stages creates a small delay in the signal transmission between the stages in real-time simulations. In this case, the delay is not significant because of the slow changing nature of the DC-link voltage quantity where the model is split.

2 Model

The top level schematic of the demo model is depicted in Fig. 1. The PWM generation and the power circuit run on the same RT Box. The “Railway Traction System” subsystem has to be configured as **atomic** and enabled for **code generation** by right-clicking on the subsystem and choosing **Subsystem + Execution settings...**.

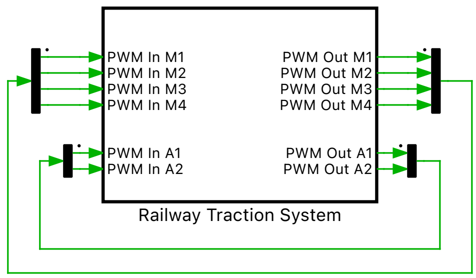

Figure 1: Top level schematic of the railway traction system

2.1 Plant

Fig. 2 shows the circuit model of the plant. The plant comprises parts of an electric locomotive, including the overhead supply, traction unit, and auxiliary applications. The model is split in three stages: the input stage, the traction stage and the auxiliary stage.

In the model, the stages are connected via system-split mechanism. This is required to create separate state-space systems allowing the coder to generate code for each individual stage. The system-split concept is explained more in details in the “Modular Multilevel Converter” demo model of the RT Box Target Support Package. For the real-time simulation, each stage is placed on its own CPU core of the RT Box 2 or 3.

One reason that four motor drives, one three-phase inverter and one DC/DC Buck converter are included in this demo application is that a total of 32 PWM gate signals are needed, which utilize all the Digital I/O channels of an RT Box 2.

Input stage

The input stage includes the overhead supply and a single-phase transformer with primary, secondary and tertiary windings. The secondary and tertiary windings are connected to single-phase uncontrolled rectifier bridges and DC-links, in this case capacitors. The split into the stages is made possible due to the slowly varying DC-link voltage quantity.

The VCB model is explained in details in section 2.3. Its implementation is done on a system level, and it is a reaction dependent model.

The grid used in this case provides 15 kV at $16\frac{2}{3}$ Hz, like in large parts of Germany, Switzerland, and Austria [1].

Traction stage

The traction stage includes four sets of inverters driving the induction machines. The inverters take the power from the DC-link. In this demo model, all four traction motors have identical parameters. These four motors provide in total approximately 1 MW power.

Further, it is not defined, whether the traction motors drive a wheelset or a single wheel. The model only shows as many motor drives as possible on an RT Box 2 due to its digital input channel count. The user can pick their implementation and apply it as needed.

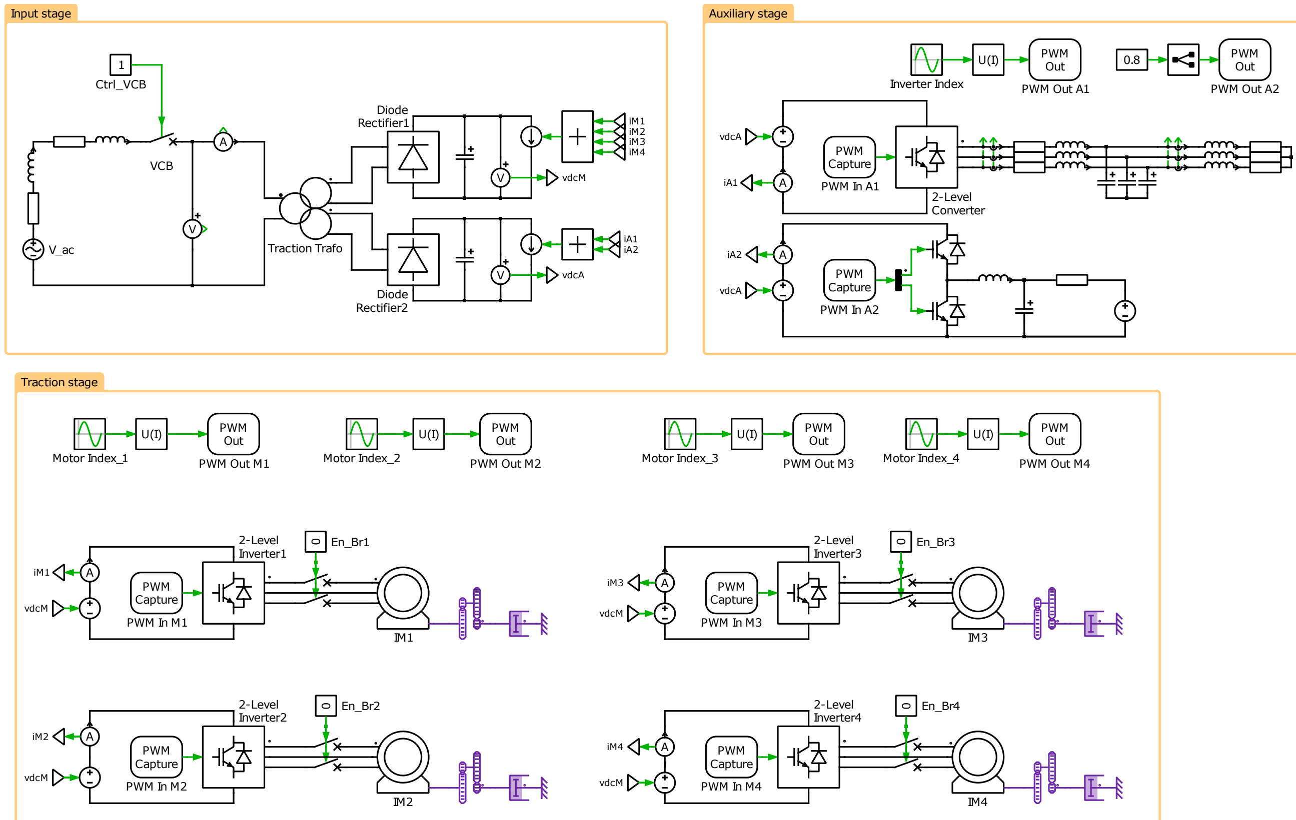

Figure 2: Circuit schematic of the railway traction system

Auxiliary stage

For the sake of completion and for increasing the load on the RT Box 2 or 3, the model also includes the auxiliary stage. This allows, for example, to model all load elements that act on the DC-link. It also allows to show the effect of the blackout on the auxiliary components. The auxiliary stage takes power from the DC-link connected to the trafo secondary winding.

The auxiliary stage consists of a three-phase inverter and a DC/DC Buck converter. The three-phase inverter is connected via an LC filter to an RL load. The Buck converter is loaded with a voltage source, which models the battery on the train. The auxiliary stage provides approximately 220 kW power.

2.2 Controls

The system operates in open-loop. As the focus of the simulation lies on the VCB transients that propagate through the system, a closed loop is not necessary and would take away unnecessary computational power of the RT Box. For HIL testing, closed-loop controls are usually implemented on an external controller connected to the RT Box.

In this demo, the PWM generation is executed in the same box using the PWM Out block. Those PWM signals generated at the box's digital outputs are then fed back to the digital inputs by using a physical loop-back cable. These PWM signals are sampled into the box with the PWM Capture block.

In the traction stage, the three-phase inverter driving its induction machine is controlled with three-phase PWM modulation indices, varying in a sinusoidal fashion.

In the auxiliary stage, the three-phase inverter with the RL load is also controlled with sinusoidal PWM modulation indices. The Buck converter operates with a fixed duty cycle.

2.3 Vacuum circuit breaker (VCB)

A circuit breaker that uses vacuum as a medium to extinct an arc is called a vacuum circuit breaker. In this type of circuit breaker, the fixed and moving contacts are enclosed in a permanently sealed vacuum interrupter. The arc gets extinct due to the separation of the contacts in high vacuum. High vacuum possesses extremely high dielectric strength. So, the vacuum circuit breaker can easily withstand medium voltage ranging from 11 kV to 33 kV.

Construction of the VCB

The vacuum circuit breaker comprises a vapour condensation shield in the center-symmetrically arranged ceramic insulating envelope. Their construction is mainly divided into three parts, i.e. a fixed contact, a moving contact and a shield, which are placed inside the arc interrupting chamber. Fig. 3 depicts the sectional view of a VCB [2].

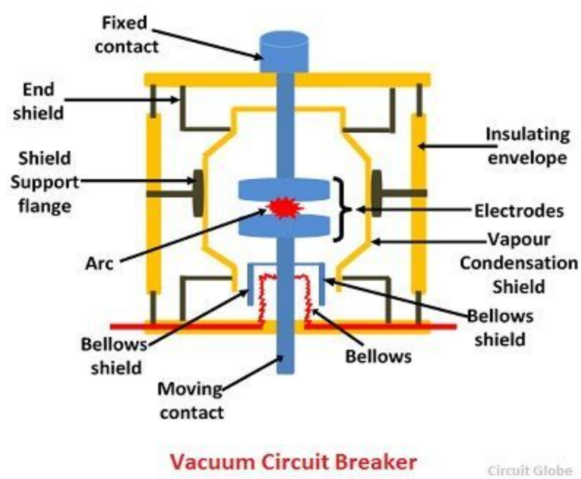

Figure 3: Sectional view of the construction of a vacuum circuit breaker

Working principle of the VCB

When a fault occurs in the system, the moving contact is moved away from the fixed contact. As the contacts move apart an arc develops: When the contacts start to separate, they are still carrying current. So, the temperature of the contacts is high, which causes ionization. Due to the ionization, the space between the contacts is filled with vapour of positive ions. These ions are discharged from the material of the contacts.

The density of vapour depends on the current in the arc. Due to the decreasing value of the current the release rate of the vapour falls. After the current reaches zero and the vapour density around the contacts is reduced enough, the circuit breaker regains its full dielectric strength very quickly. This quick recovery is due to the absence of gas molecules, allowing the vaporized metal to diffuse rapidly. Hence, the arc does not restrike any more.

The recovery rate of the dielectric strength is represented by the variable in the field “Voltage rise slope during quenching” in the mask dialog of the VCB subsystem. In this VCB model it is chosen as 100 V/ms. The VCB maximum withstand voltage is set as 30 kV in the model.

Modeling of the VCB

The modeling of the VCB is implemented based on a PLECS Breaker component with extra control circuitry. The circuit schematic beneath the VCB mask is shown in Fig. 4. The control circuitry of this Breaker represents the main working principle explained above. The `Ctrl` Signal Inport receives a Boolean signal that controls the ON/OFF signal of the VCB.

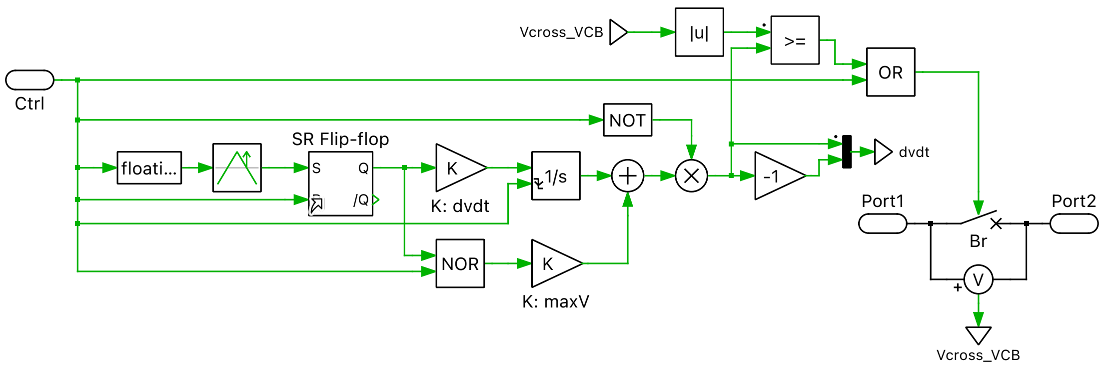

Figure 4: Schematic of the VCB model under the mask

The recovery of the dielectric strength is modeled with an Integrator with the slew rate as “voltage rise slope during quenching". The integration action stops at the maximum withstand voltage.

The NOR gate path ensures the maximum withstand voltage when the VCB is in static OFF state. Therefore, the output of the Product component models the dynamic breakdown voltage limit of the VCB.

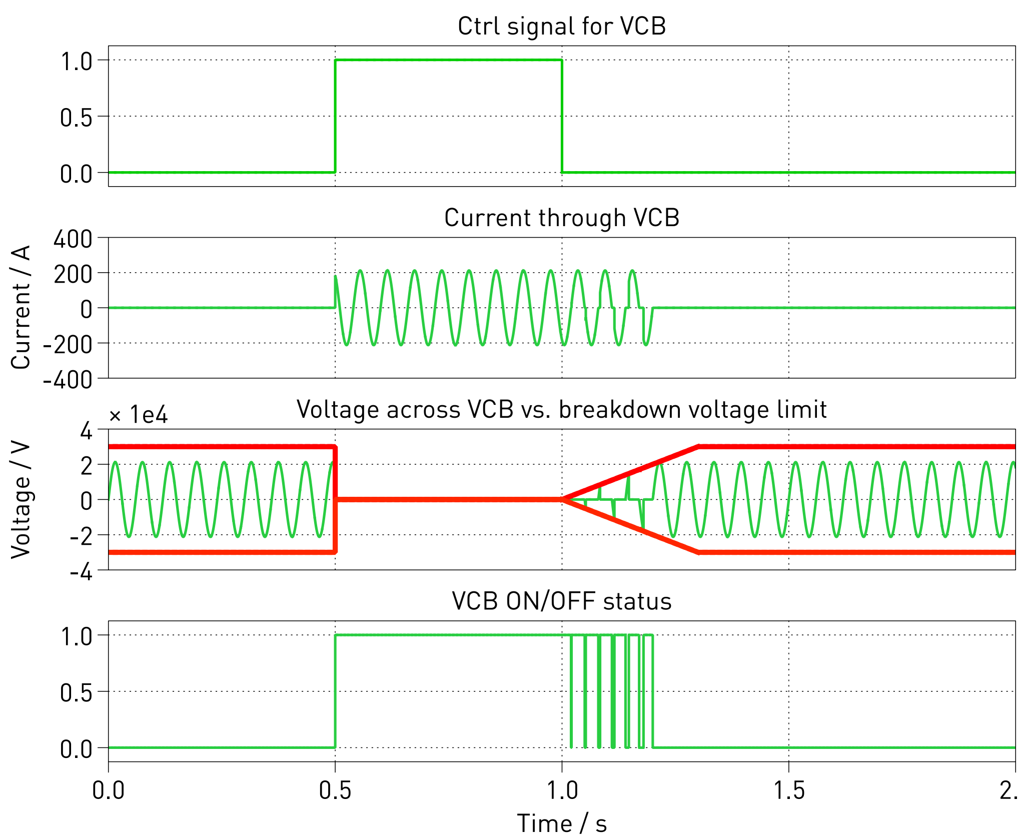

Figure 5: Illustrative waveform of the VCB model under different control signal status

The Relational Operator (in "greater or equal" configuration) models the scenario when the measured voltage across the VCB goes beyond the dynamic breakdown voltage limit, the VCB goes briefly back into ON state. It continues for several cycles of alternating between ON and OFF status, until finally the line current is successfully interrupted.

This behaviour is illustrated in an offline simulation in Fig. 5, with the VCB `Ctrl` signal going through OFF-ON-OFF status.

3 Simulation

This section describes the main operating scenario of the model. This model can run both in offline mode on a computer or in real-time mode on an PLECS RT Box 2 or 3.

Please follow the instructions below to run in real-time mode on an RT Box:

- Connect the Digital In interface to the Digital Out interface of the RT Box, i.e. by using a 37 pin Sub-D cable.
- From the **System** tab of the **Coder options...** window, select the “Railway Traction System” and go to the **Scheduling** tab. Make sure the tasking mode is chosen as `multi-tasking`.
- Click **Build** to deploy the model onto the RT Box.
- Once the model is uploaded, from the **External Mode** tab, **Connect** to the RT Box and **Activate autotriggering**.

3.1 VCB on and motor breakers disrupted

In the initial status, the VCB is passing through normal current, i.e. `Ctrl_VCB` equals to `1`. Only the auxiliary stage is powered up, but the traction motors are not connected in the circuit yet. This represents the scenario when the train is stopped and lights are on. The train is ready to depart at the station.

Fig. 6 shows the voltage and current waveforms of the transformer primary side. Fig. 7 shows the nominal operating waveforms of the three-phase inverter at the auxiliary stage.

3.2 Engage the breakers connected to traction motors

Now we want to represent the scenario when the train starts running. Select the four Constant blocks (named `En_Br1, En_Br2, En_Br3` and `En_Br4`) at the same time and change them from 0 to 1. This action engages all four circuit breakers. Each circuit breaker is connected to one of the four motors. The train starts running when the four motors generate traction effort.

Fig. 8 shows the waveforms of the transformer primary side under nominal traction effort and auxiliary stage.

Fig. 9 shows the stator currents, rotor position and electrical torque of one traction motor under nominal traction effort.

3.3 Signal the VCB to break the current

We now want to represent the scenario when the train is going across a section insulator in the overhead lines. In reality, the grid supply will be disconnected from the traction trafo for a very short period of time. During this temporary blackout in the catenary, the VCB quenches the arc, causing nonlinear disturbances on the voltage and current of the device. Here, we represent this event by giving a disenable signal to the VCB, changing the status of the VCB from ON to OFF. So, we change the Constant named `Ctrl_VCB` from 1 to 0. This signals the VCB to break the current.

Fig. 10 includes the trafo primary side voltage and current waveforms around the transition of the catenary power blackout. Distorted voltage and current can be observed due to the quenching effect

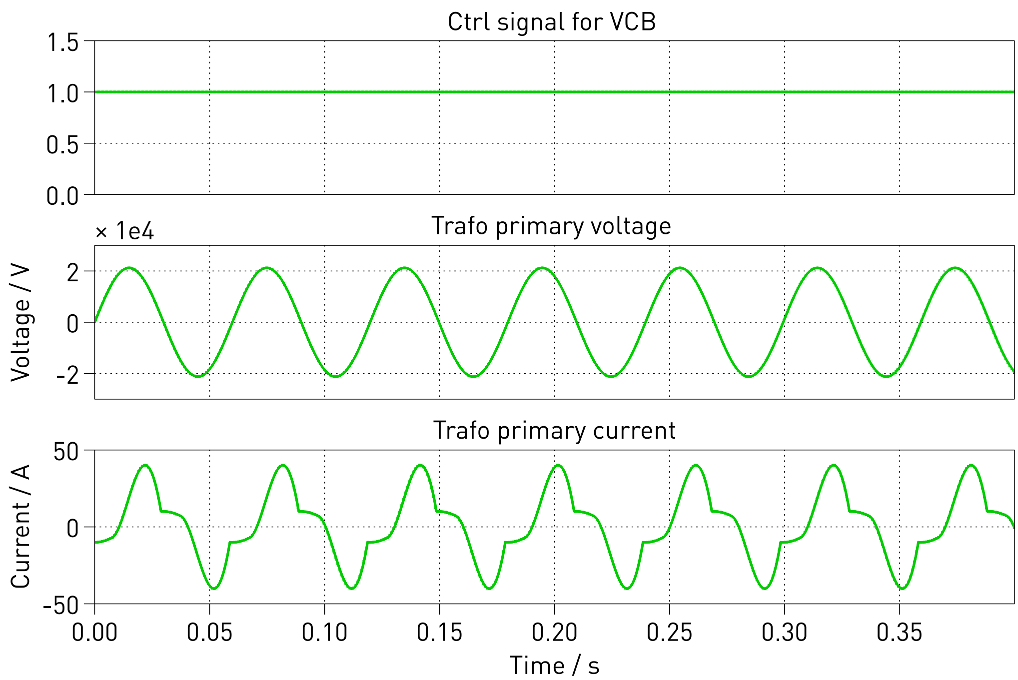

Figure 6: Traction trafo primary side waveforms when the VCB is on but the motors are not connected yet

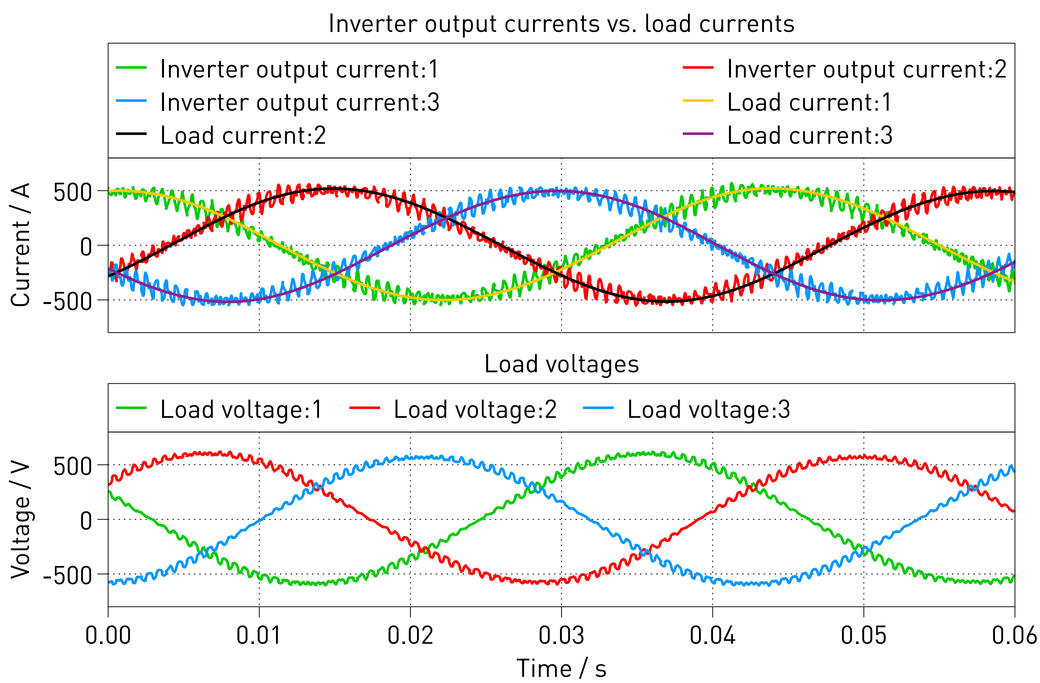

Figure 7: Auxiliary stage three-phase inverter nominal operating waveforms

of the VCB. As a result of the interrupted line's current, the two DC link voltages suffer from gradual drop (see Fig. 10).

As a result, this disturbance travels through the DC capacitors to the respective motor and auxiliary stages. In real practice, the auxiliary converters and motor drive inverters are always controlled in closed-loop fashion. The closed-loop control is used to combat this temporary dip in the DC link voltages. This way, the converters can continue delivering the desired power to the loads. This phenomenon is not the focus of this demo and is therefore not included.

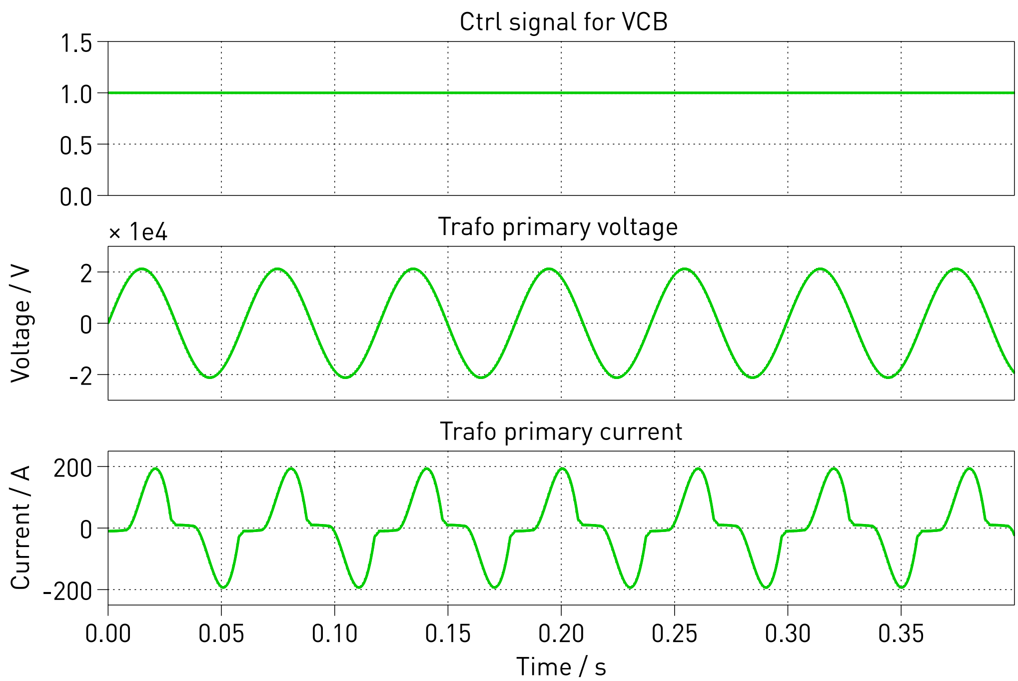

Figure 8: Traction trafo primary side waveforms under nominal traction effort and auxiliary load

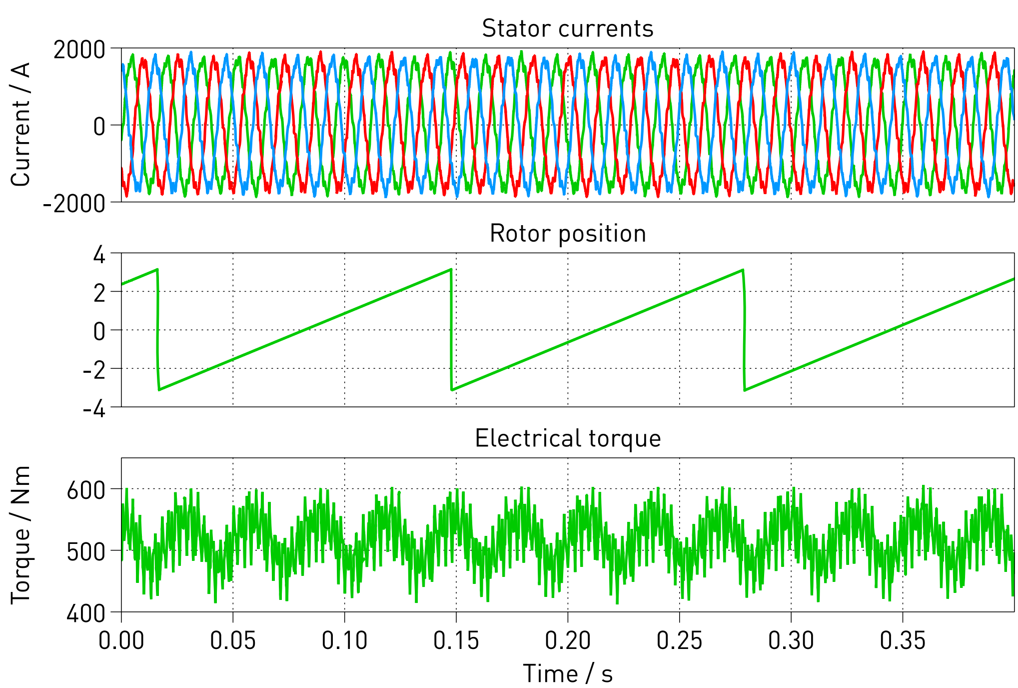

Figure 9: Waveforms of one traction motor under nominal traction effort

Fig. 11 shows the detailed waveforms inside the VCB subsystem model at the same transition. Upon the disruption of the catenary supply voltage, every time the line current reaches 0 the VCB quenches the arc while the withstand voltage builds up. It continues for several cycles of alternating between ON and OFF status (approx. 200 ms), until finally the line current is successfully interrupted.

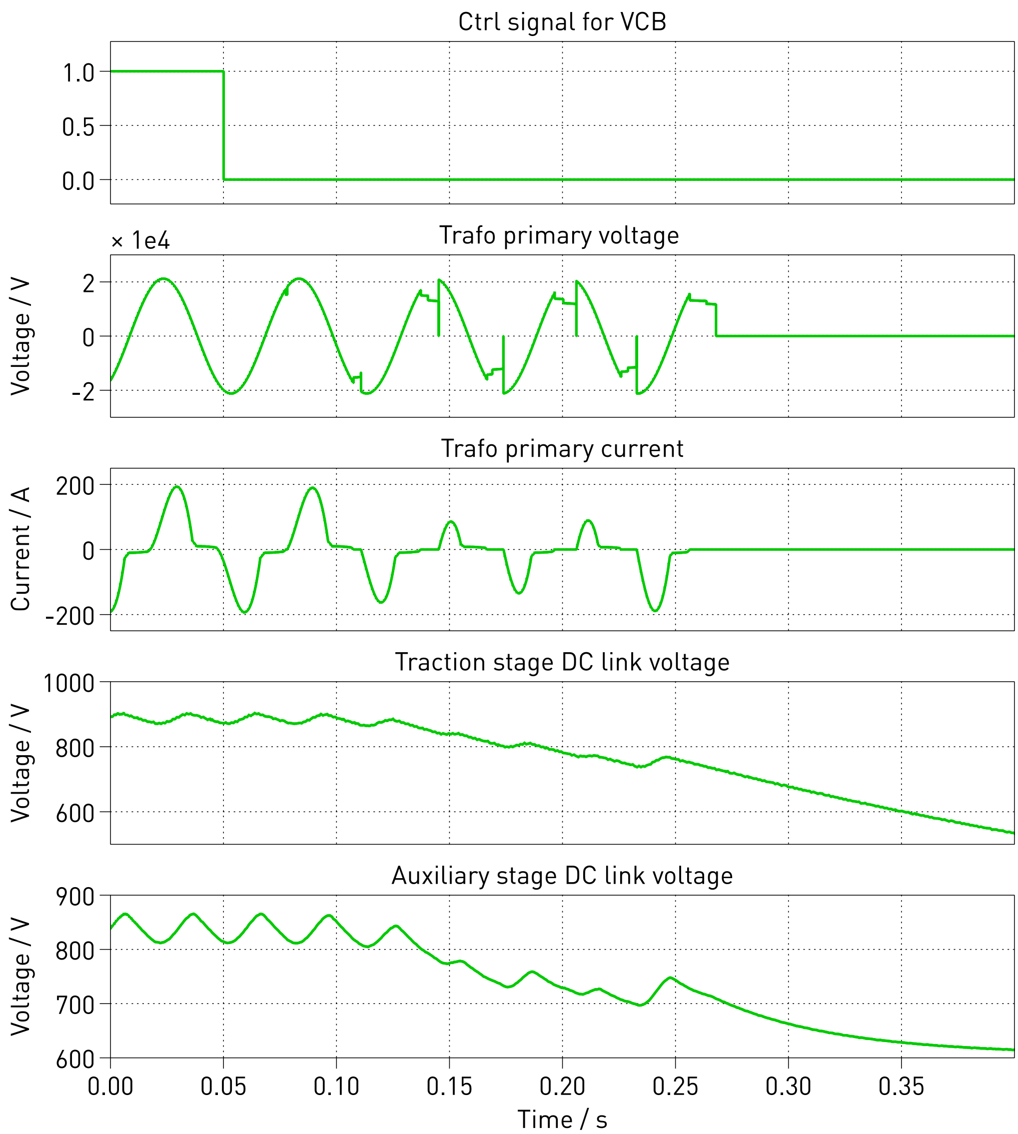

Figure 10: Traction trafo primary side waveforms and DC link waveforms during the VCB turn-off transition

4 Conclusion

This demo model shows a generic railway traction system. It demonstrates the current breaking behaviour of a VCB. The demo model shows a large traction system split into three stages. Each stage runs on one of the three cores of the RT Box 2 or 3.

A feature of both RT Boxes is running a simulation in multi-tasking mode using all three CPU cores. The individual CPU load for each core becomes smaller and due to this, the average execution time can be reduced considerably. A reduced discretization step size leads to a better frequency resolution, and therefore fidelity of the real-time simulation is improved.

References

[1] “Open Railway Map”, [Online]. Available: https://www.openrailwaymap.org/?lang=null&lat=50.56928286558243&lon=11.151123046874998&zoom=6&style=electrified. [Accessed: Oct. 26, 2023].

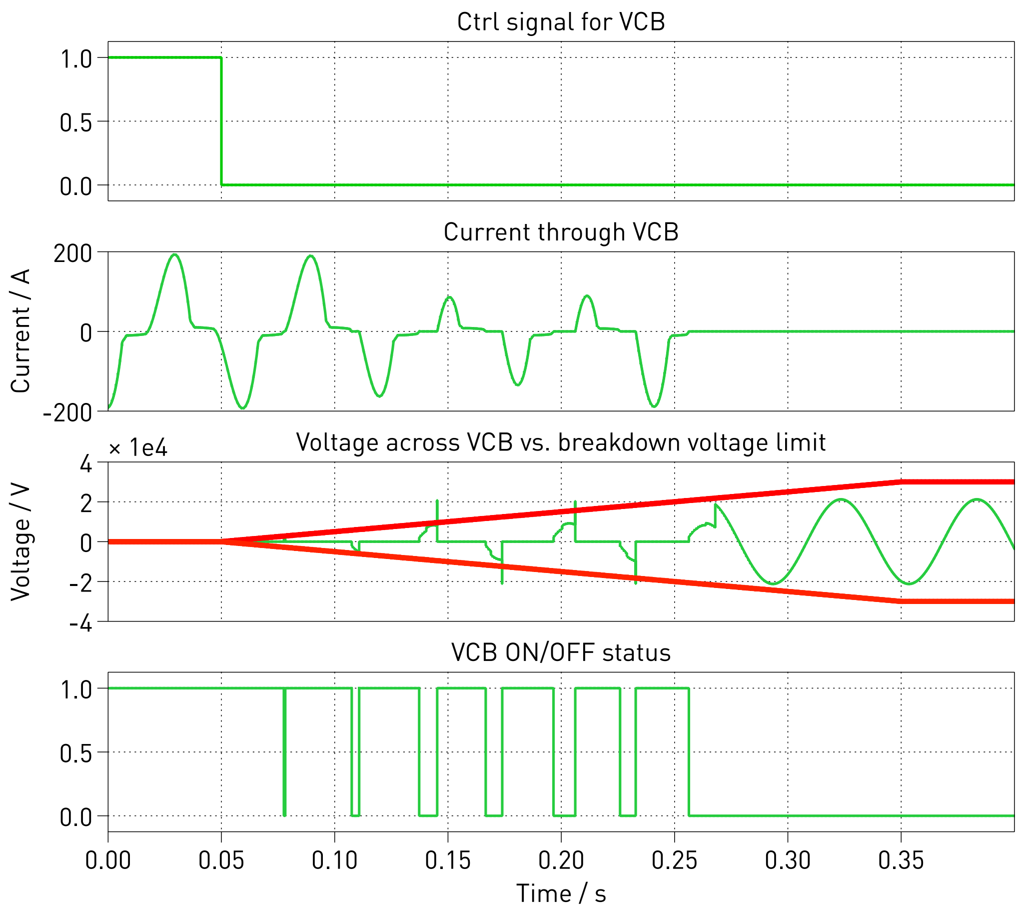

Figure 11: Detailed waveforms inside the VCB during the VCB turn-off transition

[2] "Vacuum Circuit Breaker", [Online]. Available: https://circuitglobe.com/vacuum-circuit-breaker.html. [Accessed: Oct. 17, 2023].

Revision History:

RT Box TSP 3.0.1	First release

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