An Elegant Solution Using Hybrid Power Filter to Improve the Line Current Spectrum of Multiphase PWM Locomotive Rectifiers with Load Unbalance

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ABSTRACT

Locomotive PWM Rectifiers employed in A.C traction systems represent several megawatts of electrical load. Typically they use multiple rectifiers/converters in parallel in order to secure high power ratings and high frequency operation. The rectifiers are supplied from a single-phase A.C. traction transformer with multiple secondaries of high leakage inductance. The switching instants of the PWM rectifiers are phase shifted and interlaced in order to achieve high ripple current cancellation, assuming that the converter loads are balanced. This would ensure the rectifiers to provide better harmonic performance and also redundancy of operation with multiple units in operation. However, in practice, rectifiers may be closely coupled to a traction inverter supplying an axle or a group of axles and the real power developed will depend upon the traction conditions. Creep and slip can give rise to variations in power and perfect power balance at the rectifiers is an improbable proposition.

There is high degree of interest to examine the possibility locomotive systems that degrade gracefully with equipment failure. Failure of one traction inverter would lead to load unbalance for the rectifier modules. Or sometimes, partial failures may result in unbalanced operation which can cause reduced ripple current cancellation and generate switching frequency harmonic current components. This may adversely impact the signalling systems and/or result in over voltage effects due to resonance in the overhead supply system. This paper examines a 4 MW locomotive with three rectifier modules and a device switching frequency of 900 Hz. This results in a 5400 Hz ripple frequency in the mains current. And this paper will consider what may be the most frequently occurring case; that of loss of load in one traction motor due to wheel slip. Current ripple cancellation is partially lost in this case and lower frequency current components can be produced. Traditionally, number of solutions has been employed in the industry like passive filters, active filters etc., for this type of a problem. However, this paper explores an elegant, attractive and economical solution of using hybrid filters in order to achieve a level of acceptable satisfactory harmonic performance and thereby improving the power quality of the rail systems.

1. INTRODUCTION

Pulse Width Modulated Rectifiers offer quite popular choice of selection over other conventional rectifiers in AC traction applications. They provide number of attributes to the power system like regenerative power capability, better power factor, reactive power control and reduced harmonics. PWM traction converters operate in multiple units at megawatt power levels to achieve high power and high switching frequency operation. The use of multiple converters not only provides better harmonic performance but also allows a higher degree of redundancy.

Under normal conditions, it is expected that the rectifier operations are power balanced in order to ensure ripple cancellation. However, in normal practice, with several PWM converters in operation, such a condition is not always feasible. Some degree of unbalanced operation of multiple converters might be expected. This will influence the overall performance of the traction system. There has been great deal of interest in the traction systems to investigate the problem of equipment failures and the ways of achieving a graceful degradation to improve the performance of rail systems. This forms the rationale as well as the motivation to study the issue, in this paper.

Mechanical friction, traction motor unbalances, on board filter resonances, static converter switching and interaction between locomotives operating at different frequencies are some of the major concerns of low frequency harmonic injection of traction vehicles into the feeding overhead line. Switching frequency harmonics, although are small in magnitude, can be quite significant due to their interference with the railway line communication and signalling systems and result in over voltages in the overhead system due to resonance effects.

The adverse effects of harmonics can pose serious threat to both smooth running of train operations as well as economic suppression of harmonics. Valid power quality management [9] and early prediction of harmonics in the line currents become vital issues. There is a significant probability that the permissible harmonic limits and thresholds [1, 2] stipulated by the regulatory authorities, on the signaling systems may be exceeded.

Railway signalling systems are quite sensitive over a specific range of frequency, especially for power frequency track circuits. And the harmonics generated by the PWM rectifiers, due to the load unbalance, might fall into the similar range and can cause great concern to the safety related issues.

It is quite worthwhile to note that the lifetime of the locomotives is around 30-40 years and the old generation locomotives would continue to be used, even in future for quite some time and therefore the suppression of the harmonic currents continues to be a hot topic area in the years to come.

Line current harmonics can cause over heating of power system components and might trigger protective devices prematurely. This calls for an effective as well as an economically viable cost effective industrial solution for the 'harmonic filtering' and 'harmonic suppression' issues in rail power systems, since they are quite crucial from the safety point of view. This has to be achieved without any degradation of the existing normal operation of the rail systems, which might even pose greater challenges to the safety and security issues.

Accordingly, it is quite important to investigate robust ways of improving the line current spectrum of the AC traction power systems. This may be achieved with better harmonic controls under such adverse unbalanced conditions of operation.

There have been number of conventional approaches for harmonic suppression using power filters like passive filters, active filters etc., however, this paper explores the possibility of employing an elegant solution using a hybrid power filter for the compensation of unbalanced operation of traction power converters in the locomotives. The Hybrid power filter provides a desirable cost effective solution to the rail industry and also improves the harmonic performance of the converter under unbalanced conditions, reducing the impact on the rail systems.

2. HYBRID POWER FILTERS

Hybrid filters are seen as the most viable cost effective alternative for improving the line current spectrum of the converters. A hybrid filter can provide an economical solution to the harmonic suppression of converter harmonics, in which the active elements work like variable fictitious elements to dynamically adjust the performance of the passive filter systems. Converter loading unbalance can be corrected by employing hybrid filters.

By improving the compensation characteristics of the passive filters, hybrid filters get a reduction in the rating of the active filter. The VA rating of the active element can be reduced drastically to reduce the power losses. It provides an alternative economical approach to the harmonic filtering in order to retain an acceptable level of harmonic performance without compromising the power quality.

It is an important alternative to improve the line current performance, when supplying high power non-linear loads. The mains power supply needs to supply only the fundamental component of line current, thereby improving the power quality of the supply system [3].

A hybrid filter is an integrated model of the passive and active filters. Hence, the main features as well as the benefits of both the active and passive filters can be fully exploited by employing the hybrid filters for harmonic filtering applications in the rail systems. Hybrid filters have developed as a natural progression of developments from the purely passive tuned filters. They use a combination of passive elements to reduce the ratings of the active elements. Such an approach covers an entirely different topology for the harmonic suppression of traction systems, which can contribute to great difference from the performance and economy points of view in the rail industry.

Hybrid active filters inherit the efficiency of the passive filters and the improved performance of the active filters and thus constitute a viable improved approach for harmonic compensation. They can provide a quite robust approach to the harmonic suppression problem in rail power systems. At the hybrid filter, the passive filter constrains the harmonic currents generated by the load and the active filter improves the filtering characteristics of the passive filter. The coordination and cooperation of active filters and passive filters in such an integrated approach takes a vital role for performing effective compensation.

A hybrid filter in the association of active and passive filters, can offer an elegant solution, where the active filter acts as impedance inserted in the system, changing its harmonic behaviour. The aim is to combine the passive filter robustness with active filter performance, improving the system reliability.

3. LOCOMOTIVE PWM RECTIFIERS

Multiphase locomotive PWM rectifiers for traction applications have become quite attractive as the technology has matured progressively. Although they have significant merits, the PWM rectifiers do expose the system to the possibility of interference. Locomotive PWM rectifiers typically employ parallel converters supplied by multiple windings of a traction transformer with high leakage inductance. The switching of the converters is phase shifted to provide ripple cancellation. Under unbalanced conditions, the cancellation effect is reduced and switching currents may exceed the limits. This paper will examine a typical case which is the most commonly occurring reason for unbalanced loading of the converters.

This paper presents a case study using a full SIMULINK model of 4MW Locomotive with three independent PWM converter modules, each supplying a pair of traction inverters and other induction motor loads. The PWM device switching frequency is selected as 900Hz and there are three converter bridges in the model, resulting in a ripple frequency of 5400Hz.

4. BASIC CONVERTER OPERATION

A detailed study and analysis of the converter model for a 4MW locomotive has been carried out in MATLAB and SIMULINK. Considering a typical traction load of about 4MW, for the three converters under consideration, under balanced load conditions, each converter is loaded to 1.33MW under full load. The separate rectifier outputs allow easy isolation of a failed rectifier or an inverter.

The block diagram of the complete traction system is shown in Figure 1. The physical arrangement of the traction converter system under consideration, along with its three PWM power converters, is shown in Figure 2.

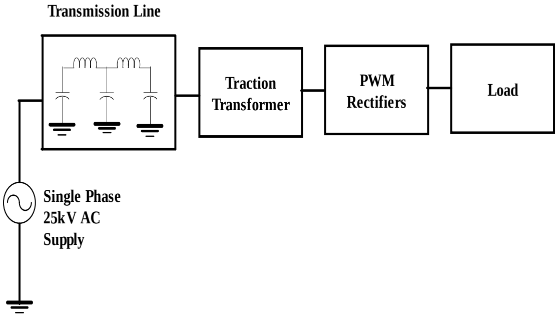

Figure 1. Block Diagram of the Traction System Model

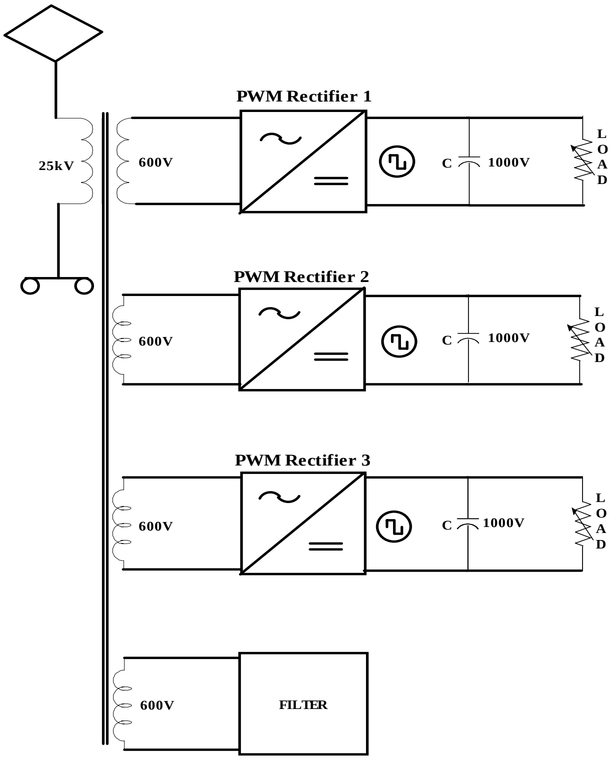

Figure 2. Physical arrangement of Traction Converter System

5. PWM MODULATOR/SYMMETRICAL SWITCHING CONTROLLER MODEL

Each PWM rectifier is a full bridge converter, which operates as a boost mode rectifier as shown in Figure 3. The B4 Bridge is universally employed since it is very well suited to high power operation.

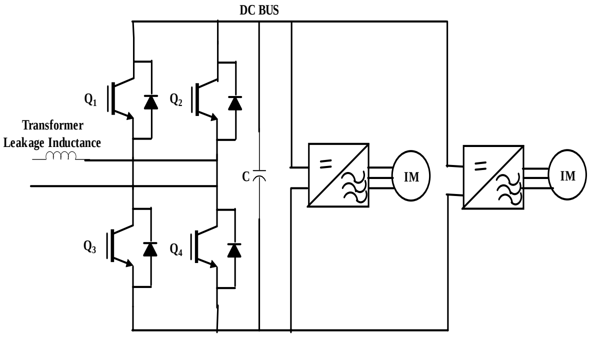

Figure 3. Rectifier and Inverter Group

Naturally sampled PWM is used with PWM switching instants being determined by the intersection of a reference waveform with a symmetrical triangular carrier waveform with a frequency of 900Hz. The triangular carrier waveform is phase displaced for each of the three rectifier converters to produce ripple cancellation.

Each bridge rectifier incorporates a predictive current controller scheme, where at the beginning of each switching interval a total volt-second requirement is calculated for each bridge to force the input current to track a reference with zero error.

The bridges follow a sinusoidal current demand signal that is generated by the locomotive DC bus voltage regulator, which determines the real power required to control the DC voltage. The power signal is determined using a reference model following controller [4], which produces a harmonically clean sinusoidal demand signal. As the locomotive application is single phase the DC bus has significant 100 Hz ripple and this does cause difficulties with other control schemes [4]. Hence, model following controller scheme is selected for this application.

Under a balanced case of converter operation the total pantograph line current waveform for the three, phase shifted converters, its line voltage waveform and the total line current spectrum along with its single converter's waveform are shown in the following figures.

Figure 4 shows the currents drawn by one of the three converters on the 600V secondary winding. The switching components are quite evident in this waveform. Significant current cancellation is shown in the total pantograph current shown in Figure 5. This current is measured on the transformer primary side.

Figure 6 shows the pantograph current spectrum for the balanced case. A small current component at 5400Hz should be noted.

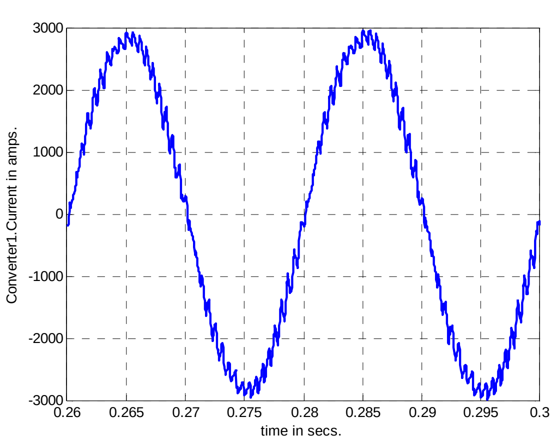

Figure 4. Single Converter Current Waveform (PWM Conveter1 Current waveform)

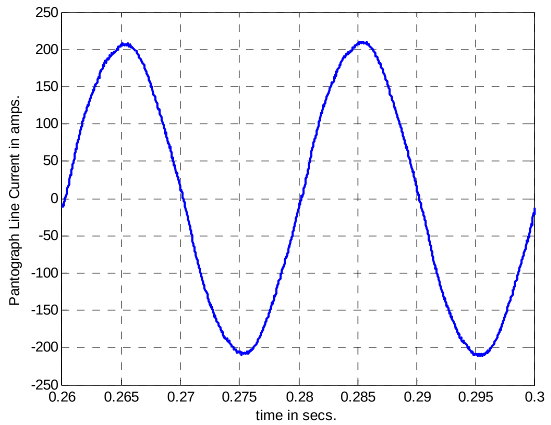

Figure 5. Pantograph Line Current waveform With phase shifted PWM Converters

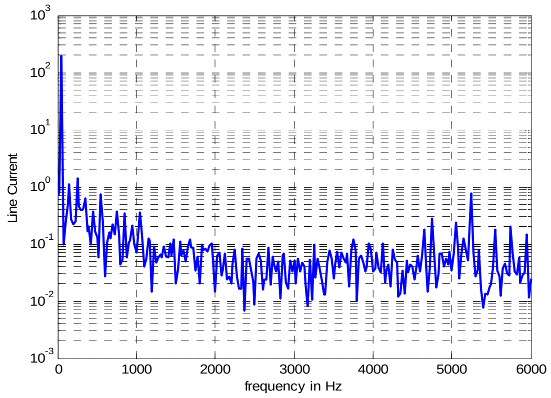

Figure 6. Pantograph Line Current Spectrum for balanced case of phase shifted PWM Converters

Figure 7 shows the pantograph voltage and some harmonic voltage amplification is visible with a dominant frequency of 5400 Hz. In this simulation, the line length was chosen to be 3/4 wavelength at 5400 Hz to purposely demonstrate the resonance effect.

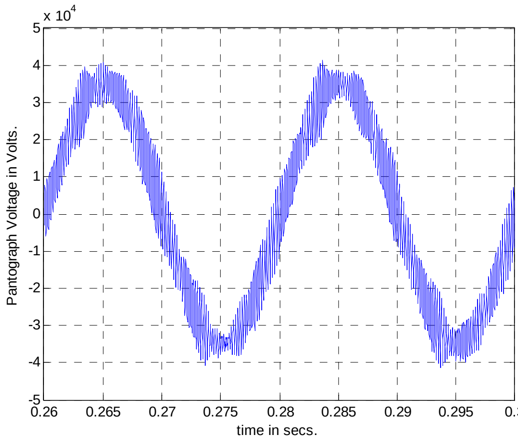

Figure 7. Pantograph Line Voltage Waveform

Figure 8 shows the line current components between 1000 Hz and 2000 Hz. The currents are determined by capturing two cycles of the line current, determining the FFT, zeroing all components outside of the frequency range of interest and reconstructing the 1000 – 2000 Hz current using the inverse Fourier transform (IFT). An evaluation of RMS value of Line Current shows that 448 mA rms already exists even in the balanced case.

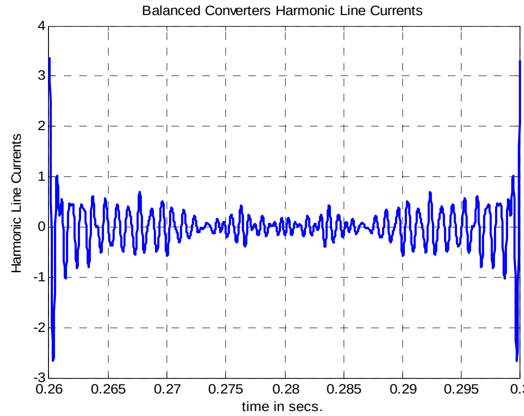

Figure 8. Harmonic Currents for the Balanced Converters for the frequency range of 1 kHz-2 kHz

These currents are surely small in magnitude compared to traction currents, approximately 160A, but already large enough to be of sufficient concern for railway signalling. This situation deteriorates substantially with converter loading unbalance, which is discussed below.

If there is loss of load in one traction motor due to wheel slip or when one of the inverters fails, the rectifier loading is unbalanced. Under such an eventuality, which is a most frequently occurring case of failure in general, two of the rectifier units are fully loaded to 1.33MW, while the other unit is only half loaded to 0.665MW. For such an unbalanced case, a comparison is carried out with the balanced case and it is represented in the following figures and discussion.

Figure 9 shows the current waveform for the lightly loaded converter. The reduction in power is evident as the current is half that of Figure 4. The PWM voltage waveform determines the bridge current ripple. A small magnitude and phase change is required to generate the necessary 50 Hz current change in the input inductance. This requires small modulation changes which alter the current ripples so that ripple cancellation is less complete.

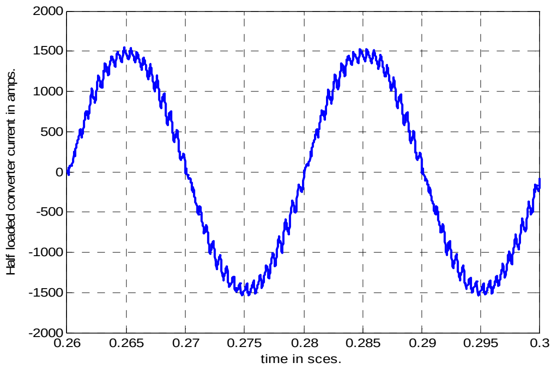

Figure 9. Half loaded Converter Current Waveform (Unbalanced case)

Figure 10 shows the total primary side current. The increased 1800 Hz component resulting from reduced cancellation is not evident with the scale shown.

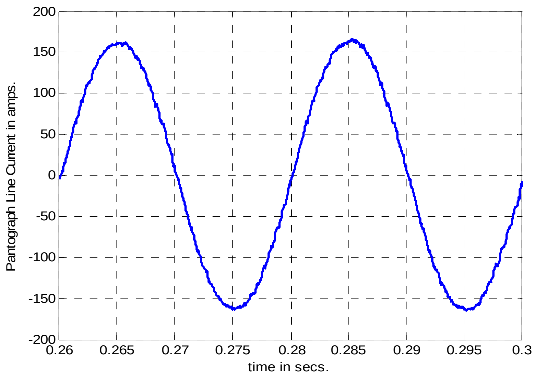

Figure 10. Pantograph Line Current Waveform With phase shifted Converters (Unbalanced case)

These components are evident in the current spectrum shown in Figure 11. The current spectrum shows a distinct set of four switching lines around 1800Hz.

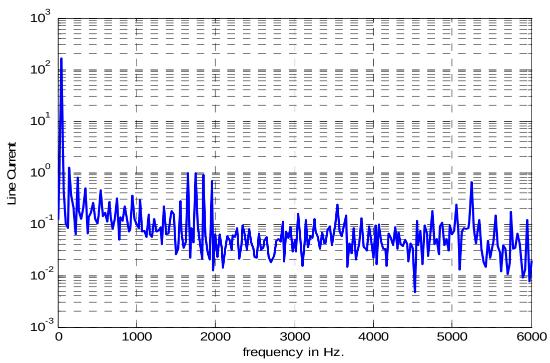

Figure 11. Pantograph Line Current Spectrum for the unbalanced case

Figure 12 shows voltage harmonics around 1800 Hz that were not previously present.

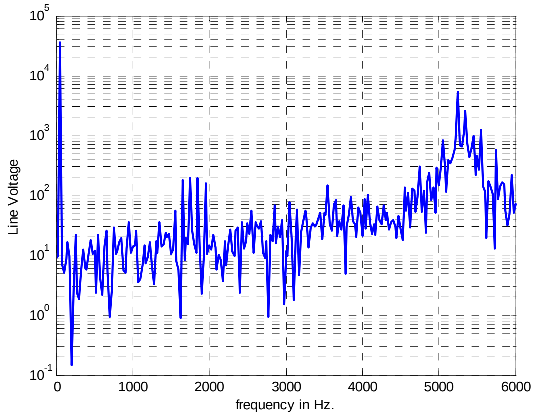

Figure 12. Pantograph Line Voltage Spectrum (Unbalanced case)

Figure 13 shows the harmonic currents in 1000 Hz - 2000 Hz range and these have increased to 1.33A rms.

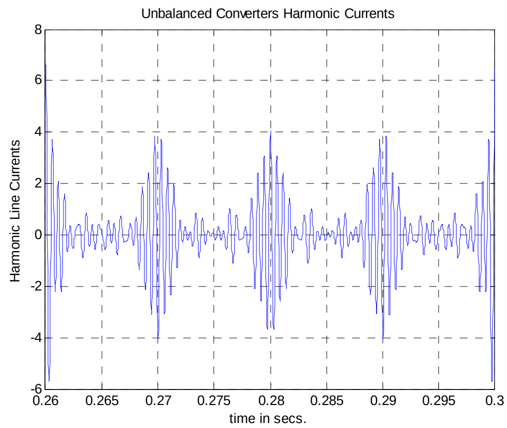

Figure 13. Harmonic Currents for the Unbalanced Converters for the frequency range of 1 kHz-2 kHz

There can be various solutions for this type of frequently occurring problem. The most appropriate solution depends upon the site conditions and requirements, keeping the right balance of both cost and performance of operation.

6. CONVENTIONAL APPROACHES

Harmonic Filtering is the crucial aspect of the rail power systems because of the stringent limitations imposed on the harmonic current generation due to railway signaling requirements [11].

Traditionally, the unwanted harmonic distortion components in the power systems have been removed by the use of passive filters. They have been employed primarily due to their simplicity and low cost with reasonably good efficiencies and marginally adequate service. And they have remained popular over a long period of time because of their reliability, ruggedness and less complexity.

Passive filters can be used to absorb uncancelled harmonics. However, in a railway system, where vehicles move continuously on the track, it becomes quite difficult to predict or control the system characteristics. Consequently, a passive filter may absorb harmonics [5] generated by other vehicles.

Also, they are quite bulky in size and weight. And, they have tuning problems [10] as well as associated resonance along with their own aging problems over a long period of operation. Accordingly, passive filters are not able to provide the required harmonic filtering as they are not capable of adequately solving the problem of varying harmonic components under variable load and varying load current conditions. So, resistance damping might be quite necessary to limit the filter currents. This reduces the performance and results in losses.

Active filters can avoid the short comings of the passive filters by employing a switch-mode power electronic converter [3] to supply harmonic currents equal to those in the load current. Since, the load current harmonics are measured and then supplied by the current - regulated converter of the active filter; the filter performance does not depend upon the utility system impedance. However, their VA ratings become quite large. They tend to become quite expensive as the power ratings are high enough, due to increased power levels. Also, they are subjected to full supply voltage and current levels, increasing their power levels, when they are employed as shunt Active elements for harmonic filtering application. And the VA ratings of the active elements can become quite excessive since they suffer from high power losses. Building a large capacity PWM converter for Active filter application, with fast current response and low losses can pose great challenges for practical implementation. This causes their limitation in the viable industrial applications of harmonic filtering from the economics point of view.

Active damping [6, 7, and 8] is normally used to improve the dynamics of the power system in order to improve the THD of the line current.

The active filter filters only the measured harmonics. No harmonic current from anywhere else, will flow into the active filter, as it can happen with passive filters. This shows that the active filter acts more or less like a private filter while passive filter behaves like a social filter, because it filters all the harmonics in the line. This is a very important feature because it may influence how the consumer and the utility can share the cost of the filter. The hybrid combination of the active filter and a passive filter is quite an interesting solution for very high power applications.

Accordingly, this paper will examine hybrid filter solutions as alternatives to passive and active filters. Hybrid filters inheriting the advantages of both passive filters and active filters provide improved performance with cost effective solutions. Current harmonic compensation can be achieved by reducing the impedance of the hybrid filter. The filter must have a wide bandwidth with very low impedance at the frequency of harmonics being compensated [12].

7. SIMULATION RESULTS

Figure 14 shows a hybrid damper solution for this problem of unbalanced converters. The main challenges faced during this simulation are the simultaneous reduction of active filter rating as well as the harmonic components reduction in the supply current. Both these factors are contradictory to each other in performance. Accordingly, it becomes necessary to arrive at a kind of trade–off solution to achieve an optimal performance for the hybrid damper solution.

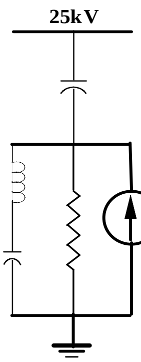

Figure 14. Hybrid Filter/damper

Figure 15 shows the simulated results of the psophometric currents in the frequency range of 1 kHz and 2 kHz, using a hybrid filter for the unbalanced converters. The total locomotive current in the 1 kHz – 2 kHz frequency range is reduced to 200 mA rms.

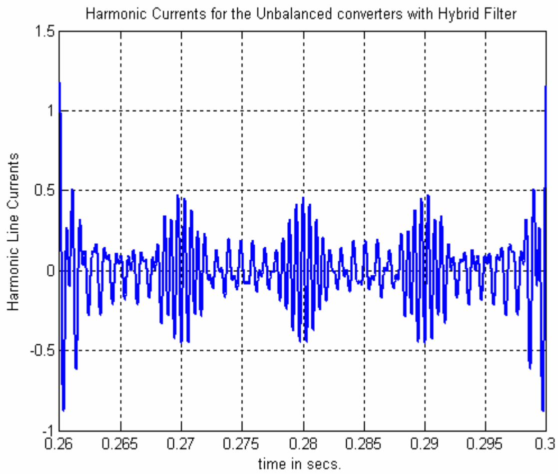

Figure 15. Harmonic Currents for the Unbalanced Converters with a Hybrid Filter for the frequency range of 1 kHz-2 kHz

Figure 16 shows the line voltage is much cleaner with hybrid damping, suppressing the 5400 Hz resonance as well.

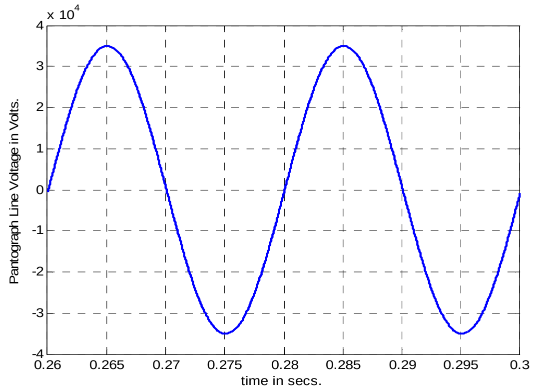

Figure 16. Pantograph Line Voltage with a Hybrid filter

8. CONCLUSIONS

The introduction of hybrid filters for this type of unbalanced operation of converters has provided an effective solution for reducing the harmonic currents in the line current spectrum of the traction converter system. It has been found that the harmonic current limits are within the permissible limits of operation for the railway signalling systems, thereby ensuring a secured and sustained operation of converters, even in the event of single point failures. This study has also proved that the safety critical limits of the harmonic currents imposed by the rail authorities need not be exceeded even under adverse operating conditions. The active element rating of the hybrid filter has been reduced to nearly 18KVA compared to its rating of 50KVA with an active filter solution [8].

9. ACKNOWLEDGEMENTS

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