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General Problems of AC-AC Traction

This note describes very shortly the 4 most important general problems related to railway vehicles with AC-AC propulsion system and 4-quadrant line converters.

1. Amplification of PWM Harmonics

The impedance characteristic of the overhead line (OHL) and catenary system of an electrified railway is characterised by:

- Series inductance and series resistance
- Capacitance and conductance to earth

This transmission line characteristic causes distinct series and parallel resonances, meaning that the impedance is alternately inductive and capacitive along the frequency axis.
The resonance frequencies depend on numerous factors, such as the length of the line feeding section, the configuration of the OHL, other elements such as the supply transformers, feeding cables, any station or depot tracks, etc., etc. In other words, the resonances can occur at any frequency, and the resonance points moves in case the line is reconfigured (e.g., if a substation is disconnected due to a failure).

Against this, the impedance of a vehicle is characterised by the almost purely inductive main transformer, except for the case of a vehicle equipped with a harmonic filter.

The combination of a capacitive (at certain frequencies) line and an inductive vehicle causes electrical resonances. If such a resonance happens to be located exactly at a frequency of a dominating harmonic in the voltage spectrum of the 4-quadrant line converter, then this harmonic will be amplified, thereby causing excessive levels of voltage and current distortion as well as psophometric currents.

The semi-discrete nature of this problem (the maximum amplification occurs only at certain conditions) necessitates a thorough test program supported by theoretical analysis. The fact that a vehicle performs well at certain conditions does not necessarily mean that it is acceptable at other conditions as well.

The possible countermeasures are:

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- Interlaced switching of more 4-quadrant converters, thereby reducing the generation in the first place
- Higher transformer inductance, leading to a better damping of the line-vehicle resonance
- Damping of the resonances by adding resistance to the system, in the form of filters
- Increased switching frequencies, however, this might just move the problem to another frequency band

2. "Active" Vehicle Impedance and Control System Instability

In general terms, the 4-quadrant line converter (4QC) controls the power flow to/from the vehicle by controlling the voltage drop across the main transformer leakage reactance. The 4QC does this by measuring the actual line voltage, adding (with an appropriate phase angle) the said voltage drop, and letting the result serve as the 4QC bridge voltage reference.

However, this control does not only operate at the fundamental frequency of 50 Hz or 16 2/3 Hz. It is obviously active over a wider frequency range. In addition, due to the sampling process of the digital control, time delays and thus phase shifts are introduced.

The combined effect of this is that the input impedance characteristic of the vehicle seen from the line is mainly determined by the digital control system, in particular in the lower frequency range.

Due to:

- The already mentioned sampling process
- The flashy technical solutions that some control systems engineers tends to build into their system (harmonic anticontrol to take an example)
- Pure "accident", e.g., in case parts of the control software is written by computer experts, not traction engineers,

this input impedance characteristic of the vehicle may take almost any shape - high impedance here, low impedance there, inductive here, capacitive there.

In the most critical cases, the impedance characteristic shows negative real parts at some frequencies ("negative resistance"). In such cases, the classical control system stability criteria (e. g., the gain must be < 1 at a phase shift $\geq 180°$) can easily be violated.

Such control system instability can occur between the vehicle and an empty line, but also between different vehicles. The phenomenon has (among other places) been seen in Switzerland, as described in Eisenbahn-Revue 7-8/1999.

Due to the complexity of the system - and even small details play a significant role - it is hardly possible to perform a purely theoretical analysis of the system, or to model it for simulation by means of tools like Simulink. On the other hand, it is difficult to measure the input impedance of an already existing vehicle, due to the high voltage and power level.

The problem of inadequate "active" vehicle impedance and control system instability is by far today's biggest challenge for the overall railway industry, in relation to EMC and functional compatibility.

3. Interharmonic Modulation and "Harmonic Avalanche"

With the variable frequency control of the AC motors, the vehicles are in fact equipped with a powerful source of signal interference currents at interharmonic frequencies such as 75 Hz. If the 3-phase inverter generates a harmonic at say 125 Hz on its DC side (i.e. e., into the DC link of the propulsion system), then this 125 Hz component is modulated by 50 Hz by the 4QC, thereby producing 75 Hz at the line side.

While on one hand it is the general impression of the author that the criticality of a return current at a certain frequency with respect to wrong-side failures of the track circuit is often somewhat overstated, there are on the other hand two reasons why a simple measurement of the interference currents produced by a vehicle at some random conditions is not a sufficient demonstration of compliance:

- Certain failure conditions within the propulsion equipment will cause an increased generation of interference, but not any other reaction such as protective shut-down

- The 4QS control system plays a dominating role in the modulation of harmonics from the DC link to the line side. This has often been overlooked by traction engineers, who calculate the modulation at what they call steady-state (i.e., a constant 4QC reference signal). However, it is important to notice that due to the various (and strong!) feedback loops (from DC link voltage, bridge current, line voltage, etc.), the very presence of a DC link ripple makes in itself the assumption of steady-state illegal!

For the same reason as mentioned earlier (the complexity of the 4QC control system), the said coupling through the control system is difficult to analyse or model with any accuracy. So very generally speaking: A traction engineer cannot predict the level of interharmonic generation from a vehicle that has not yet been built.

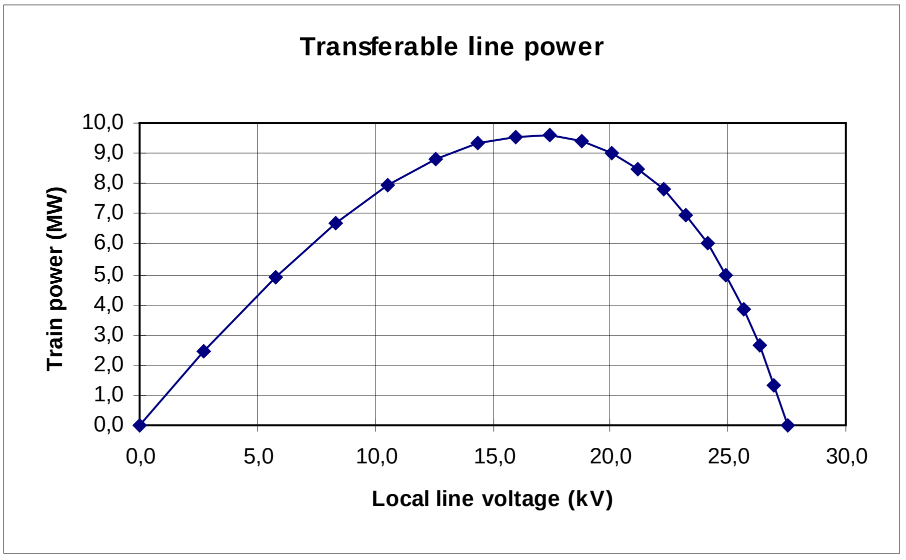
On top of this comes the problem of "Harmonic Avalanching": A harmonic in the line voltage can be modulated through the 4QC, appearing at 50 Hz distance in the DC link voltage. It is then modulated to the line side again by another 50 Hz, thereby occurring at a distance of 100 Hz from the original frequency. In principle, this process can go on forever, thereby producing more and more components. Even the

3-phase motor inverter can take place in this, modulating DC link ripple by the stator frequency.

It is likely that the "Harmonic Avalanche" effect is rather weak at normal conditions. But considering the resonant character of both the line and the DC link, and the nonlinear frequency response of the 4QC control system, this need not always to be the case.

4. Power Control and Line Voltage Collapse

The relationship between 50 Hz line voltage locally at a vehicle, and the power transferred to that vehicle, is shown in the figure below, at a certain line length and line impedance, with cos(φ) at the vehicle = 1.



It is noticeable that an AC-AC vehicle cannot operate at the left side of the peak of the curve. This would create a positive feedback in the overall control loops, and cause a rapid collapse of the line voltage.

This means that the vehicle must be equipped with some kind of trail-and-error control, aiming for maximising the power on weak lines: As close as possible to the top, but never above.

In case several different vehicles, each with their own control strategy, operate on the same weak line, then it is likely that one will fail, and cause a voltage collapse. This will cause significant disturbances of the traffic, and is clearly a problem in the case of disconnected supply stations and extended feeding conditions.

Again, acceptance testing of the vehicle must not be restricted to the normal condition, and to the vehicle operating on its own.