A4 APPENDIX 4: ADDITIONAL INFORMATION FOR STABILITY STUDIES

A4.1 Low frequency power oscillations

A4.1.1 Background

- Inverter vehicles typically control the line current and the dc link voltage depending on the train's operation point and the line voltage. The involved control loop includes the substation (rotary or static), the ohmic-inductive line and the vehicle's dc link capacitors. All these elements store and exchange energy. The number of vehicles, the impedance of the line and the tuning of the controllers have a large influence on the stability margin of the control loop.
- Responsible for the oscillations are the time delays and the tuning of the vehicle controllers. With increasing line impedance and number of vehicles instabilities can occur. The resulting oscillations have an eigen-frequency up to half the line frequency (e.g. 8 Hz) and lead to low frequent variations in the line voltage (phase and amplitude), pole angle of rotary converters, dc link voltage and motor torque. An unstable situation can also lead to protective shutdown of vehicles and / or infrastructure.
- This means that if a vehicle is controlled to consume constant active power by increasing its current when the voltage at pantograph decreases it can cause pole angle oscillations in a rotary converter. The variation in current is enough to give active overhead contact line losses which may obstruct damping of the oscillation or excite pole angle oscillation in the converter (pole angle oscillations in rotary converters are mostly excited by variations in active power load which consists of both train load and transmission losses).
- There are also vehicle controllers which act in a discontinuous way, e.g. adhesion control (sudden reduction of motor torque to prevent wheel slip) or line voltage limitation (to prevent breakdown of voltage at pantograph). Such interventions provoke the power supply system to answer with a step response, which is not critical by itself. However, if the action is continued repetitively and with frequencies close to eigen-frequencies of the supply system, low frequency oscillations may occur. This effect could occur both with inverter and phase angle controlled vehicles.

A4.1.2 Definition of a simulation model

- According to earlier projects the described effects can be reproduced in time domain simulations with a good accuracy.
- The simulation model must contain all relevant subsystems. It can either be off line or based on a hardware-in-the-loop simulation including a real-time simulator and the original control units. The modelling depth must be chosen such that the critical effects can be reproduced in simulation. The model should contain the following subsystems:
    - o A vehicle model with a transformer, line converter including controller with accurate timing (time discrete implementation with sampling and delay

effects), DC link and the motor side with motor inverter including controller and motors to simulate the load.

- Line with adjustable impedance. An R-L-impedance is sufficient. The parameters are provided by the infrastructure manager (see chapter A1.5.9 and A1.5.10 of this document).
- Substation (rotary converters). The dynamic behaviour is provided by the infrastructure manager, see chapter A5 of this document. No models of static converters can be given, since they include proprietary knowledge of the respective manufacturer, but some time constants should however be possible to retrieve. Experience so far has shown that the vehicles are compatible with static converters if they are compatible with the rotary ones for all required operational conditions.

A4.1.3 Stability study

- Based on the simulation model as described above, a stability analysis of the new vehicle together with the existing power supply system has to be performed.
- It has to be shown that neither self excited oscillations due to feedback effects nor repetitive excitation of power system resonances due to discontinuous controllers occurs.
- Typical parameters for this sensitivity analysis can be taken from Appendix 1: Infrastructure data and related Information of this document. Minimum / maximum values have to be taken into account as well, but it is not necessary to combine all values to a “worst worst” case.
- The parameters (power supply, operation) on which the stability margin (and therefore the acceptance criterion) is based may be quite different for various types of operation (long distance freight traffic, or rapid mass transit) and can not be given with concrete values in this document. They have to be defined and agreed between vehicle manufacturer, operator and infrastructure manager right at the beginning of the study (EN 50 388:2005, clause 10, steps 1 and 7 of the compatibility process). They must be realistic for the planned operation, including a sufficient margin to guarantee stable operation.
- It has to be shown that the stability of the system is robust. The goal is to show that the foreseen operation is stable with sufficient margins. (Example: “It is possible to run up to 10 vehicles at the end of a 50 km long line. Only 4 are required. There is enough stability margin.”).
- Testing of the vehicle (EN 50388:2005, clause 14) will be based on the same conditions as for the simulation studies.

A4.2 Electrical resonance stability

A4.2.1 Background

- The control of the line inverter (four-quadrant power converter) of a vehicle reacts on the line voltage with short time constants, since the control e.g. has to shape the line current regardless of the line voltage waveform, or has to suppress specific frequency contents in the line current (compatibility with signalling installations). Delay times in this reaction are inevitable, due to both microprocessor control cycles and pulse width modulation (PWM).

- Seen from the power supply system, the vehicle has a frequency response of its input admittance Y(f), i.e. the ratio between line current and line voltage. If the admittance has a phase angle above / below +/– 90° (i.e. Re(Y) <0) the vehicle is „active“ on the corresponding frequency, and may excite power system or filter resonances. This leads to corresponding instabilities and overvoltages. Such resonance and instability effects occur on frequencies higher than the line frequency. Linear or linearised methods can be applied for a stability analysis.
- Note that anti-control of a frequency component in the primary current of a vehicle (e.g. a 100-Hz anti-control) can result in the fact that the vehicle is active around this frequency.
- Most critical with respect to electrical resonance stability is the lowest system resonance frequency. This is valid for all type of networks. In contact line network, this frequency is typically between 800 and 1500 Hz in central Europe, but lower in Finland, Norway and Sweden due to the system build-up in these countries, i.e. booster transformer systems. It but may be even lower if a lot of cables are installed or if the lines are very long. The lower the frequency, the worse the damping is. Natural damping is mainly caused by eddy current losses in synchronous machines and substation transformers. Excessive cabling may lower the resonance frequency to critical values.
- Typical resonance frequencies in a 132-kV network are between 100 and 200 Hz, strongly depending on the geographical extension of the network as well as on the installed generator power. High voltage networks (including autotransformer systems) are, therefore, critical with respect to electrical resonance stability. Compared to filter resonances in converter stations or vehicles, transmission network resonances are much more critical due to their lower damping.
- Both static frequency converters and vehicles can include passive filter components, in order to reduce harmonic currents produced by the converter. These filters have resonances, which can also be excited to oscillations by the line converter control of vehicles. The situation is less critical compared to resonances in contact line and high voltage lines since the filters include damping resistors.

A4.2.2 Definition of a simulation model

- For electrical resonance stability investigations with respect to vehicle requirements as defined in this document, only a vehicle simulation model is required.
- The model must have a similar form as described above for low frequency oscillations.
- It is very important that all sampling and time delay effects (controllers, pulse width modulation) are correctly included.
- The motor side of the vehicle can be omitted if no fast feedback from the motor side to the line-side inverter and current circuits exists.

A4.2.3 Stability study

- The frequency response of the input admittance of the vehicle has to be simulated with the model as defined above.
- The frequency response has to be simulated for different operation points (typically zero power, maximum traction power, maximum braking power).
- As long as the vehicle holds the requirements as defined in the main part of this document (section 6.5.2) no simulation of the power supply network and other vehicles is necessary. If a vehicle can not hold this requirement, a full stability study according to EN 50388:2005, clause 10, has to be performed in order to demonstrate that the vehicle is stable together with the railway system.