A5 APPENDIX 5: DYNAMIC BEHAVIOUR OF ROTARY CONVERTERS

A5.1 Summary

The following general characteristics apply to rotary converter units:

- Even small steps in contact line power excite noticeable oscillation in the converter rotor.
- The direction of the power step (increase or decrease) has no significance for the magnitude of the rotor oscillation.
- The oscillation magnitude decreases greatly when power consumption occurs as a ramp of limited steepness instead of as a step.
- Even small repetitive power changes of limited steepness cause considerable oscillation when occurring at an unfavourable frequency (1.0 – 2.0 Hz). If a relative steep reduction of power under certain conditions is necessary, e.g. due to the function of wheel slip and slide protection, the amount of oscillation may to some extent be limited by imposing considerably stricter restrictions on following power increase.
- The time until an oscillation is damped increase with the oscillation magnitude, and is for large oscillations of the size of 10 – 15 s when rolling stock does not contribute to maintaining the oscillation.
- The rotor oscillation results in oscillations in the contact line voltage amplitude and the voltage’s steepness and zero crossing every 16 2/3 Hz period is displaced relative to a ideal sine.
- Depending on the train current-voltage characteristic, the contact line impedance may result in deviation between the voltage oscillation amplitude at the pantograph and at the converter station. Trains having power output independent of voltage will increase the amplitude while the amplitude will decrease for constant impedance load characteristic trains.

A5.2 Examples of converter unit response to changes in load.

A5.2.1Introduction

The dynamic behaviour of rotary converter units is in the following text illustrated by computer simulations for a 5.8 MVA rotary converter unit (Q38) which on the single-phase side supplies the train without interconnection with other converter units. The train is simulated with voltage independent power consumption. Further description of the simulation model can be given by Norwegian National Rail Administration on request.

A5.2.2 Definitions

Definitions/Abbreviations used:

U 60km:	Pantograph voltage at 60 km from the converter station when contact line has a resistance of 0.18 ohm/km and an inductive reactance of 0.19 ohm/km (16 2/3 Hz)
PA 60km:	Angle of pantograph voltage at 60km from the converter station when overhead contact line has a resistance of 0.18 ohm/km and an inductive reactance of 0.19 ohm/km (16 2/3 Hz). Phase angle is relative to the 50 Hz power supply of the converter station.

A5.2.3 Frequency response

Figure 4b.1 shows the converter unit's frequency response characteristics for active power between the single-phase and the 3-phase side in the 0 – 5 Hz frequency band, i.e. the dynamic, electromechanical connection between a single-phase power disturbance ΔP1 and the response in 3-phase power ΔP3 for the converter unit. It is assumed that the disturbance is sine shaped.

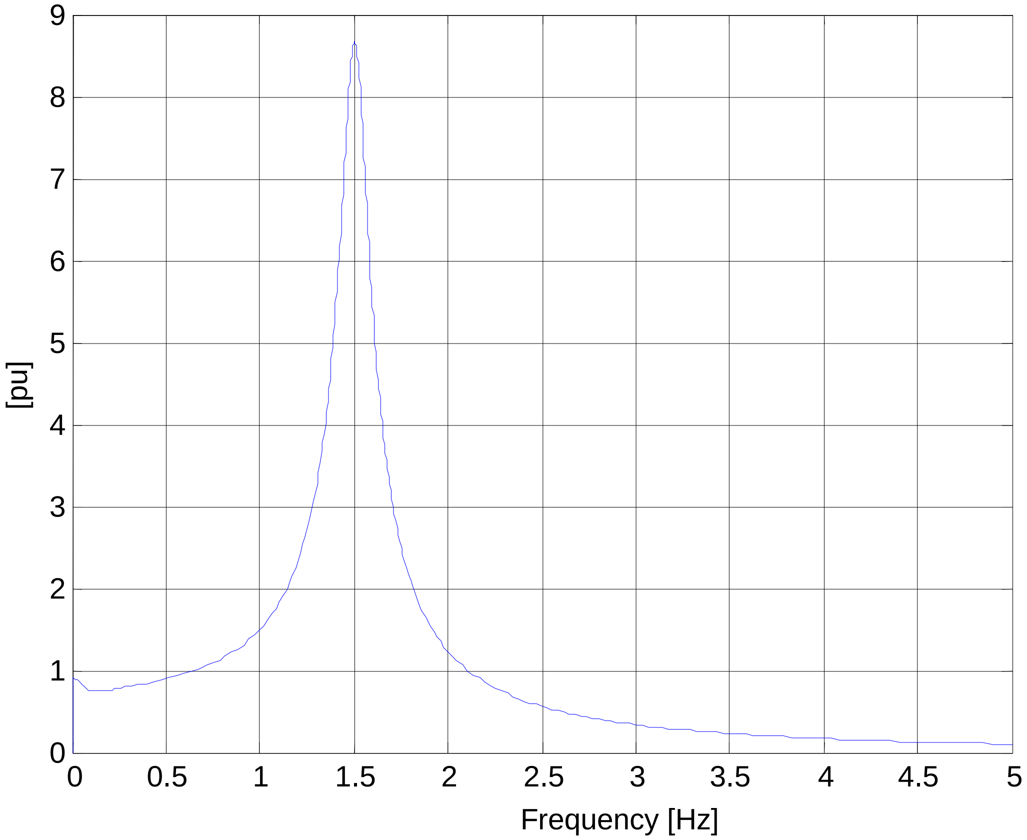


Figure A5-1 Example of the converter unit’s frequency response characteristic, ΔP3/ΔP1, for sine shaped change in single-phase power ΔP1.

The frequency response characteristic for this converter unit has a distinctive resonance crest at approximately 1.5 Hz with an amplification of 9 pu.

A5.2.4 Active power step response

The voltage oscillations shown in the figures below arise due to changes in the converter rotor velocity when the converter’s pole angle oscillates.

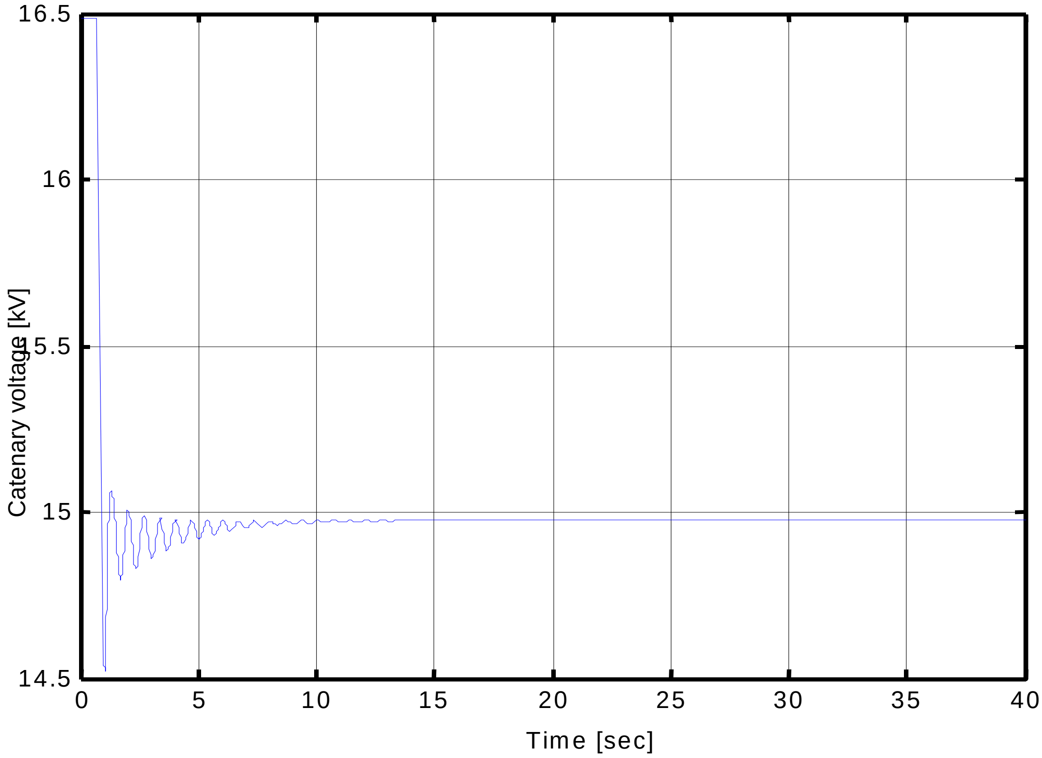


Figure A5-2 U 60km for active power step in the train of 0 – 2.0 MW

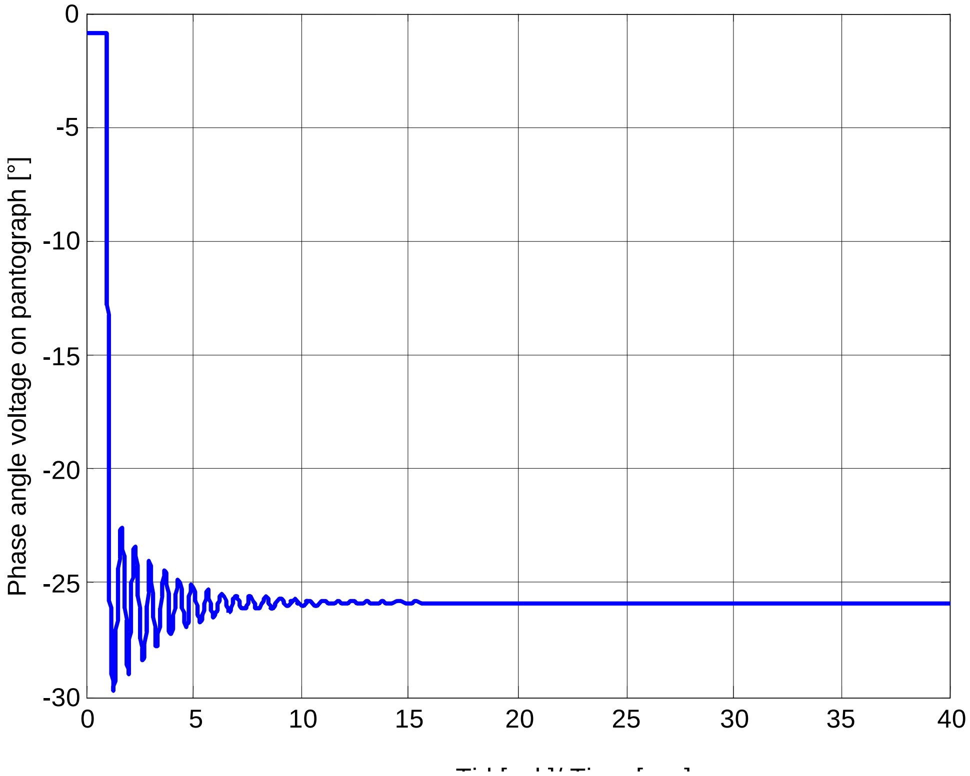


Figure A5-3 PA 60km for active power step in the train of 0 – 2.0 MW

Maximum oscillation (top – bottom) varies with the power step size as follows:

Power step in train	Max. oscillation	
	U 60km	PA 60 km
0 – 3.50 MW	≈ 690 V	≈ 13°
0 – 2.00 MW	≈ 270 V (Shown in Figure A5-2)	≈ 7° (Shown in Figure A5-3
0 – 0.25 MW	≈25 V	

Comments:

- Sudden step changes in active power cause heavy oscillation in the converter rotor position (pole angle).
- Even small power steps cause noticeable oscillation.
- Whether the power step is caused by load decrease or load increase has little significance for the oscillation’s magnitude.

A5.2.5 Active power ramp response

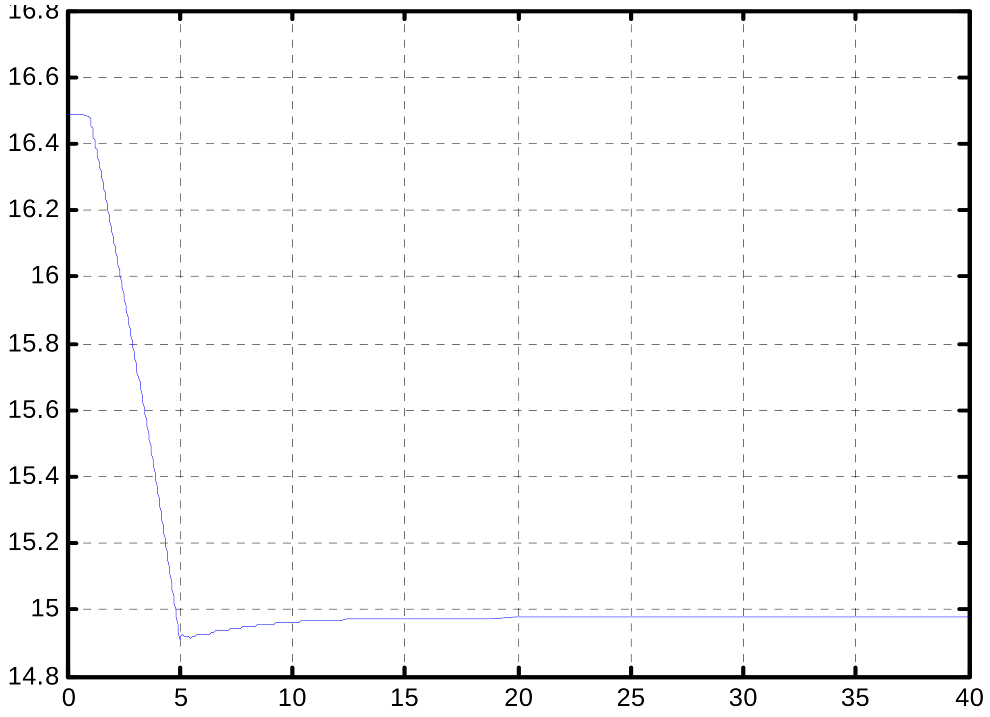


Figure A5-4 U 60km for increased power 0 -2.0 MW for linear steepness of 0.5 MW/s

Maximum oscillation (top – bottom) varies with the power step (ramp) steepness as follows:

Power change in the train 0 – 2.0MW	Max. oscillation U 60km
Step	270 V (Shown in Figure A5-2)
1,5 MW/s linear steepness	14 V
0,5 MW/s linear steepness	5 V (Shown in Figure A5-4)

Comment:

- The oscillation magnitude due to change in active power decreases significantly when the power change take place as a ramp of limited steepness. Whether the oscillation is caused by load decrease or load increase has little significance for the oscillation's magnitude.

A5.2.6 Repetitive changes in active power

Figure A5-5 shows U 60km for a train that in the beginning consume 4.0 MW and then an unsymmetrical saw-tooth shaped change in load with maximum unfavourable frequency (1.6 Hz) and flank steepness of -1.5 MW/s and + 0.5 MW/s respectively. Repeating power change in each saw-tooth period is 234.375 kW with 4.0 MW as maximum power.

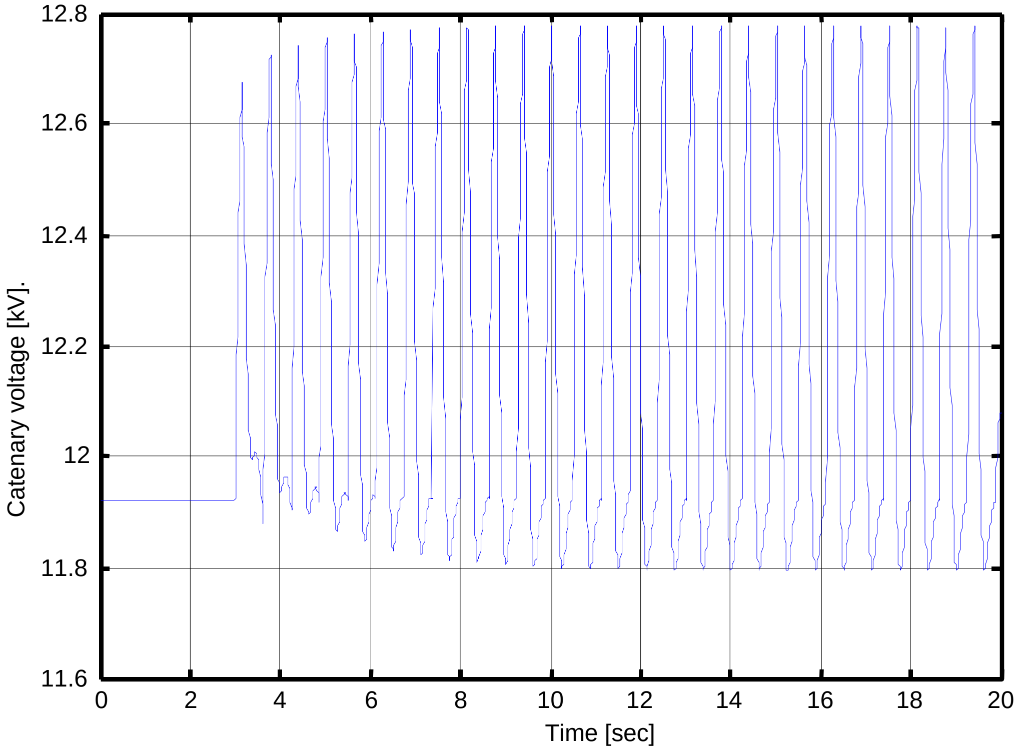


Figure A5-5

Maximum oscillation in contact line voltage (top – bottom) is as follows:

Periodic power change 1.6 Hz:	Max. oscillation U 60km
234.375 kW	990 V (Shown in Figure A5-5)

Comparatively, a repetitive symmetric load change having the same change in each saw-tooth will have flank steepness of +0.75 MW/s and -0.75 MW/s and cause about 5 % larger oscillation in the contact line voltage.

Comment:

- Even small power changes will after a few oscillation periods cause considerable oscillation if they are repeated at an unfavourable frequency. If being able to allow rapid repeating power changes in one power direction (e.g. power reduction when activating wheel skid or glide protection) is technically desirable, the converter rotor oscillation can to some extent be limited by implementing stricter restrictions for power changes in the opposite direction.

A5.2.7 Reactive power step response

Figure A5-6 shows U 60km for a converter having 2.0 MW preload and voltage independent load for steps of 0 – 1.0 MVAr inductive power.

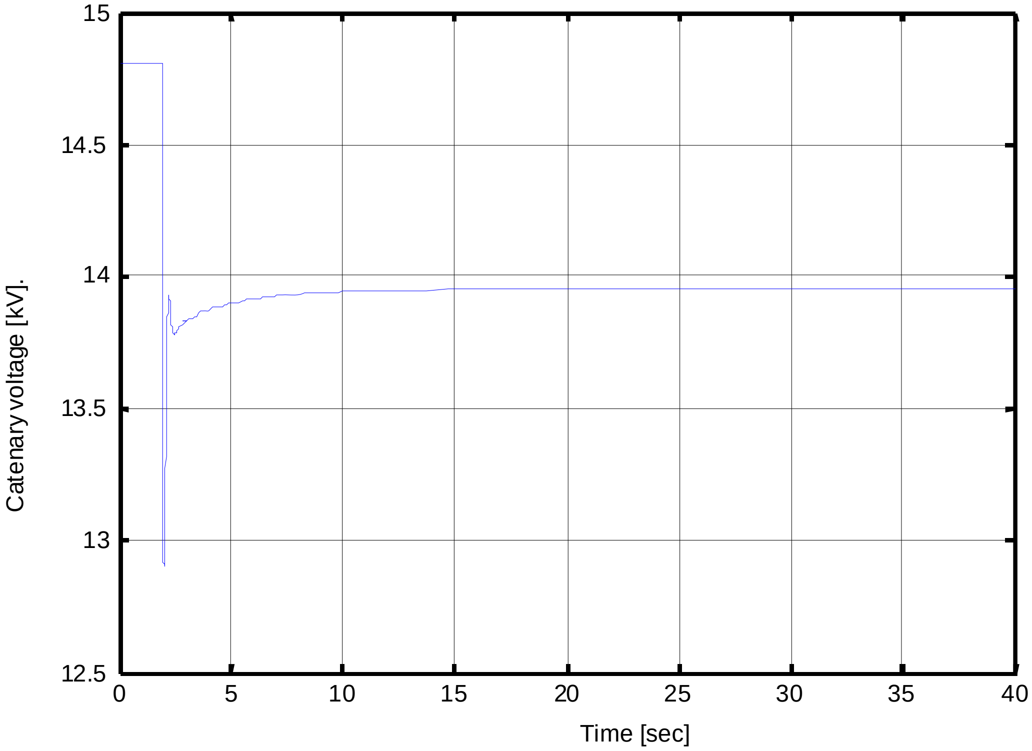


Figure A5-6

Maximum deviation in contact line voltage will be:

Reactive power step:	Trancient reduction U 60km
0 - 1,0 Mvar	ca. 1000 V (Shown in Figure A5-6)

Comment:

- Steps in reactive power in themselves cause only marginal oscillation in the converter unit’s pole angle. However, due to converter unit and contact line inductance, a big initial contact line voltage variation occurs. Indirectly, steps in reactive power may cause some oscillation due to the resulting changes to active losses in the system.

Step reductions of reactive power will also cause brief powerful variations in contact line voltage, but causing the voltage to rise rather than drop.

A5.3 Voltage phase angle variation with load

During increasing load the converter units' power angle and thus the phase angle for generated single-phase voltage decreases considerably relative the voltage in the 50 Hz grid. The 1-phase phase shift relative to the 50 Hz grid can be calculated as:

$$\Psi = \Psi_0 + \Psi_{\text{conv}} \quad \text{where}$$

$$\Psi_0 = \text{angle differnce between the } 50\text{ Hz and } 16.7\text{ Hz at no load on the converter and}$$

$$\Psi_{\text{conv}} = -\left[\frac{1}{3}\arctan(x_{qM}\cdot i_G \cdot \cos\varphi_G) + \arctan(\frac{x_{qG}\cdot i_G\cdot\cos\varphi_G}{1 + x_{qG}\cdot i_G \cdot \sin\varphi_G})\right]$$

where

x_{qM}	is the converter motor quadrature-axis synchronous reactance in p.u.
x_{qG}	is the converter generator quadrature-axis synchronous reactance in p.u., including the short circuit impedance of the transformer
i_G	is the current of the converter generator in p.u. of rated current

$i_G = I_G/I_{n\_G}$

I_G	is the current of the converter generator [A]
I_{n_G}	is the rated current of the converter generator [A]
φ_G	is the phase shift between the current and voltage of the generator

In the equation the following assumptions are made:

- Both the 3-phase synchronous motor and the 1-phase synchronous generator are modelled as synchronous machines with salient poles.
- The 3-phase motor is not magnetized, i.e. $Q_{50} = 0$.
- The axle between the synchronous motor and 1-phase synchronous generator is stiff and has no losses.
- All losses in the motor and generator are neglected.

Figure A5-7, below, shows 1-phase phase lag for 10 MVA converter units. 5.8 MVA converter units have approximately 10 % larger phase lag for the same relative load. The figure is plotted for and inductive load when cos(φ) < 1. In the figure Ψ_0 is set to zero.

As can be seen from the figure all lines goes through the origin. If the losses in the motor and generator were to be included there should be a death-band around the horizontal line $-\Psi=0$, i.e. positive active power would mean that the line would start from lag greater than zero and for negative active power the lines would start from a lag less than zero.

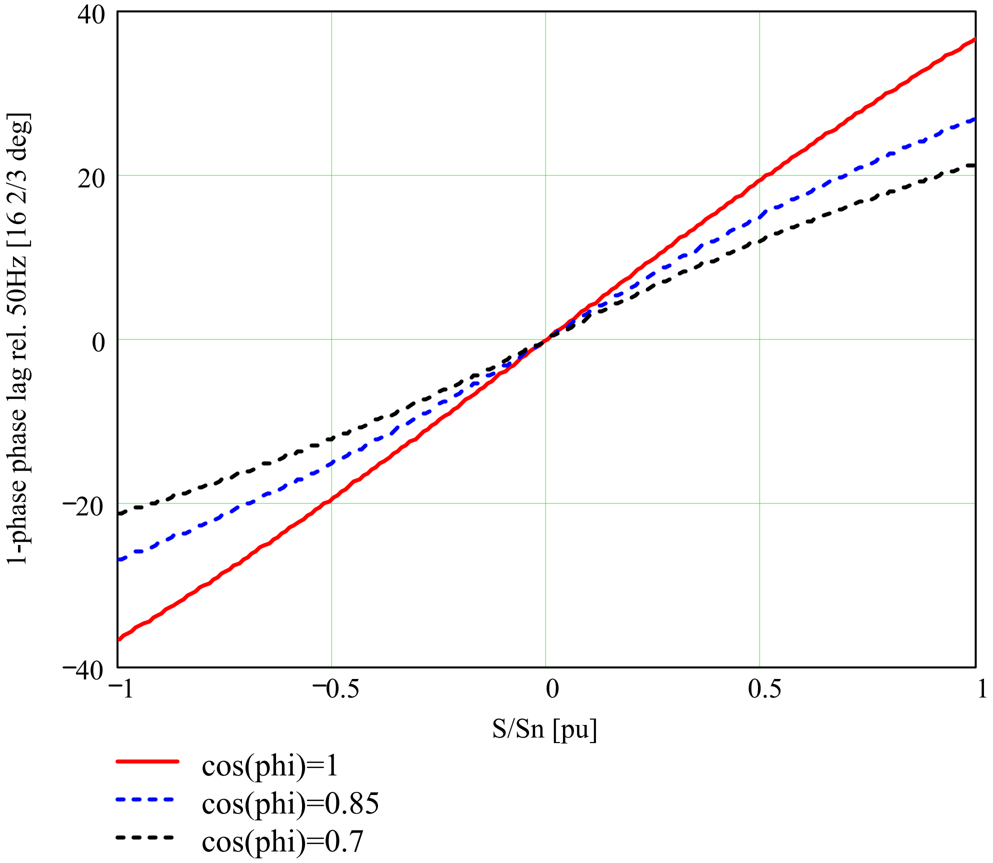


Figure A5-7 Phase angle lag single-phase voltage relative to 3-phase voltage for 10 MVA rotary converter units.

Note that the figure depicts the phase lag, not the phase shift. The angel lags more and more with increasing load. Note also that the figure is valid also for negative active power, i.e. when feeding from the 1-phase side to the 3-phase side, but only the active power is reversed. The reactive load is still the same, i.e. an inductive load at the 1-phase side which correspond to a electrical braking vehicle with cos(φ)-control.

While the converter unit change power angle, the voltage’s steepness change and the voltage zero crossing will be displaced, increasingly with the speed of change. By increasing the distance to the converter station, the voltage’s phase will vary even more with the load due to the contact lines inductive impedance.

A5.4 Time domain Model

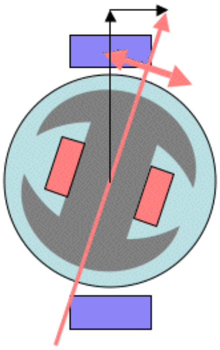
This chapter describes a simple time domain simulation model for rotating converters as they are in operation in the Norwegian and Swedish railway system. This model can be used by railway vehicle manufacturers for compatibility studies prior to first tests with new vehicles. The model is derived by emkamatik, document 06-0132. It is derived from more detailed models implemented by SINTEF Energy Research, Trondheim. The document includes some validation examples and an application guide on how to use the model.

The model is programmed in Matlab / Simulink and is available as a Simulink block on request.

A5.4.1 Physical background

The rotating frequency converters in Sweden and Norway consist of a 50-Hz synchronous motor directly coupled to a 16 2/3-Hz synchronous generator. They perform a frequency conversion by a factor of three and allow a power flow in both directions. The converters used in Sweden and Norway do not have damping windings on the rotor of the 50-Hz machine (3-phase side), therefore the corresponding eigenfrequency of the pole angle oscillation (between 1.6 and 1.8 Hz) is poorly damped (quality factors up to 10). Excessive oscillations of the rotor around its stationary pole angle can be produced by either strong or repetitive power variations of a train (e.g. adhesion control) or by feedback loop effects with the vehicle control in general. Negative effects of excessive converter oscillations include higher mechanical stress in the machines as well as significant periodic variations („flicker“) in weaker parts of the 50-Hz network.
Seen from a railway vehicle, the rotating converter shall be modelled as a „black box“ with the following main characteristics:

- Inner impedance of the generator. This also an RL impedance and is, therefore, not considered specially. In principal it has the same effect as a longer line.
- Voltage control, depending on the load. Normally, the output voltage is controlled to a nearly constant value, by means of variation of the excitation current of the machine.
- Pole angle variations. The angle of the induced voltage of a synchronous machine varies with the load current in the machine. The angle is lagging if load is drawn. For steady state operation, the relation between load current and angle follows a sine curve, but for small variations of the angle the behaviour can be linearised. Therefore, the generator reacts like a spring. Together with the rotating mass of the generator an oscillating system of 2nd order is formed. The following small figure shows a sketch of the spring – mass system formed by the rotating converter.



For all following considerations, the converter is always treated as a whole, not making any difference between 50-Hz and 16 2/3-Hz machine.

A5.4.2 Model structure

Chapter A5.2 contains the description of the behaviour of a rotating 5.8-MVA converter which is widely used in Norway and Sweden and a number of active and reactive load step and ramp responses. The task of the simulation model is to reproduce the shown behaviour in a "black box" manner, i.e. the reaction of the converter is just modelled as transfer functions while the motor and generator are not included as detailed electrical circuits and controllers. The figure below shows the simplified model of the rotating converter as a Matlab / Simulink model. It contains the following functional units:

- The model contains one output, the generator voltage U_{Gen}. It is calculated by the following expression:

  $$U_{Gen}(t) = A(t) \cdot \sin\left(2\pi f_N t + \varphi(t)\right)$$

  where
  - $f_N = 16\tfrac{2}{3}\,Hz$ is the nominal line frequency,
  - $A(t)$ the amplitude and
  - $\varphi(t)$ the pole angle.

  Both amplitude and pole angle depend on the active and reactive power. The corresponding functional simulation blocks are marked with yellow background colour.

- The electric power delivered by the generator is calculated as

  $p(t) = U_{Gen}(t) \cdot I_{Line}(t)$, where $I_{Line}(t)$ is the line current.

  The active power $P(t)$ is calculated as the mean value of p(t) over one fundamental line period

  $$P(t) = \frac{1}{T}\int_{t-T}^{t} U_{Gen}(\tau) \cdot I_{Line}(\tau)\, d\tau\,.$$

  The reactive power $Q(t)$ is calculated as

  $$Q(t) = \frac{1}{T}\int_{t-T}^{t} U_{Gen}^{*}(\tau) \cdot I_{Line}(\tau)\, d\tau\,,$$ where

$U^*_{Gen}(t) = A(t)\cdot\cos(2\pi f_N t + \varphi(t))$ is the 90° phase shifted generator output voltage. The simulation blocks which calculate $P(t)$ and $Q(t)$ are marked with light green background colour.

The functions for the generator voltage’s ***phase*** $\varphi(t)$ and ***amplitude*** $A(t)$ describe the dynamics of the generator and are conveniently formulated in the s domain (see also structure figure below).

- **Phase angle function:**

In the simplified model, the phase angle $\varphi(t)$ depends only on the active power $P(t)$:

$\varphi(s) = [G_0(s) + k(P)\cdot G_1(s)]\cdot P(s)$ where $P(s)$ is the Laplace transformed time domain signal $P(t)$.

$G_0(s) = \dfrac{A_0}{T_0^2 s^2 + 2d_0 T_0 s + 1}$ is an “oscillation component”.

$G_1(s) = \dfrac{A_1}{T_1 s + 1}$ is a “static component”, which is combined with

$k(P) = \varphi_0 + k_\varphi \cdot abs(P)$ the load depending gain $k(P)$, which approximates the nonlinear load – pole angle characteristics of the generator (included in the block “F1” below).

- **Amplitude function:**

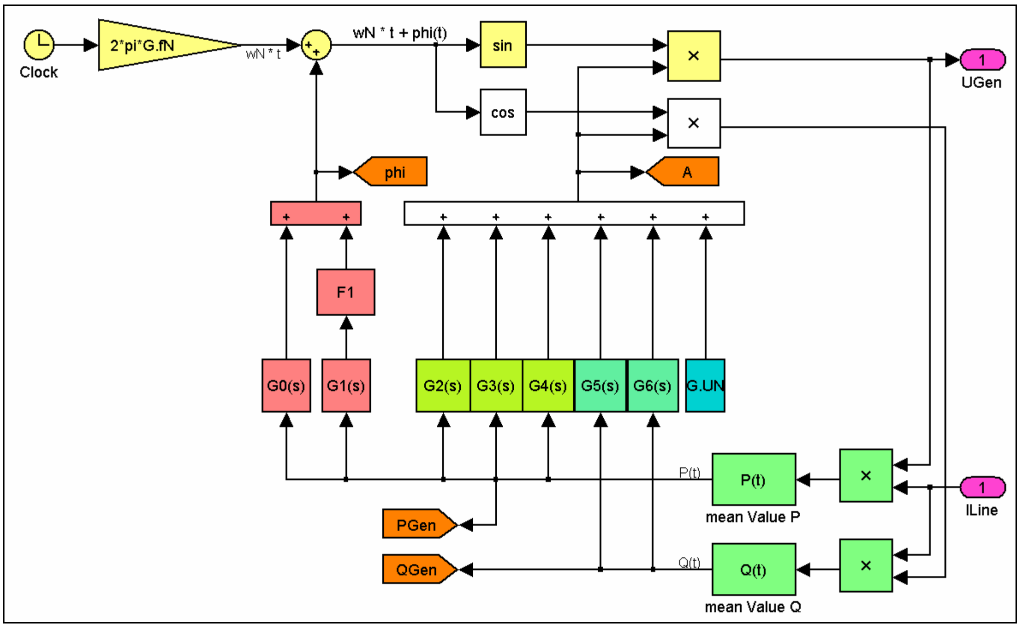
In the simplified model, the amplitude $A(t)$ depends on active and reactive power:

$$A(s) = U_N + [G_2(s) + G_3(s) + G_4(s)]\cdot P(s) + [G_5(s) + G_6(s)]\cdot Q(s)$$

$U_N = \sqrt{2}\cdot 16.5kV$ is the nominal line voltage amplitude,

$G_2(s) = \dfrac{A_2 s}{T_0^2 s^2 + 2d_0 T_0 s + 1}$ is an “oscillation component” (same denominator as $G_0(s)$)

$G_i(s) = \dfrac{\mathrm{A}_i}{T_i s + 1}$ with i = 3 … 6 represent transient effects.



A5.4.3Model parameters

The following parameter sets have been determined and allow the reproduction of the step responses shown in chapter A5.2 with good accuracy:

	Q 38 weak 3-phase network
A_0	$-12.25° / 5.8\ MW$ $= -3.6863 \cdot 10^{-8}\ W$
T_0	$\dfrac{1}{2\pi \cdot 1.5 Hz} = 0.1061\text{s}$
d_0^*	0.045
A_1	1
T_1	$0.05s$
φ_0	$-1.3541 \cdot 10^{-7}$
k_φ	$6.0184 \cdot 10^{-15}$
A_2	$1.5 \cdot 10^{-5}\ V/W$
A_3	$-2.0 \cdot 10^{-4}$
T_3	$0.05s$
A_4	$2.0 \cdot 10^{-4}$
T_4	$1.5s$
A_5	$1.5 \cdot 10^{-3}$
T_5	$0.25s$

A_6	$-1.5 \cdot 10^{-3}$
T_6	$0.001s$

*** Remark:**
Measurements done with different vehicles around Lunner and Oppdal (Norway) have shown that the damping ratio d_0 can be in the range from 0.025 to 0.07 and the oscillation frequency from 1.45 to 1.9 Hz.

A5.4.4 Line parameters

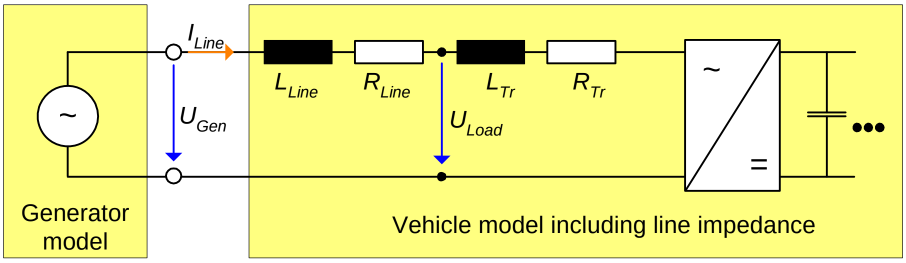
To create a complete power supply model a line impedance has to be added between the models of converter and train (see below). Typical values can be taken from section A1.5.9. For the investigation of realistic cases of low frequency behaviour the following values can be taken:

- $Z_{Line,km} = 0.18 + j\,0.19\,\Omega/km$
- The line of 60 km, which gives a line impedance of $Z_{Line} = 10.8 + j\,11.4\,\Omega$.

The resulting model is then comparable to the situation in Gjøvik, a single-side fed line in Norway, which has been taken already several times to test the behaviour of new trains.

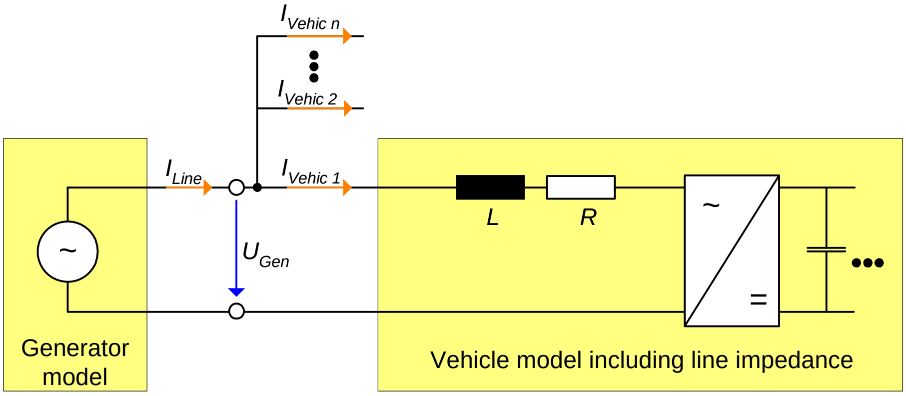
A5.4.5 Simulations with vehicles

The operation of railway vehicles in networks with high line impedance can lead to low frequent power oscillations. The risk of such oscillations is reduced significantly if the vehicle controllers are tuned and verified with time domain simulations.
The simulation model as described above contains a simplified, however appropriate model of the power supply infrastructure. This model can now be combined with a detailed model of the vehicle including its control systems. The motor circuits and control shall be included in the vehicle model.
For the integration of a single vehicle the line impedance must be combined with the vehicle transformer short circuit impedance as shown below. The reason is that the current through the line and transformer inductance are equal and must be treated as one state variable in the simulation model. The pantograph voltage U_{Panto} can be calculated easily (Z_{Line} and Z_{Tr} form a voltage divisor).



A5.4.6 Simulation of several vehicles

For the situation with more than one traction chain or several vehicles, it is normally still sufficient to simulate only one vehicle. This saves a lot of simulation time. It is assumed, that all vehicles are fed by the same catenary voltage and behave identically. This is a simplification, but yields good results as long as interactions between vehicles and the power supply system are investigated.



For this case the parameters of the converter and line model are scaled as follows:
As the voltage drop along the line depends on the number of simulated vehicles, the combined line and transformer impedance is now calculated with the following values:

$$R = R_{Tr} + n \cdot R_{Line}$$

$$L = L_{Tr} + n \cdot L_{Line}$$

n is the number of simulated vehicles, R_{Line}, L_{Line}, R_{Tr} and L_{Tr} are the same as above.
The generator current I_{Line} is equal to the sum of all vehicle line currents:

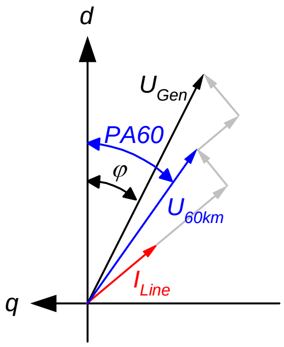
$$I_{Line} = n \cdot I_{Vehicle}$$

A5.4.7 Validation examples

The simulation model shown in this chapter, A5.4, has been tested and compared both for an RL load and with a detailed simulation model of an existing train. Each simulation is documented with the following signals:

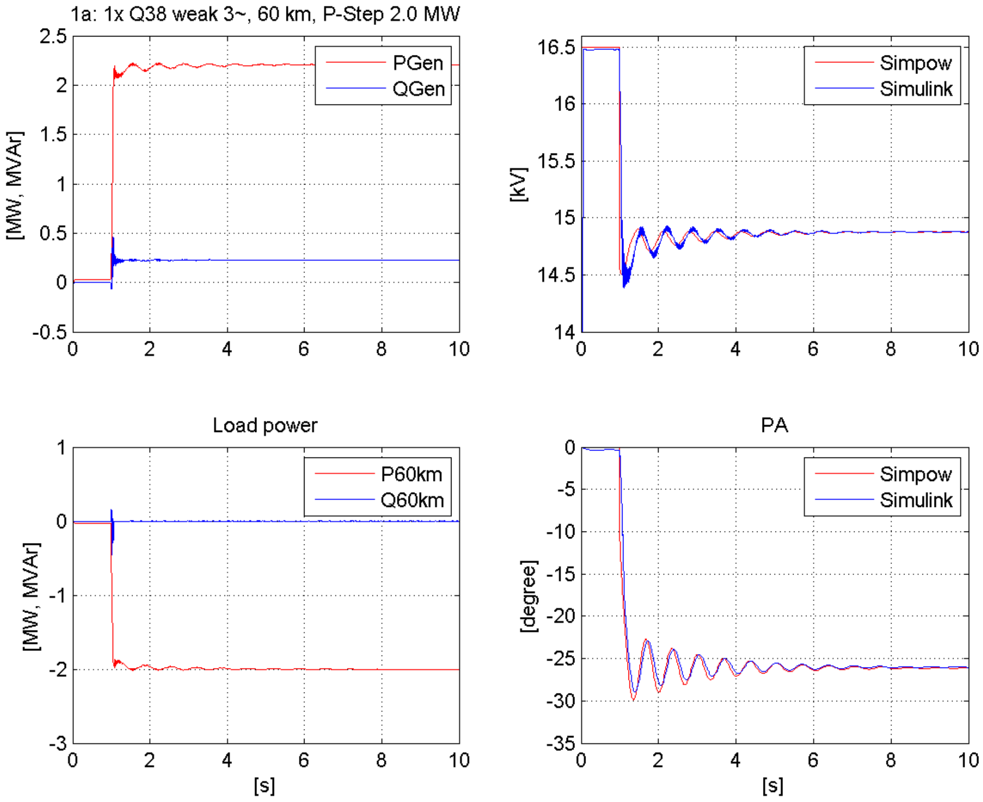
- Upper left plot: active and reactive power at generator (P_{Gen}, Q_{Gen})
- Lower left plot: active and reactive power at line end (P_{60km}, Q_{60km})
- Upper right plot: line voltage at line end (U_{60km})
- Lower right plot: phase angle of voltage at line end (PA_{60km}).

  PA60km is the sum of the generators load angle and the phase shift caused by the line impedance and is measured relative the d axis. The d axis represents the phase angle of the generator for the no load situation.



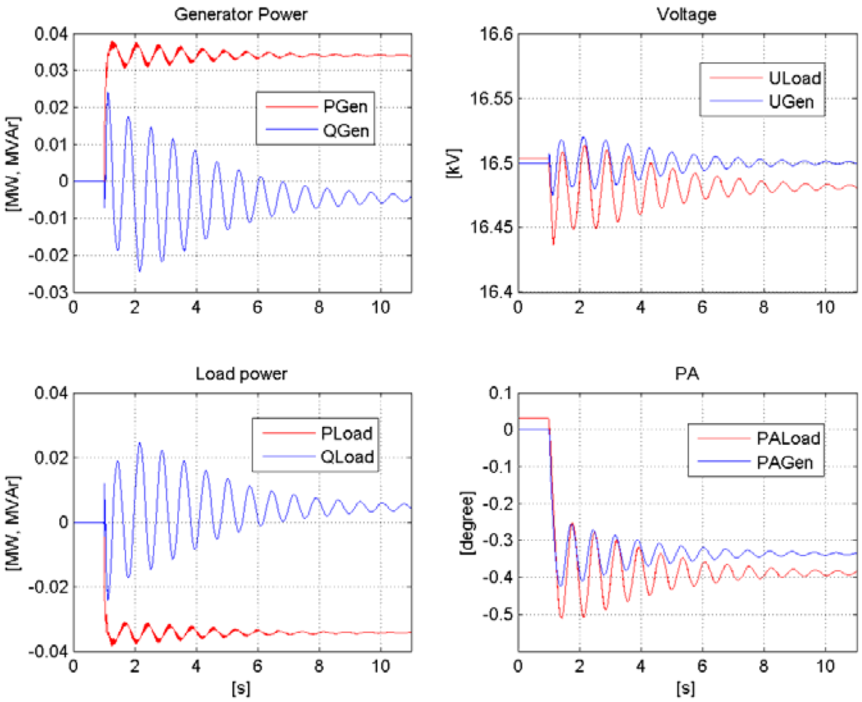
A5.4.7.1 Simulation with RL load

The following plots show the reaction of a 2.0-MW active power load step, and the comparison with the SIMPOW simulations shown in chapter A5.2.4.

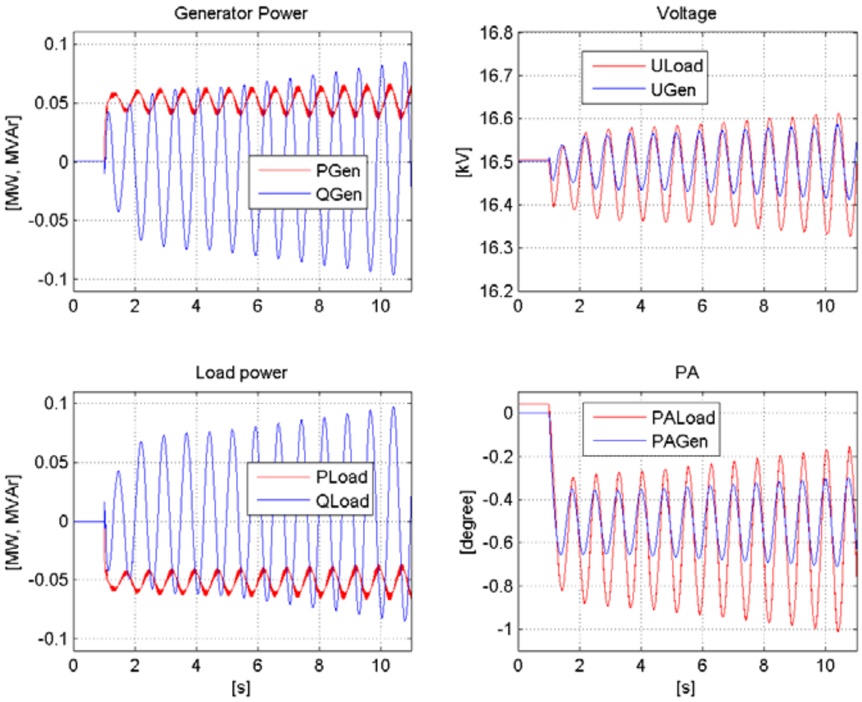


A5.4.7.2 Simulation with a vehicle

The simulation model contains one 5.8 MVA converter of type Q38 / Q39 and a 60 km long line. The structure and parameter of the vehicle model represents a modern EMU with two inverter traction units, being present in the system in a certain number.
At t = 1 second, the motor power of the vehicle is slightly increased in a stepwise manner to excite the system. The increase of active power is clearly visible at the generator. All signals show short transients with the quite well damped 1.5-Hz oscillation.



In the situation with twice the number of vehicles the 1.5-Hz oscillation is increasing and the situation unstable:



A5.4.8 Application of the model

When applying the converter model for compatibility studies, the following items shall be considered:

- The model shall help to evaluate and optimise the control structure and parameters of the inverter and traction control of electrical rail vehicles. Therefore, the simulations shall be done for various configurations of power supply and vehicle models. It must be the goal to reach a robust controller design rather than a sophisticated optimisation for one case derived from this simplified converter model.
- Typical numbers of converters are one to three, typical numbers of vehicles one to about five. A variation and combination of these numbers shall be performed until the stability limit can be derived. However, not all combinations will allow a realistic simulation for all operation points of the vehicle Example: one converter plus the maximum number of vehicles at full power and longest line length will not be a realistic case.
- Typical line lengths are between 10 and about 60 km. A line length of less than 5 to 10 km is not realistic, since in the model configuration the line impedance contains also the internal impedance of the synchronous generator.
- The parameters shall be varied also to change the eigenfrequency between 1.5 and 1.9 Hz.
- The damping ratio of the generator oscillation shall be varied between 0.03 and 0.07. The low values have been observed in situations with low load power.
- Various effects caused by different controller parts of the vehicle shall be checked, including:
    - Closed loop stability in steady state operation at zero power, half and full traction power, half and full braking power.
    - Operation under bad rail – wheel conditions with active adhesion control.
    - Line power limitation due to low or high pantograph voltage in traction and braking.

A5.5 Phasor domain model

Description and input data for a phasor model of a rotary converter including utility network can be handed over by Norwegian National Rail Administration on request.