CONTROL OF TRACTION SUPPLY POWER QUALITY USING LOCOMOTIVE PWM CONVERTER CONTROLS

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Abstract

Railway traction systems are highly susceptible to severe harmonic distortion, poor voltage regulation and line resonances. Electric locomotives, which are concentrated high power loads, move continuously along the supply line, rendering the topography of the supply system, a time-variable. Under those conditions, the resonant impedances vary as the traction vehicle moves along the track. Parallel resonances with feeder line inductance and capacitance between feeder line and earth, cause harmonic magnification. This paper will examine the use of small retrofit converters to improve the performance of multiphase PWM rectifiers as found in locomotive applications.

1. INTRODUCTION

Railway traction systems have significantly higher impedances than transmission systems of the same power level. As the overhead system is only used at its peak capacity for short periods of time, losses are less significant from an economic viewpoint. Higher regulation figures must be tolerated. It is usual to see variations in overhead supply voltages of +10% and –30%. As the overhead system serves a dedicated application the normal limitations on distortion do not apply. Voltage distortions may reach 10 or 20%. The issues that are important for single-phase railway applications include, [1-3]:

- A desire to increase traffic and distance between substations while maintaining the regulation limits of +10% and –30%
- The absolute need to control the effects of harmonic currents on signalling circuits, especially track occupancy systems that use audio frequency signals
- The need to avoid unexpected equipment failures due to harmonic effects - locomotives have experienced failures in switched power factor capacitors and insulator flash overs due to increased peak voltages do occur.

A particular issue with railway overhead systems is that harmonic resonances due to transmission line effects. In higher power applications, a 25kV system voltage is widely used. Substations are typically placed up to 70km apart. A locomotive midway between substations will see very high levels of transmission line impedance at frequencies corresponding to an electrical quarter wavelength of 35km and odd multiples of this frequency. The first, and lowest frequency resonance should occur around 2.1 kHz. Recent trends in locomotive designs have included the use of PWM based rectifiers to achieve the following benefits:

- Improved power regeneration capabilities to allow energy recovery while braking
- Control of reactive power to assist in overhead voltage regulation
- The reduction in lower frequency harmonic currents, hopefully improving overhead voltage wave shape.

The advantages of PWM rectifiers do however expose the locomotive to the possibility of overhead system resonance. Even if the locomotive switching frequency is lower than the expected lower resonance frequency, current harmonics at multiples of the switching frequency can often have enough magnitude to cause problems. Current magnifications of 20 fold have been reported due to this effect, [4-5].

2. LOCOMOTIVE RECTIFIERS

Locomotive PWM rectifiers often use as many as six parallel modules, supplied by individual windings on the locomotive transformer to raise the effective switching frequency. SIMULINK and the MATLAB Power Systems Block Set has been used to model four phase-shifted converters, using nine pulses per half cycle to produce interleaved PWM as shown in Figure 1. The corresponding spectrum is seen in Figure 2. The PWM converter waveforms are most often combined in a purpose designed traction transformer with multiple secondary windings. The multiple secondaries are designed for relatively high leakage reactance allowing the converters to switch independently. The use of multiple converters not only improves lower order harmonic performance but allows a level of redundancy.

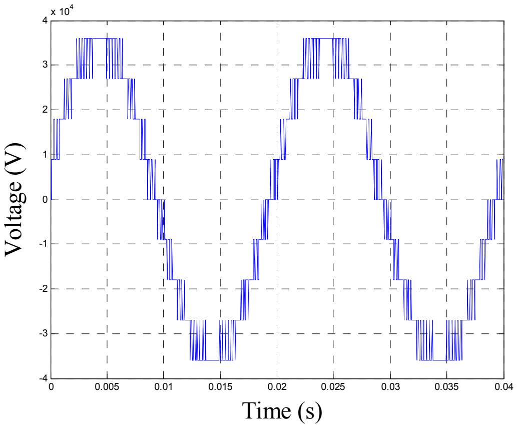


Figure 1 Effective PWM Voltage

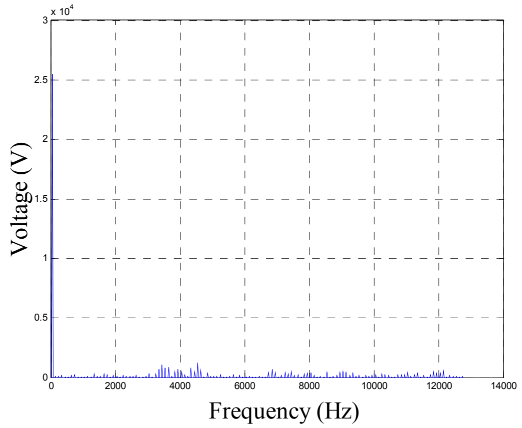


Figure 2 PWM Voltage Spectrum

Figure 3 shows the locomotive current for a typical regeneration case. While this waveform appears to have negligible distortion, and this is confirmed by the current spectrum in Figure 4, the switching frequency terms now can fall squarely in the areas where resonances can occur.

The resulting supply voltage waveform and spectrum for a practical case are shown in Figures 5 and 6. Significant over voltages are observed. The physical arrangement of the supply system and locomotives is described by Figure 7. In this case a conventional thyristor rectifier equipped locomotive, drawing approximately 2.5 MW and a PWM locomotive, regenerating 3.7MW are placed 33.5 km from a substation. The overhead system is representative of a 25kV/50kV autotransformer supplied system. The overhead transmission line parameters are, [6]:

- R = 0.15 Ω/km
- L = 1.4mH/km
- C = 8.1 nF/km.

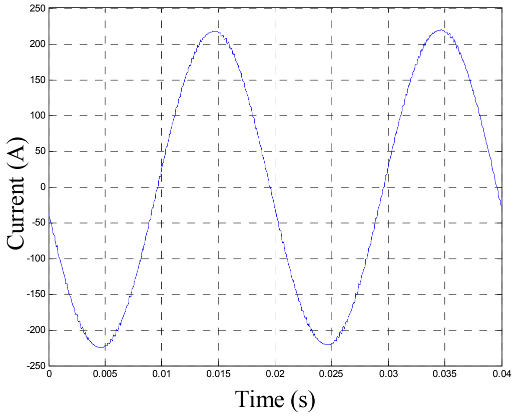


Figure 3 PWM Locomotive Regenerated Current

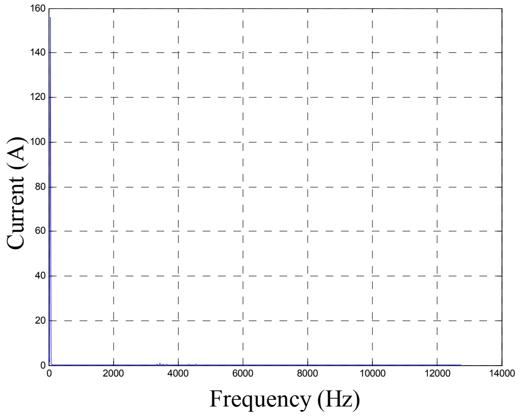


Figure 4 Regenerated Current Spectrum

Frequency	**λ/4**	**3λ/4**
3 600Hz	20.8km	62.5km
7 200Hz	10.4km	31.2km

Table 1 Quarter Wave Resonance Lengths.

The four interlaced nine pulse per half cycle PWM rectifiers produce small but significant switching terms around 3.6kHz and its multiples. Some resonances and their corresponding free space wavelengths are shown in Table 1. The switching frequency components are distributed as sideband families, [7], as a consequence resonant effects of varying severity will occur for some kilometers around these points. The case at hand shows a 3λ/4 resonance excited by the PWM components at twice the converter basic switching frequency.

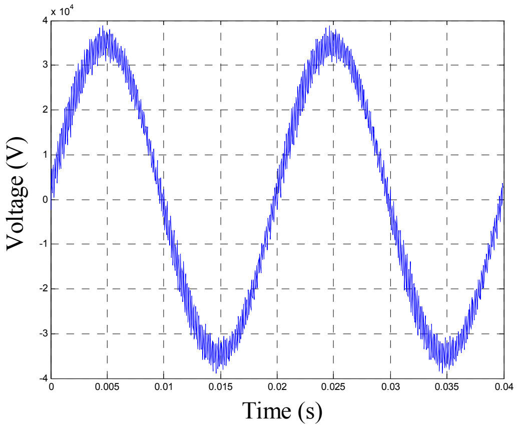


Figure 5 Overhead Voltage – Undamped

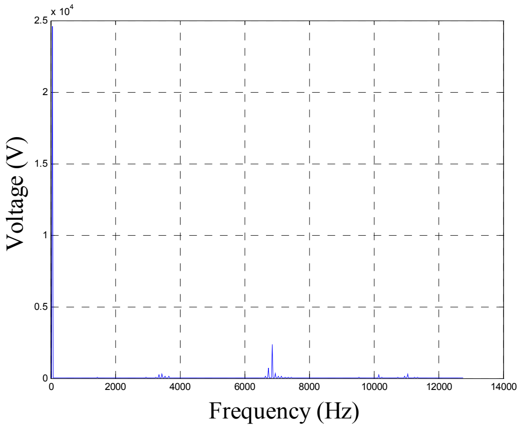


Figure 6 Overhead Voltage Spectrum

3. PASSIVE RESONANCE CONTROL

One solution has been to place damping networks on the overhead system, these reduce the resonance effects but do so at some expense and power loss, [8]. Figure 8 (a) shows a passive damper using a 1μF capacitor and 250Ω resistor. This network provides high frequency damping with a corner frequency of 670Hz and is representative of traditional passive solutions. As Figure 9 shows, the network is very effective in damping the resonance effects, nothing of note can be seen in the voltage spectrum.

While the solution is reliable and robust, the capacitor rating is 190 kVAR, and the resistor dissipates approximately 14.4 kW. The resistor voltage waveform, Figure 10, shows a significant 50Hz voltage component. This generates the majority of the losses. The next section will examine the use of small retrofit converters to improve locomotive performance. The proposed method is to have the high frequency converter mimic a resistive behavior for higher frequency harmonics by sinking currents in proportion to the distortion voltage while ignoring all fundamental frequency components.

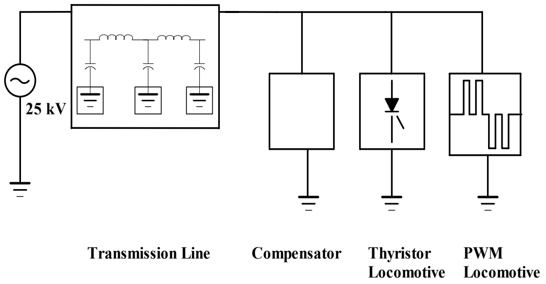
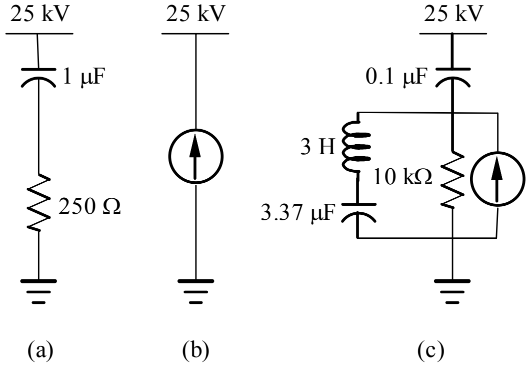


Figure 7 Physical System



Proposed Compensators

Figure 8 Damper Networks

4. ACTIVE RESONANCE CONTROL

A controlled current source can be directly connected across the 25kV system, as shown in Figure 8(b). The current source provides resistive damping at all frequencies other than 50Hz. A suitable converter control is shown as Figure 11. A 50Hz notch filter removes the fundamental component of the supply voltage waveform to reveal any distortion components on the overhead supply. The notch is implemented by using a synchronous transformation – all fundamental components are frequency shifted to DC by multiplication with fundamental sine and cosine terms and low pass filtering. Second order low pass filters are used with a 100r/s corner frequency and $\zeta=1$. Re-multiplying the low pass filter outputs by sine and cosine terms recovers the fundamental. This is subtracted from the supply voltage to reveal all distortion terms. The distortion voltage is used to generate a demand signal for a controlled current shunt filter element. The distortion voltage is simply divided by a fixed damping resistance value, 250Ω in this case.

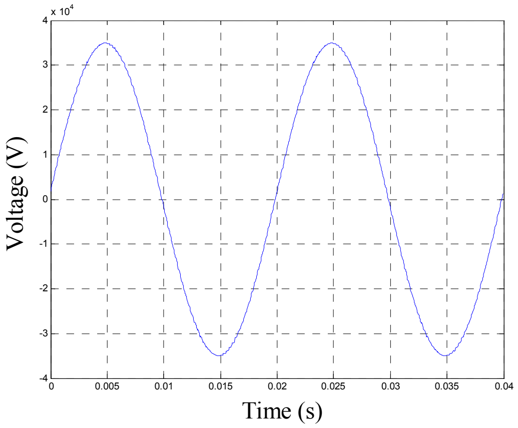


Figure 9 Bus Voltage – Passively Damped.

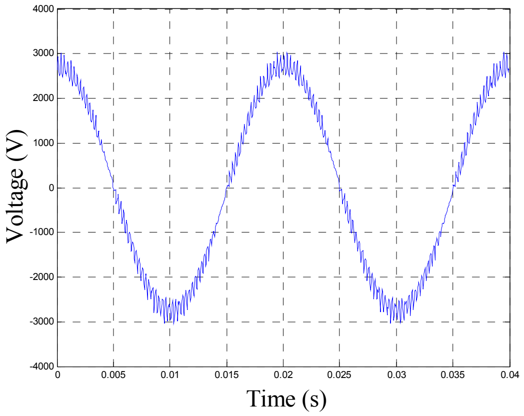


Figure 10 Damping Resistor Voltage Waveform

The shunt element effectively appears as a resistive element at all frequencies other than the fundamental and automatically damps any resonance effect. The bus voltage is not distinguishable from the passively damped case. The active damper current and its spectrum are shown as figures 12 and 13. The major ripple current components of the main converter can be seen at 3600 and 7200 Hz. The current rating of the damping converter is clearly determined by the main PWM converter ripple current. These will divide between the damper and overhead network according to their relative impedances.

While these currents are low, these simulations have shown that significant over voltages are still possible. More importantly, very stringent restrictions on high frequency currents do exist when locomotives must operate in regions where audio frequencies are used for track occupancy detection. In a current locomotive refurbishment program, Queensland Rail has set a total locomotive current limit of 100mArms for the frequency band 3kHz to 5 kHz to avoid disruption to their signaling systems, [8]. Clearly the on board passive damper provides a mechanism for reducing these signal system disturbing currents.

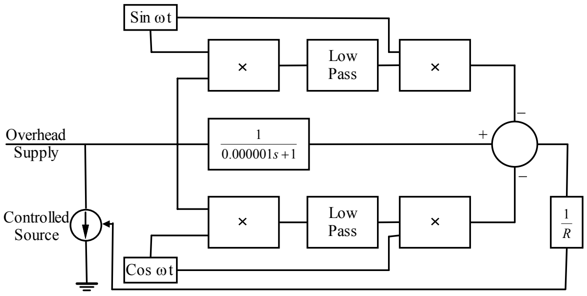


Figure 11 Active Damper System

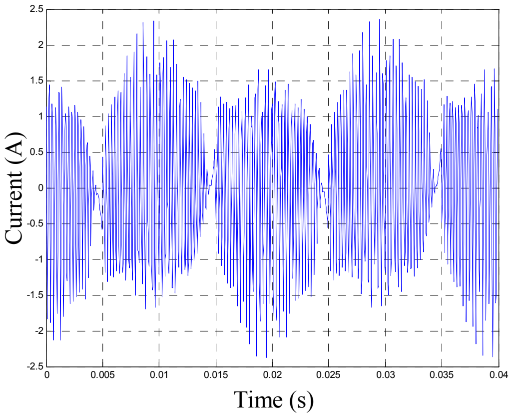


Figure 12 Active Damper Current Waveform

The RMS value of the damper current is quite low, 0.95Arms. However the damper device is subjected to the full supply voltage, resulting in a rating of approximately 24 kVA. This reduction of this rating will be illustrated by the use of a coupling network to remove the fundamental voltage from the damper in the following section.

The controlled current source would be implemented as a high frequency switching converter. Phase shift considerations dictate a switching frequency above 100kHz. In this paper, for the purposes of illustration, a linear model is applied. It will be shown that the ratings of the switching converter can be quite small, especially in the hybrid cases discussed in the following section.

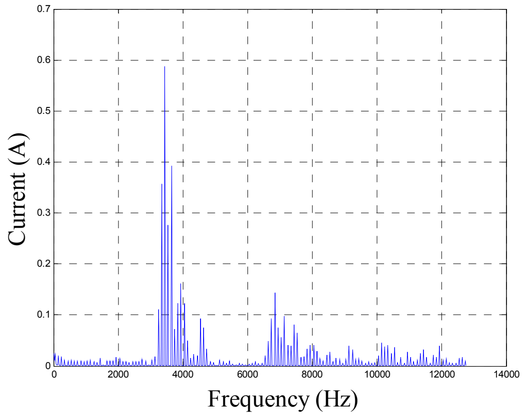


Figure 13 Active Damper Current Spectrum

5. HYBRID CONTROL APPROACHES

The active component rating can be reduced by the use of a coupling network to remove any fundamental frequency components from the active device. Figure 8(c) shows this approach. The coupling capacitor has been reduced to 0.1μF. The controlling factor is the voltage requirement of the controlled current source. The reactance of this capacitor, and the damping element current of 0.95Arms, results in approximately a 500Vrms requirement for the active element. The active device rating is approximately 475VA. The 50Hz coupling capacitor rating is much lower than in the passive damper case, approximately 19kVAR. The fundamental capacitor current, 0.76 Arms, is diverted to a series resonant branch, L = 3H, and C = 3.37 μF. These have 50Hz ratings of 500VA each. A small parallel resistor was found necessary to stabilise the closed loop damper system. A 10kΩ resistor is used and dissipates 24W.

The coupling network can be implemented with a wide range of component values and it is likely that the network can be optimised for a specific application. A key consideration will be the operational range of frequencies to be compensated. Larger coupling capacitors, and lower coupling reactances, may lead to lower converter ratings for lower frequencies.

Again, Figure 14 shows the bus voltage waveforms are well damped and no resonance effects are observed. Figures 15 and 16 show the current and voltage waveforms for the damping element. The damper current spectrum, shown as Figure 17, is very similar to the active damper case. As the converter is a current source, its terminal voltage adjusts to maintain the same waveform shape. Once again the main PWM converter distortion components are clearly visible.

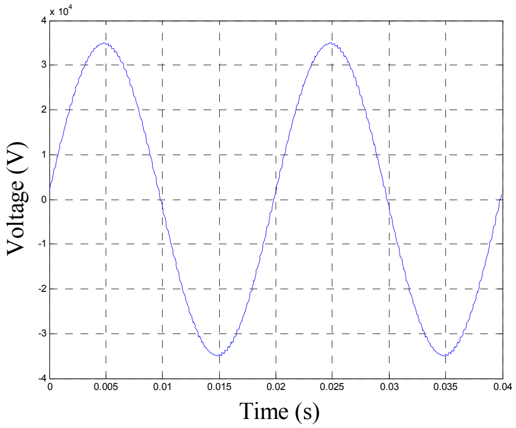


Figure 14 Bus Voltage - Hybrid Damper

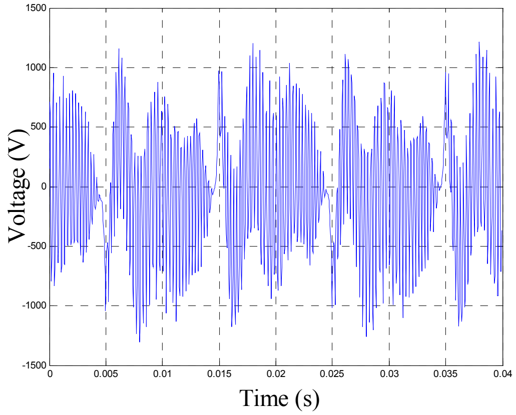


Figure 15 Current Source Voltage – Hybrid Damping

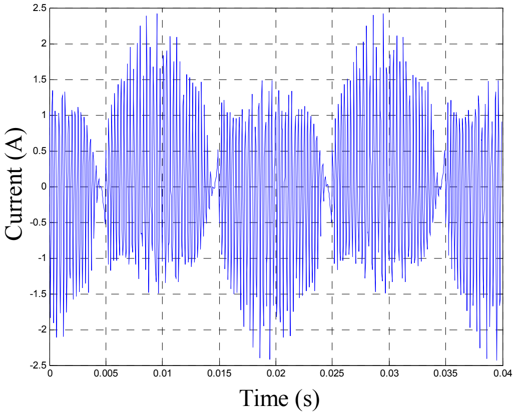


Figure 16 Hybrid Damper Current Waveform

It is worthwhile reflecting on the damper ratings. These are extremely small, given the total converter rating, 2.5 MVA. The extremely low rating, four orders of magnitude less than the main converter, is a consequence of:

- The low value of the main converter ripple current – around 1% of rating
- The removal of the 50Hz components from the damper converter.

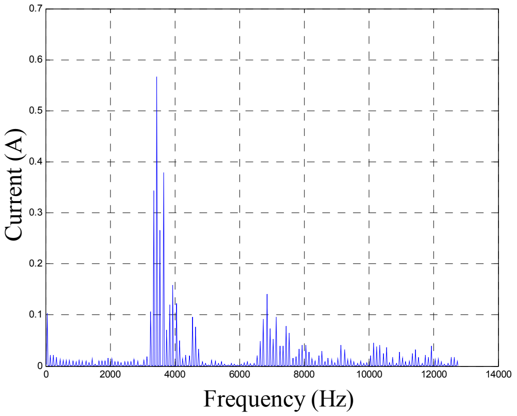


Figure 17 Hybrid Damper Current Spectrum

6. CONCLUSIONS

The introduction of PWM converters into the railway systems has posed significant challenges with respect to supply system resonances and strict limitations on high frequencies currents imposed by track signalling systems. Some solutions to these challenges, other than the use of passive dampers are presented. Hybrid filters can result in effective damping with very small active components.

Further work is required on the study of this approach to deal with several practical issues. The design needs to be extended to fully consider the entire frequency range of power supply distortions including lower frequency harmonics. A capacity to deal with these will affect the design of the coupling network and the converter ratings.

It is practically important to study the operation of locomotives with one failed main converter. As a reliability issue a locomotive must be able to continue at reduced tractive effort. This forces either automatic reconfiguration of the modulation methods used in the individual bridges to retain harmonic cancellation, admittedly at a lower pulse number or operation with much increased ripple currents. These cases will require higher currents from the damping compensator. A key issue is the need to guarantee that the limitations imposed on track signalling circuits, a safety critical system, will not be exceeded.

Finally, several manufacturers are exploring the use of random modulation methods to spread the current spectrum in an effort to reduce the excitation of system resonances, [8]. This will potentially affect the ratings of the active damper systems and will be an area of further work.

7. REFERENCES

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