Design and Simulation of Passive and active filters

A proposed Implementation for East Coast Mainline Railway

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***Abstract*— This paper examines the use of passive and active filters to deal with harmonics for power system applications and in particular, for railway substations on the East Coast Mainline. Filters were designed and simulated on ETAP and ORCAD to analyze and determine the most effective filters combination for implementation. Ultimately, a recommendation is made for the East Coast Mainline to use these filters to eliminate the present electromagnetic interference caused by the new fleet of Class 800 trains. By using filters to lower harmonics and compliant to the IEEE 519 limits, the new Class 800 trains will be able commissioned into passenger service.**

***Index Terms*—Passive and Active filters, Railway, Harmonics**

I. INTRODUCTION

This paper examines the harmonic distortion caused by the new electric traction that has been ordered for the ECML and is due to start for passenger service in mid-2019. However, the new electric traction is presently facing huge delays due to the presence of electromagnetic interference [1]. To overcome the effects of harmonic distortion, both passive and active filters were designed. A basic model of the railway system is modelled on ETAP software and its harmonics is analyzed using the Total Harmonic Distortion (THD) values, the harmonic spectrum as well as the waveform itself. To keep the harmonic distortion within the IEEE 519 recommended limits, passive filters were designed specifically to eliminate the 5th and 7th harmonics whilst simultaneously ensuring the filters did not have excessive negative impact on the fundamental component. An active filter was developed on ORCAD, and designed to counter higher order harmonics. Ultimately, the results with this filter were compared with the IEEE 519 recommended limits to ensure THD and individual harmonics comply with this standard.

II. THE PROBLEM

Harmonic distortion is the unfortunate side effect of electric trains, which would lead to non-linear loads and hence these can have severe consequences on the operations of the railway. In this case-study, the new Class 800 Azuma trains that were supposed to be rolled on ECML later this year are facing severe problems due to the emission of the electromagnetic interference which would cause all signals to revert back to red. The harmonic currents were emitted from the pulse-width modulation (PWM) controlled converters in an electric train. It is these harmonics that were carried through the catenary network, which then can have negative consequences on signaling systems, coupled with the fact that several trains are running within closed perimeter. This will amplify the harmonic currents thus causing a more distorted waveform in the catenary [2].

As this is such a common problem within the rail industry and other power system applications, the IEEE has published recommendations about voltage distortion limits on particular bus voltages. This is displayed in the IEEE 519 document [3] and will be applied to reduce the effects of harmonic distortion. This is shown in Table 1.

Bus Voltage	Individual harmonic (%)	THD (%)
V ≤ 1.0kV	5.0	8.0
1kV ≤ V ≤ 69kV	3.0	5.0
69kV ≤ V ≤ 161kV	1.5	2.5
161kV ≤ V	1.0	1.5

Table 1: Harmonic IEEE 519 limits

The feeding supply transformer has been upgraded to 400kV on the ECML and the voltage at the feeder substations is reduced to 25kV for the OHLE. The frequency used was 60Hz and the power rating of the AC traction feeder transformer was 6.403 MVA [4] [5] [6]. These data were used to design and simulate the system on ETAP software in order to analyse the harmonic distortion being compared to the recommended values in Table 1. From these data, the appropriate mitigation values are used, particularly that the new trains could affect signaling North of York, between two substations in the York area powering the ECML. The distances are:

1. *Hambleton Junction - York = 15.75 miles*
2. *York – Dalton = 17 miles*

These distances are typical between substations across a network ranging from 15 and 20 miles. There needs to be a distance of approximately 7-8 miles for trains to run at 125 mph safely. This means that there will only be a maximum of two trains in each section of track powered by a particular substation doing 125 mph. To make this investigation as useful as possible, the worst-case scenario is investigated which means 4 trains (i.e. 2 trains in each direction) will be modelled on ETAP software as loads. The maximum speed is at 125 mph, at which harmonics is at the highest and affects the signaling system most because the traction motors on the electric trains will be drawing a large current.

III. MITIGATION TECHNIQUE 1: PASSIVE FILTERS

One mitigation technique is the use of passive filters and/or active filters; harmonics cannot be completely eliminated but it can certainly be reduced by the use of filters. Passive filters are much simpler to design, cheaper and more flexible compared to active filters. Whilst active filters are becoming increasingly more popular in the modern era, they are still relatively expensive especially at high voltage operations, which is the case for the railways. Passive filters are tuned to eliminate a specific harmonic as oppose to active filters which are used to reduce a range of harmonics [7].

Passive filters can be tuned to a certain frequency or a band of frequencies in order to suppress the respective harmonic currents. The following types of passive filters are examined:

Single-tuned filters - These filters (as shown in Fig. 1) are placed in parallel to the load in the system in order to divert harmonic currents by offering a low impedance path [8].

C-filter - This is a second-order filter that does not suffer as much as losses at the fundamental frequency as the single-tuned filter whilst still being able to effectively reduce harmonic currents. Due to the inductor and capacitor arrangement (Fig. 2), which is in parallel to the resistor, they can resonate at the fundamental frequency which means losses in the fundamental current through the resistor is at a minimum [9].

High-pass filter - This type of filter has the inductor and resistor connected in parallel (Fig. 3) as opposed to being in series with each other. As a result, it will have a flat impedance characteristic at high frequencies. The Quality factor is the inverse of the single-tuned filter and so the typical Quality factor of a High-pass filter is between 0.5 and 2. This ensures a wide bandwidth and an asymptotic impedance behavior so the maximum value of impedance is limited at high frequencies [9].

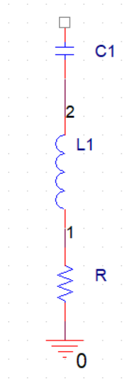


Figure 1: Single-tuned filter schematic

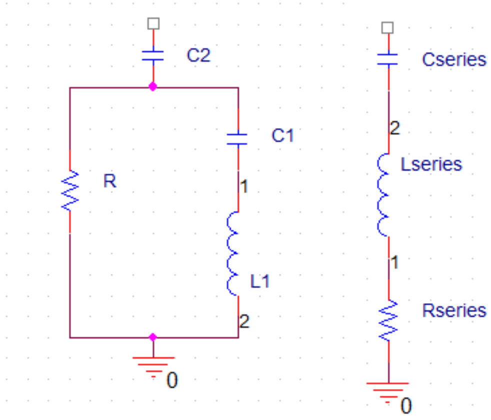


Figure 2: C-type filter (schematic and equivalent filter)

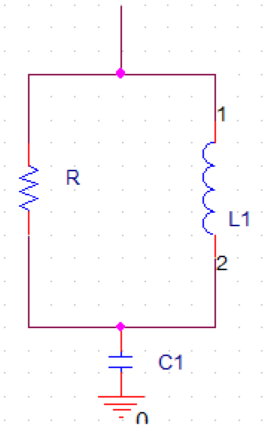


Figure 3: High-pass schematic

IV. MITIGATION TECHNIQUE 2: ACTIVE POWER FILTERS

Active power filters (APF) generate opposite harmonics to those of the non-linear load in order to compensate for harmonics and distortion caused by the non-linear load. A block diagram to demonstrate the working of an APF is displayed in Fig. 4. The train (as the non-linear load) injects current harmonics which cause hysteresis band control produces a trigger signal to the inverter. Inverter then produces a reference current in order to cancel out this reactive current. One example of an APF is the active shunt filter. This is placed in parallel to the load and it is essentially a current source but has opposite phase sequence to the harmonic currents [9] [10].

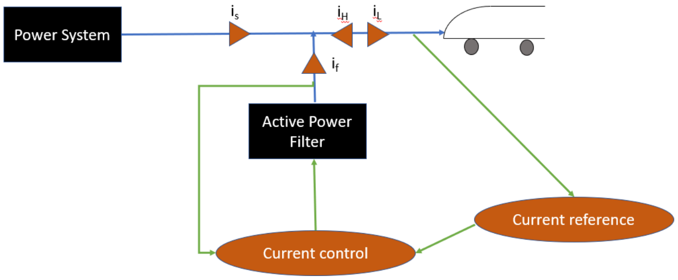


Figure 4: Block diagram for working principle of an active power filter

V. QUALITY FACTOR

When designing the filters, one important consideration is the Quality factor (Q). The Quality factor determines the sharpness of the tuning; in other words, the degree of harmonic distortion absorption. It is the ratio of the energy stored in the resonator to the energy supplied by it. The value of Quality factor will vary on the type of filter and application.

For a single-tuned filter, a high Quality factor is desired in order to reduce as much harmonics as possible. However, it should not be too high otherwise the bandwidth will be too narrow thus reducing the losses at the fundamental frequency. In this trade-off, having a high enough Quality factor is more important because the whole aim of this investigation is to reduce harmonics as much as possible. Despite the losses at the fundamental frequency, these can be compensated for using the many techniques that are used in the railway. For example, by the use of booster transformers. According to a particular research paper which analyses the effects of varying Quality factor on harmonics, a typical value of Quality factor for single-tuned filters is between 30-60 and the optimum value found in the research paper was 50 [11]. Quality factor is explored in this investigation in order to find the optimum value.

VI. CASE STUDY

Using the data for the UK rail electrification, the system is modeled, designed and simulated on etap and this is displayed in Figure 5. It consists of a power supply network supplying 400kV at 100MVA; a feeder substation, which reduces the voltage down to 25kV for the OHLE; and a non-load which is representing a train on the network. The etap software has a harmonic library and that for a typical locomotive was selected in order to make this realistic as possible. Also, in order to simulate the worst-case scenario as explained before, 4 of these identical loads were placed within the system depicting four trains drawing power from the OHLE.

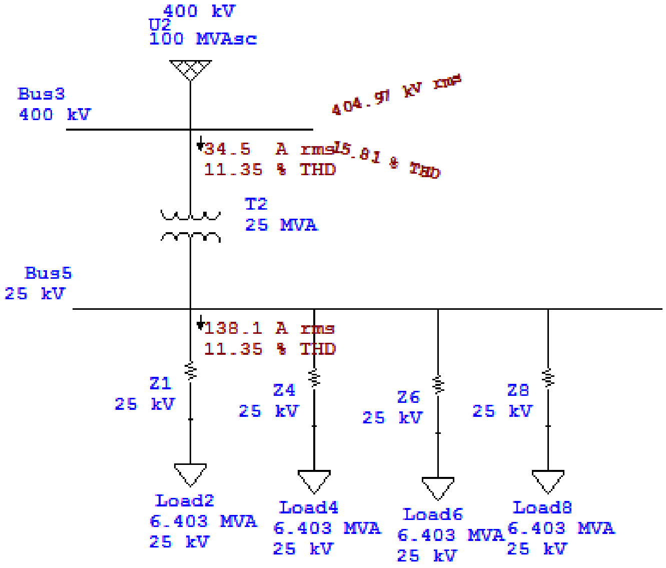


Figure 5: Model of a basic railway system

The THD is 22.45% which is over four times the IEEE 519 limit of 5% for a bus voltage of 25kV thus the much distorted waveform shown in Fig. 6. From harmonic analysis, the major harmonic currents come from the 5th and 7th harmonic so these will be the primary focus when designing the filters. However, the 11th and 13th harmonics both have individual distortions of over 3%, which means that filters will also need to be designed to reduce these in order to comply with the IEEE 519 limits. As the 5th and 7th harmonics are large, 16% and 12% respectively, passive filters will be used to reduce these harmonics since passive filters are tuned to a specific harmonic so will be more beneficial than a single APF which can reduce a range of harmonics but will not be cost effective in reducing one specific harmonic. Also, as the 5th and 7th harmonic currents are large, an APF will need to counter these harmonics with also high currents and this is expensive for high voltage applications.

The 11th and 13th harmonic currents, however, can be reduced using an active filter as these are relatively low currents so an active filter will be cost effective.

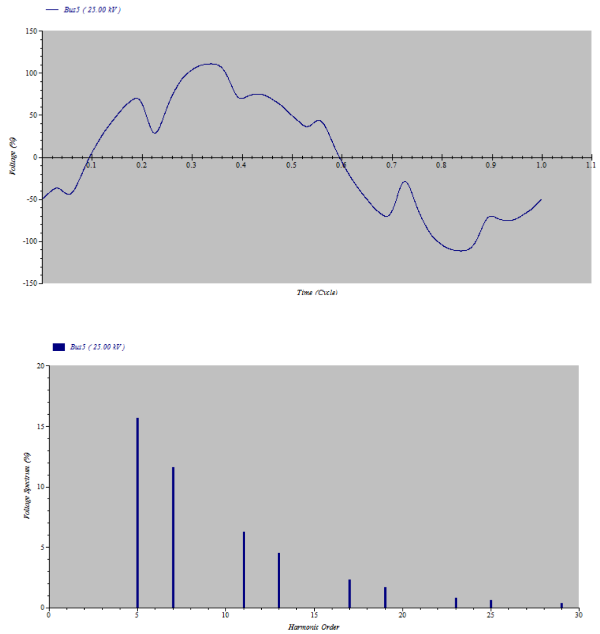


Figure 6: Bus voltage of 25kV with no filters (waveform and harmonics)

Two filters were designed, one tuned for the 5th harmonic and one for the 7th harmonic. The parameters for these filters were as follows: Q_C = 1 MVA, Q = 50, f = 60 Hz, V = 25 kV).

The circuit with the two single-tuned filters is shown in Fig. 7.

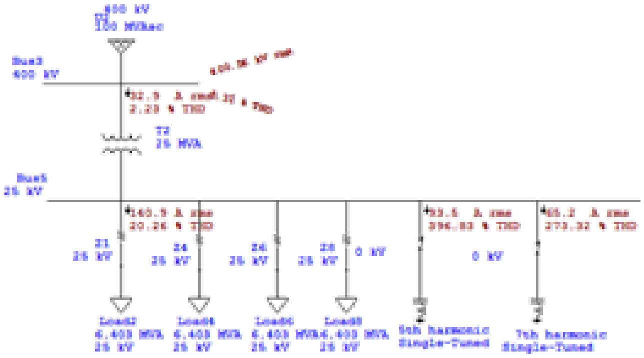
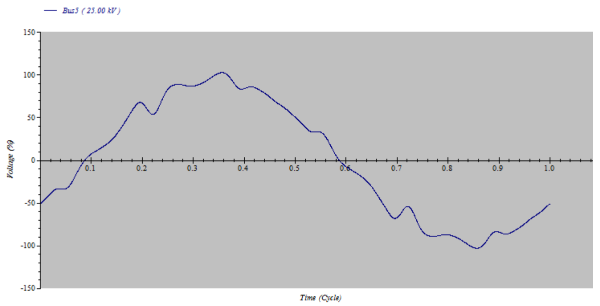


Figure 7: System with two single-tuned filters tuned to 5th and 7th harmonic

The THD has now been reduced to 7.49% which was still over the IEEE 519 limit but significantly reduced by almost three times compared to when there were no filters. As shown in Figure 8, the filters therefore, successfully reduced the respective tuned 5th and 7th harmonics thus the waveform appears to be more sinusoidal. However, the presence of the higher order harmonics, particularly 11th and 13th harmonics means that the THD still needs to be further reduced by another 2.49% to be compliant with the IEEE 519 limits.



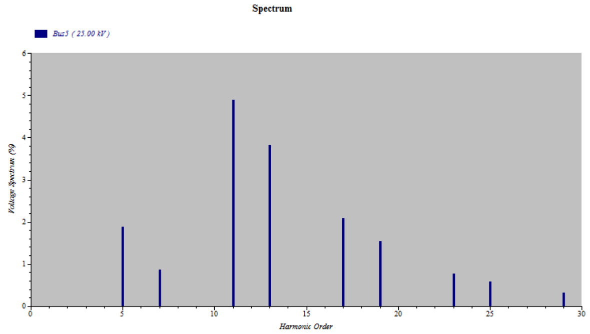


Figure 8: Bus voltage of 25kV with 5^{th} and 7^{th} single-tuned filters (waveform and harmonics)

A 'C-Filter' was then applied to the same network. The parameters were kept the same as for single-tuned filter but the component values were changed due to difference in the arrangement. The system with the two C-filters tuned at 5th and 7th harmonics respectively is shown in Fig. 9.

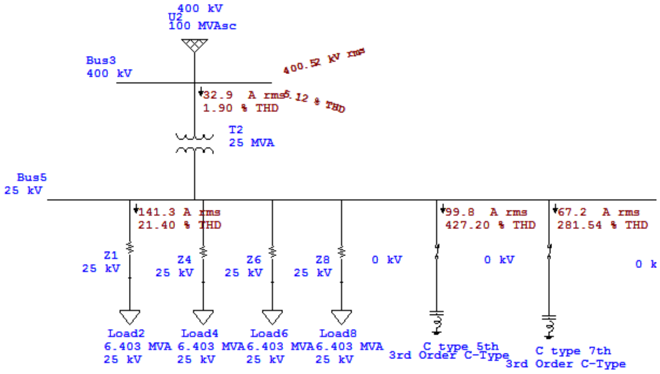


Figure 9: System with two 5^{th} and 7^{th} C- filters

These set of filters appeared to be more effective than the single-tuned filters because THD was 7.28% which is 0.23% lower because the 5th and 7th harmonics were approximately both half of the values found after the single-tuned filters. This can be seen in Figure 10 and thus the waveform is slightly less distorted. The higher order harmonics remain as expected so this will be examined in order to reduce THD further and ensure individual harmonics do not exceed 3%.

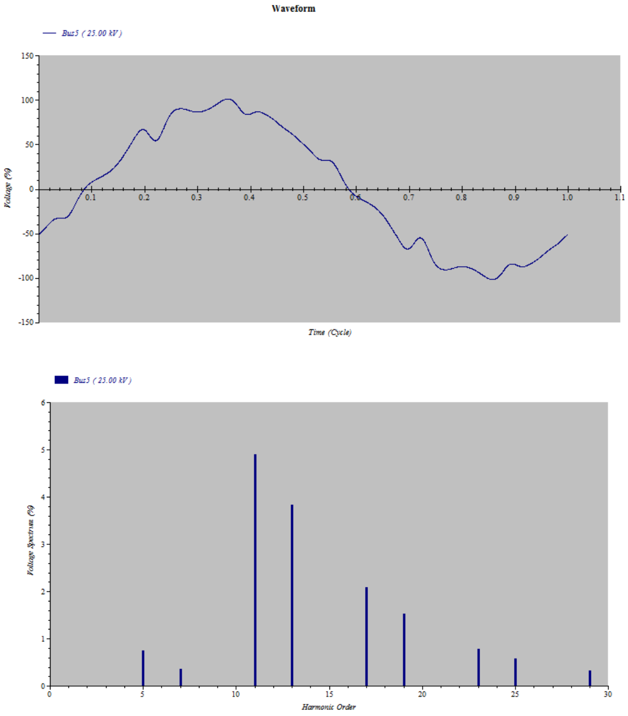


Figure 10: Bus voltage of 25kV with 5th and 7th C- filters (waveform and harmonics)

A high-pass filter was then applied to the same network. The parameters were kept the same as the single-tuned and C-filter apart from the QF because QF for a high-pass was approximately the inverse of the single-tuned filter. The QF to be chosen as 2 because removing harmonics was the main aim of the investigation so the highest value of QF from the range of 0.5-2 was chosen despite the possible larger losses at the fundamental frequency. However, having a high enough Quality factor was effective in removing harmonics and hence the losses can be dealt with separately. Fig. 11 illustrates the application of the high-pass filter to the same system.

Fig. 12 shows the 25kV bus voltage waveform and the harmonic contents when high-pass filter is connected to the railway system.

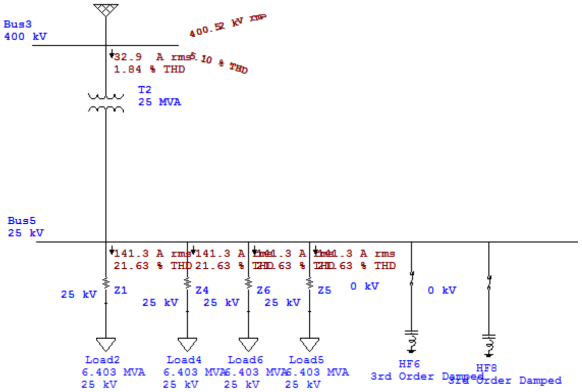


Figure 11: System with two high-pass filters tuned to 5th and 7th harmonic

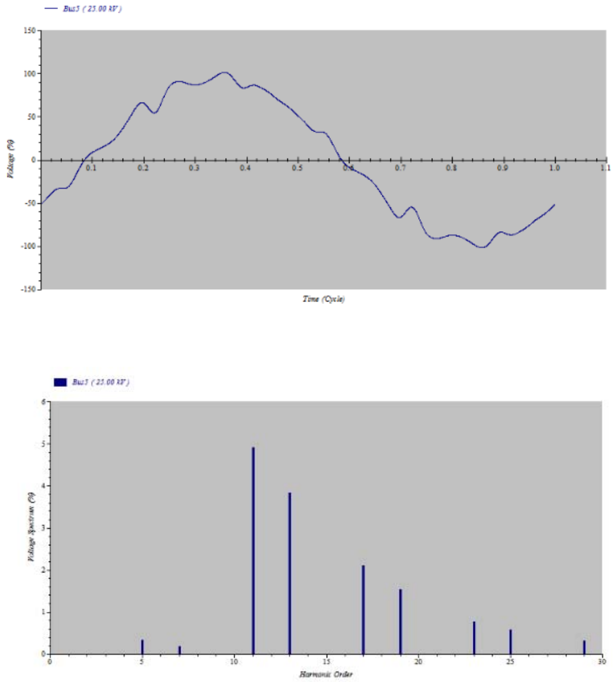


Figure 12: Bus voltage of 25kV with 5th and 7th high-pass filters (waveform and harmonics)

An active power filter was then developed on ORCAD to reduce the higher order harmonics. Current and voltage sources were used to model the non-linear loads and the APF model was based on voltage source inverter. The harmonics modelled in this section were the 11th and 13th harmonics as these were the harmonics to be eliminated using the APF method. The magnitudes and phases of the harmonic injected have been taken from the etap results:

11th harmonic: 550Hz; Phase = 99.36 degrees; Amplitude of harmonic: 1.22kV

13th harmonic: 650Hz; Phase = 61.09Hz; Amplitude of harmonic: 0.96kV

Fig. 13 illustrates the voltage waveform before compensation together with the injected 11th and 13th current harmonics. Fig. 14 illustrates the voltage waveform after the APF compensation.

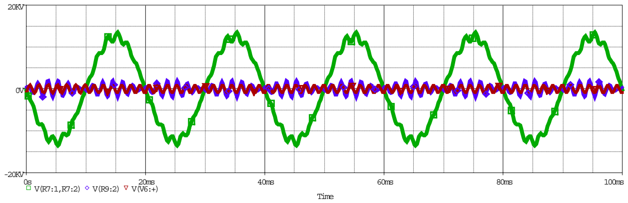


Figure 13: Bus voltage before compensation together with the injected 11th and 13th harmonic currents.

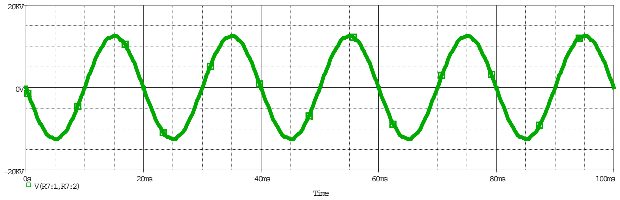


Figure 14: Bus voltage after the APF compensation

VII. CONCLUSIONS AND RECOMMENDATIONS

In conclusion, a basic railway system was modelled by ETAP and by using data found from various sources. This was used to make the model as close as possible to the case study about the ECML and the new Class 800 train loads. Various combinations of passive and active filters were designed and simulated in order to reduce harmonics to acceptable limits which was met and even exceed the IEEE 519 standards. As part of the filters, both Quality factor and locations of filters were explored in order to identify the optimum design.

The recommendations made to the ECML and Network Rail to resolve their current interference problem from their new rolling stock are as follows:

- The use of single-tuned filter to reduce 5th and 7th harmonics
- The use of APF to reduce 11th and 13th harmonics
- Choose a Quality factor of 50 for the single-tuned filters
- Place the filters between the transformer and load
- To compensate for the losses from the filters, add extra booster transformers at regular intervals to raise voltage back up to optimum
- For medium to long term future assessment consider the possibility of having several small PV arrays around the network in order to increase power from renewable sources.

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