

Harmonic filter design for electrified railways Wotonga feeder station

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Abstract

Electrification of heavy haulage rail systems in an area of relatively weak grid supply imposes onerous requirements on the design of the grid connection feeder station in terms of compliance with power quality regulations. This article describes the approach used in one particular application where a reliable, safe and enduring solution was synthesised to meet harmonic emission limits.

Extensive use was made of the DIgSILENT PowerFactory analysis package to carry out a harmonic impact study and filter design, switching transient analysis and protection coordination. These studies facilitated a robust engineering design that ensures safe operation over a long life span while meeting harmonic emission limits for a range of loads.

1 Introduction

1.1 Electrification

Aurizon operates and manages a heavy haul coal freight network, made up of 2 670 kilometres of rail infrastructure in central Queensland.

The Aurizon coal network has been electrified since the mid-1980s. Distribution of electricity to locomotives is accomplished through the use of autotransformers via a two phase system composing of a contact/catenary wire and a feeder wire. The voltage between the contact/catenary and feeder wire is 50 kV whilst the locomotives collect power at 25 kV with respect to the rails and ground.

The Aurizon electrified rail system connects to the Powerlink HV transmission system at regular intervals via so called Feeder Stations.

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1.2 Wotonga Feeder Station

Additional electrical capacity is required to service increasing levels of network traffic east of Coppabella. Aurizon have committed to construction of a new Feeder Station located at Wotonga approximately 8 km north of Moranbah to address this need. The expected completion date for this project is the end of 2013.

A simplified network representation of the feeder station and important network components is presented in figure 1. The network connection is made at the 132 kV point of connection (PoC), and the connection to the rail system is made via two sets of 132/50 kV, single phase transformers connected between two phases on the 132 kV side.

When one of the transformers is out of service it is possible to feed that section by closing the bus tie. Several traction loads are connected to the 50 kV (phase-phase) busbars. Autotransformers (not shown in the diagram) provide a reference point between the catenary and the track to allow power to be drawn at 25 kV relative to the track (and earth) potential.

The traction loads consist of rectifiers that inject a range of frequencies into the catenaries from where the harmonic current is transformed and injected into the TNSP network. The current flowing into the network impedance results in a voltage drop across the network impedance which is manifested as voltage distortion at the supply busbar.

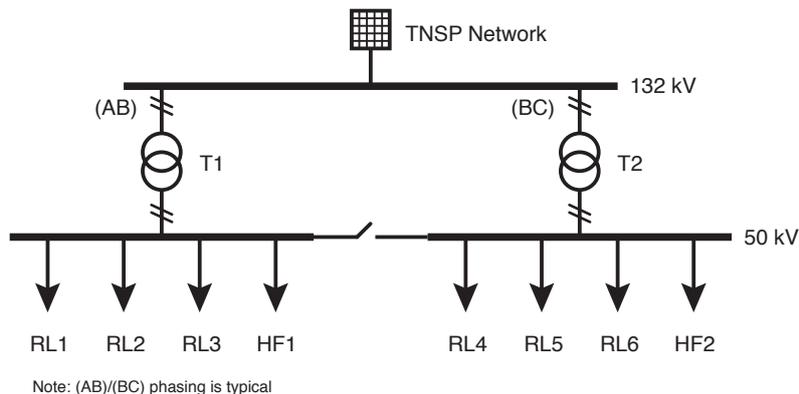


Figure 1: Simplified line diagram of Wotonga FS

A new grid connection point requires agreement between Aurizon and the transmission network service provider (TNSP) Powerlink Queensland. Such a connection agreement includes several aspects including the extent of voltage unbalance, the amount of active and reactive power drawn from the network, and the contribution to network harmonic distortion as a result of non-linear loads in the Aurizon system. Part of the connection agreement defined the emission limits at the point of connection (PoC) as detailed in figure 2.

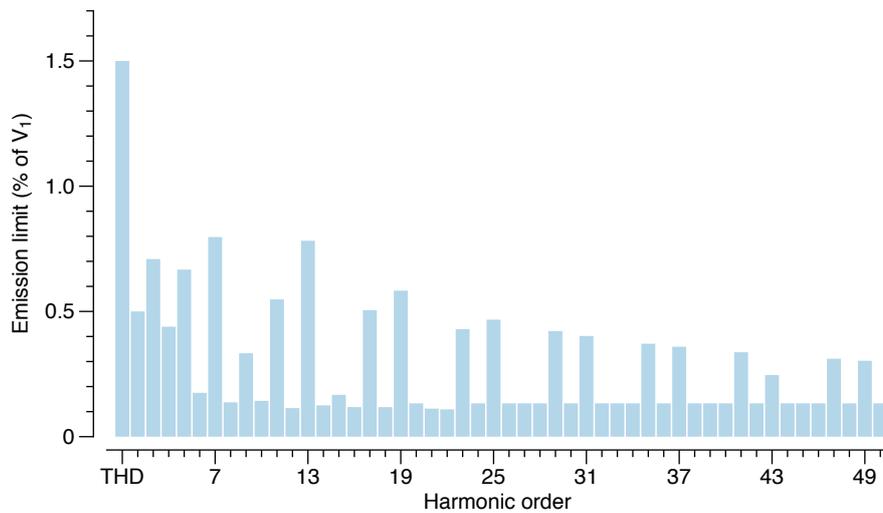


Figure 2: TNSP emission limits at PoC

2 Harmonic impact study

Optimised Network Equipment (ONE) was commissioned by Aurizon to design, supply and pre-commission a set of harmonic filters for the site. This scope included the following work:

1. Primary plant design — equipment layout and site integration,
2. Manufacture and supply of harmonic filters including primary and secondary protection equipment,
3. Design and supply any equipment required for the mitigation of switching transients.

Various constraints were placed on the design work. These included compliance with the emission limits under a range of operating modes (normal and maximum traction loads, operating with one transformer out of service and operating in emergency supply mode where adjacent feeder stations were out of service and the Wotonga feeder station feeds those adjacent loads), with a number of TNSP configurations and with a restriction on the total amount of reactive power that can be generated by the filters.

The various TNSP configurations are represented by different frequency dependent positive, negative and zero sequence resistance and reactance. This results in a wide range of source impedance values at each frequency. The graph in figure 3 provides an overview of the variation that can occur in one parameter (positive sequence impedance). The shaded area indicates the range between minimum and maximum impedance and gives an indication of the complexity of the task of selecting an appropriate filter design that provides adequate and optimised performance given variation in network impedance of up to three orders of magnitude.

Note that the figure indicates for simplicity only frequency dependent harmonic impedance magnitude ($|Z|$) whereas the model was constructed using positive, negative and zero sequence resistance ($R_{0,-,+}$) and reactance ($X_{0,-,+}$).

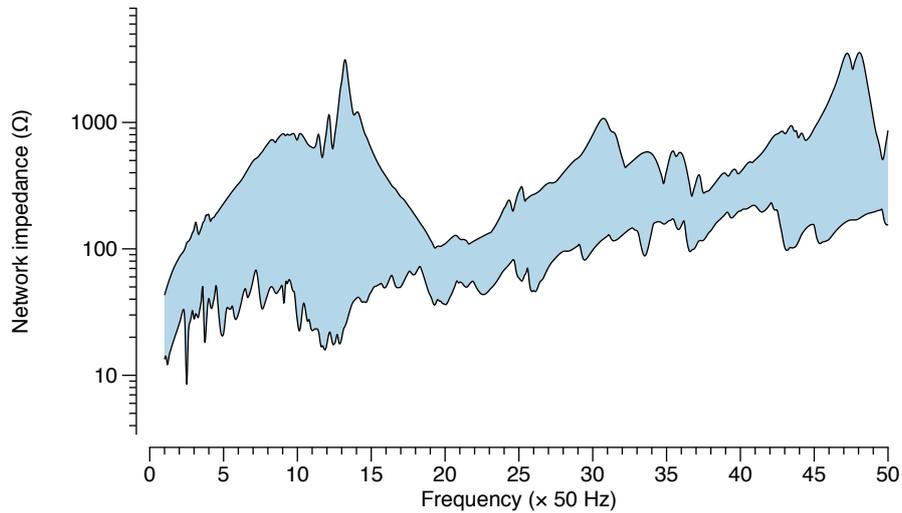


Figure 3: Frequency dependent impedance at PoC

A number of studies were carried out to aid this design process:

1. Harmonic filter design study implemented a model of the network and train loads, assess the expected emissions against limits imposed upon Aurizon at the point of connection, and design a reliable solution consisting of a number of tuned filter branches,
2. Simulate switching surges in the network and determine the required location and rating of short time over voltage mitigation devices,
3. Synthesise a protection scheme according to the Aurizon design guidelines and define the required settings for the various devices.

2.1 Data acquisition and model development

The model used was based on a PowerFactory model developed by Aurizon. The model was verified extensively by comparing measured current and voltage distortion levels under known network conditions and loading, and comparing these to the voltage and current distortion predicted by the model. Some modifications were made after concluding that a number of measured values related to fault events (harmonic analysis only considers steady state conditions) and verified by ONE.

Aurizon provided ONE with harmonic measurements. As the destination site had not been constructed at the time of the design the harmonic measurements were performed at Moranbah South FS, in the vicinity of the Wotonga FS.

Although the harmonic measurements were taken at the Moranbah South FS ONE has modified this data so the harmonics are injected at the secondary side of the Wotonga transformers T1 and T2 as displayed in Figure 1. The harmonic data modelled was extrapolated linearly based on the maximum demand values provided by Aurizon.

2.2 Network information

ONE added to the Wotonga 132 kV PCC the frequency dependent characteristics for positive, negative and zero sequence resistances and reactances as provided by Aurizon. The TNSP scenarios considered are shown in figure 3. This plot is a summary of the information used in the study which naturally also considered the zero sequence impedance and phase angle of impedance. Due to the relative short lengths of transmission lines in this model skin effect was ignored in this study. As the skin effect would tend to damp harmonics, this is a conservative approach.

2.3 Load models

Two important aspects of the load were made available: the MVA load and harmonic spectrum of the loads as measured at existing feeder stations in the network. The demand values are summarised in table 1. In addition to this information the assumption was made that the power factor of the load is a constant value of 0.85.

Table 1: Feeder station loading

	<i>T1</i>	<i>T2</i>	<i>T1 with T2 out of service</i>
Peak	49	42	52
1 minute average	47	35	50
10 minute average	34	24	36
30 minute average	15	18	25

For compliance purposes (which requires compliance under maximum and normal load conditions) the peak and 30 minute average period values were used respectively. All traction loads were modelled as current sources. All harmonic sources were modelled to be in phase.

Harmonic emissions from the load were based on site measurements carried out on a line section where older, thyristor controller rectifier locomotives were in service. These measurements were augmented to include more modern active front end IGBT based rectifiers. These latter rectifiers have lower harmonic emissions at low frequencies but higher emissions at high frequencies. It was assumed for the purposes of the study that both rectifier type can co-exist in the network and that the filter design should therefore incorporate both harmonic spectra. The original measured, new expanded and resulting load spectrum used in the harmonic filter design is shown in figure 4.

The expanded harmonic current spectrum includes frequencies higher than the 50th harmonic. As the TNSP emission limits are restricted to the 50th harmonic and the network impedance is only available up to this frequency the results reported on in this paper are limited to the 50th harmonic.

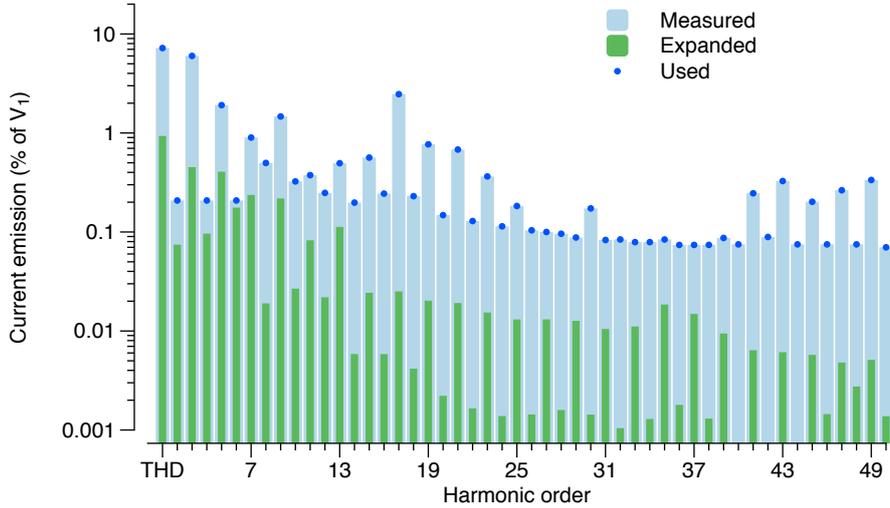


Figure 4: Load current harmonic spectra

2.4 Scenario management

Emission compliance is required for the various network condition as summarised in figure 3, and in each of those network conditions compliance is required for several traction system operating modes. In addition, network frequency can vary across a set range between 49.75 Hz and 50.2 Hz, and component tolerances need to be taken into account. Hence a large number of tests are to be done resulting in a large number of results.

These data sets can be managed readily in spreadsheets and presented in summary form using box and whisker plots, a statistical data analysis tool that allows data spread, outliers and expected values to be displayed in compact form.

In this article, the box and whisker plots indicate the minimum and maximum values, the median value and the range between the first and third quartile of all data points.

2.5 Filter design

The contribution to voltage harmonic distortion at the PoC is shown in figure 5. It is clear that emission limits are exceeded for most harmonic orders and for the overall total harmonic distortion and that harmonic mitigation is required.

The selection and configuration of appropriate filters is an iterative process in which configurations are selected, tested against criteria of cost opti-

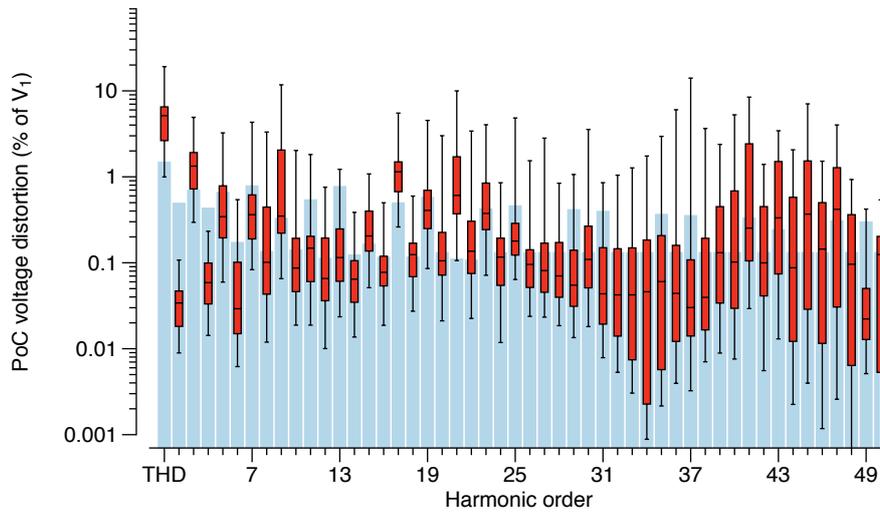


Figure 5: PoC voltage distortion without harmonic filters connected

sation, practicality in terms of manufacturing, and achieving the necessary compliance under all possible operating scenarios.

A filter configuration that meets all the requirements has been selected as shown in figure 6. The same set of filter branches were selected for both filters HF1 and HF2 shown in figure 1. Each filter consists of three filter branches tuned to the third, fifth and ninth harmonics respectively. The fifth and ninth harmonic filter branches are damped.

A shunt reactor is incorporated into the design. This reactor has no significant impact on the filter performance but is instead required to limit the reactive power output of the filter to the limits specified by Aurizon.

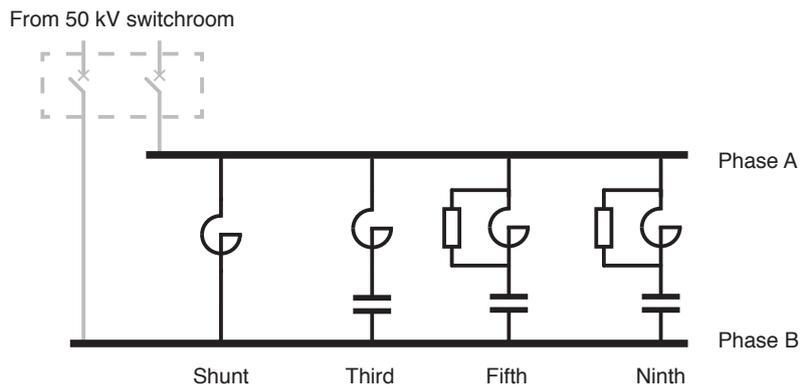


Figure 6: Harmonic filter configuration

The parameters of all components in the filters are listed in table 2.

Table 2: Filter components

<i>Branch</i>	<i>Type</i>	<i>Rating</i> (Mvar)	<i>C</i> (μ F)	<i>L</i> (mH)	<i>R_p</i> (Ω)	<i>Tuned to</i> (Hz)
Shunt	—	20	—	398	—	—
Third	Single tuned	7	7.92	142	—	150
Fifth	Damped	5	6.11	66.3	800	250
Ninth	Damped	18	22.6	5.53	50	450

The effect of the filter on harmonic distortion at the 132 kV PoC can be seen in figure 7.

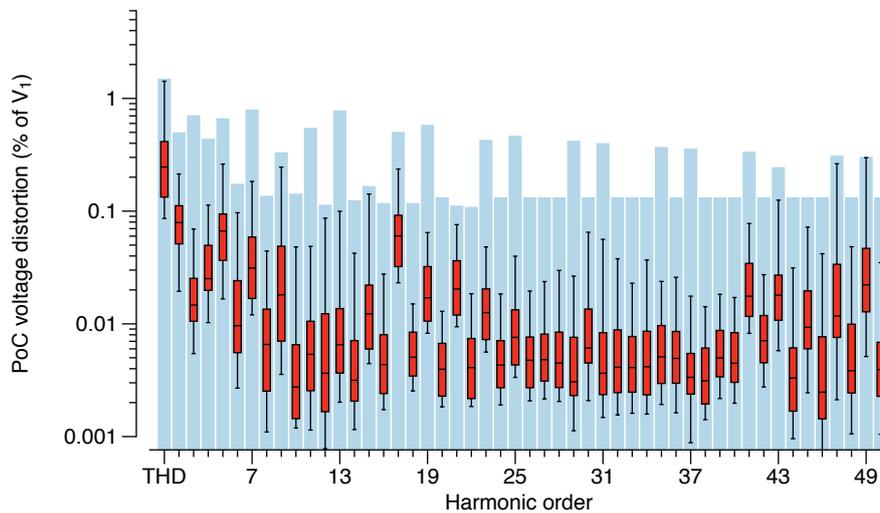


Figure 7: PoC voltage distortion with harmonic filters connected

2.6 Determination of component ratings

In addition to the filter being effective in assuring compliance of harmonic distortion under a range of operating conditions, there are also component design criteria the filter should comply with. This is not related to the effectiveness of the filter, but considers the worst case thermal and voltage stresses that the filter components must be able to comply with.

The worst case conditions were calculated as follows:

1. The scenarios were modified to achieve a fundamental frequency voltage equal to 1.1 p.u. at the filter's busbar.
2. Harmonic load-flow calculations were run for each scenario.

Table 3: Key component ratings

	<i>Capacitor V_N (kV)</i>	<i>Reactor I_{RMS} (A)</i>	<i>Resistor P_R (kW)</i>
Third	78.2	178.78	–
Fifth	64.8	117.21	16
Ninth	61.0	414.45	80

3. The maximum harmonic current through each filter element was calculated for each harmonic order.

Steady state ratings for components were selected on the basis of the arithmetic sum of voltages across the capacitors to satisfy the requirements of IEC 60871-1, the harmonic current spectrum through the reactors according to the requirements of IEC 60076-6 (section 9). Resistor ratings are determined according to the current rating losses in the resistors.

These steady state ratings are supplemented by the expected stresses in each component due to transient events such as switching and lightning events.

3 Electromagnetic transient analysis

The harmonic filter system must be appropriately rated and protected against electromagnetic transient (EMT) phenomena. An EMT analysis was undertaken to evaluate the harmonic filters response to EMT disturbances and to recommend appropriate measures to ensure adequate protection of the components and stability of the protection scheme.

The EMT analysis included a lightning surge study and switching transient study. The following steps were undertaken:

1. The power system in the immediate vicinity of Wotonga was modelled in detail in PowerFactory, this included modelling of the saturation characteristic of the power transformers, surge arresters and modelling of the stray capacitance in cables, busbars and transformers.
2. EMT events including switching events and lightning strike events were defined within individual PowerFactory study cases
3. Simulations were performed to determine the transient voltages and currents arising from expected switching conditions and simulated lightning strikes
4. The performance of the primary plant and protection scheme was compared against the results of the simulation
5. Mitigation measures were determined for results evaluated outside of performance standards and simulated to confirm an acceptable outcome

Figure 8 indicates how the PowerFactory model of the Feeder Station was augmented with additional capacitors representing stray capacitance of busbars and cable termination surge arresters.

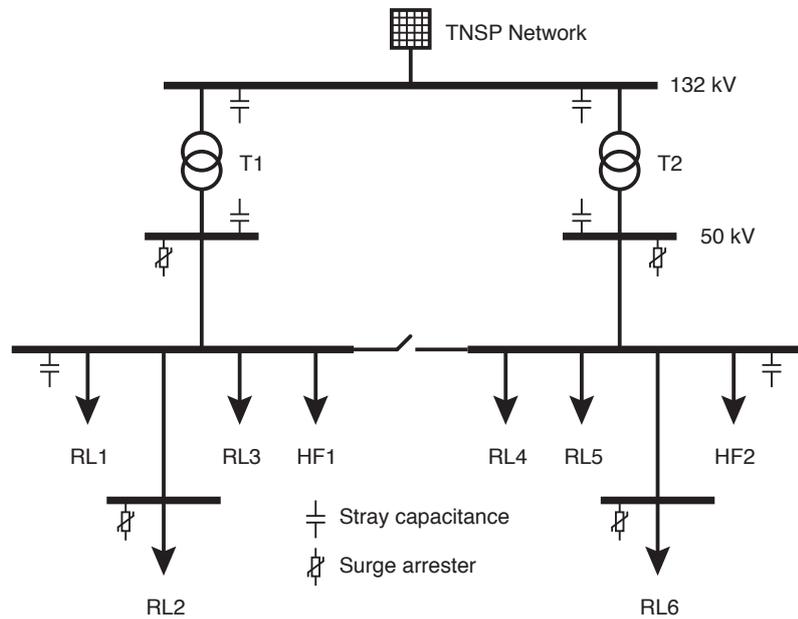


Figure 8: Simplified augmented network for EMT analysis

3.1 Switching study method

The following EMT simulation scenarios were determined as credible switching conditions to be tested:

1. Filter energisation (close the filter CB)
2. Traction feeder energisation (close traction feeder CBs)
3. Transformer energisation (sympathetic inrush — close adjacent transformer CB)
4. Filter de-energisation (CB open system normal and under fault conditions)

PowerFactory Study Cases, DPL scripts and Operational Scenarios were used to configure the network, perform simulations, tabulate results and export figures. Energisation and de-energisation was performed over 10 ms (a half cycle) at 1 ms steps to test the worst case CB opening/closing time.

One parameter which was of concern was the capacitor transient voltage. Historical client installations had incorporated surge arresters across all capacitor banks due to capacitor failures upon switching. The withstand voltage for a capacitor is defined in IEC 60871-1, this standard defines a peak transient withstand capacity of $2\sqrt{2}$ times the rated voltage.

3.2 Switching study findings

During switching transients, all filter components could theoretically withstand the voltage and current transients however the transient voltage on the third harmonic capacitor bank was within 15% of the IEC limit (192.3 kV simulated compared to 221 kV standard withstand capability defined in IEC 60871-1). Hence it was proposed to install a shunt surge arrester across the third harmonic filter capacitor banks.

Figure 9 shows the energisation response of the filter during point on wave switching 6 ms after a 0 V crossing.

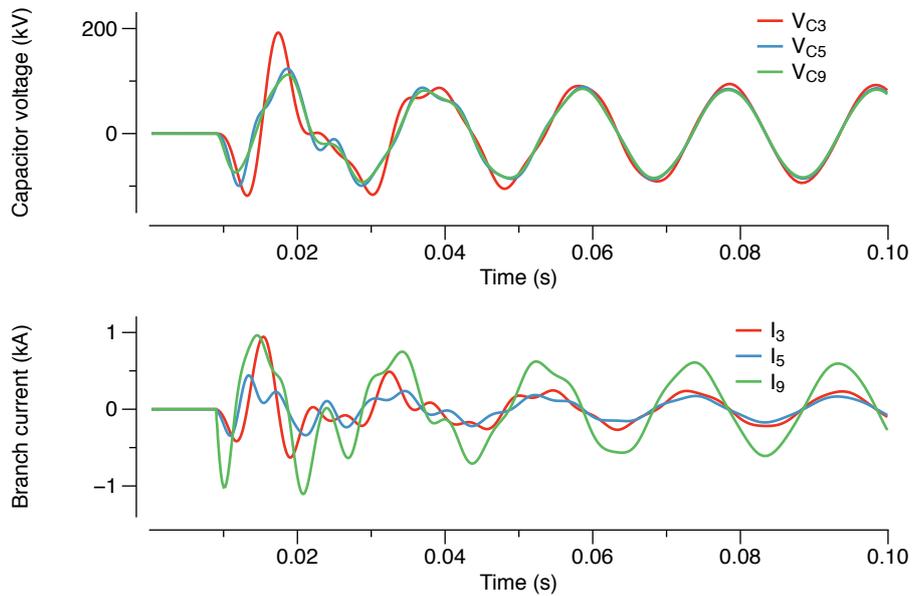


Figure 9: Switching transient — capacitor bank voltage and branch current

3.3 Lightning study method

Lightning over voltages as applicable to the Aurizon traction system are caused either by direct strokes to the phase conductors, back flashovers on the transmission system or indirect lightning surges resulting from earth flashes in the vicinity of the feeder station.

The objective of the lightning surge study is to calculate transient voltages across the harmonic filter system produced by credible lightning strikes.

Standard lightning pulses were implemented via current sources, with the waveshape defined by DSL function blocks in accordance with AS 1768 and IEC standards. EMT simulation was used to determine the transient voltage stresses on the filter equipment. Lightning strikes were simulated at:

1. The 50 kV traction supply outside of the Wotonga Feeder Station

2. The harmonic filter rigid busbars (strike applied at the furthest distance from the harmonic filter cable termination, which is fitted with a surge arrester)
3. The harmonic filter rigid busbars with the harmonic filter supply isolator open

As with the switching study, PowerFactory Study Cases, DPL scripts and Operational Scenarios were used to configure the network, perform simulations, tabulate results and export figures.

3.4 Lightning study findings

The lightning simulations showed that for the majority of lightning strikes, the existing surge arresters placed on cable terminations and the 50 kV GIS switchgear would be sufficient to dissipate the lightning energy and inhibit harm to the connected filter equipment.

The lightning surge would however create severe overvoltage conditions if the harmonic filter isolator was open (harmonic filter disconnected). Under this scenario the voltage on the equipment would increase to a level at which a flashover would occur where the insulation was weakest, a somewhat unpredictable location.

To protect against this scenario, surge arresters are required on the harmonic filter tubular busbar to divert the lightning surge current in a predictable way and inhibit flashover conditions across the primary plant.

3.5 Application of surge arresters

As detailed in preceding sections, simulations showed that undesirable transient overvoltages could result from switching and lightning surges. It was determined that surge arresters should be placed in shunt across the 3rd tuned harmonic branch capacitor banks and from the harmonic filter busbars to ground. In this way the equipment is protected from high switching and lightning transients.

Calculation of the required surge arresters were undertaken by conducting quick manual calculation of size and energy requirements and then implementing the surge arresters with the appropriate characteristic in PowerFactory. Repeating the EMT simulations for each of the scenarios, with the surge arresters modeled then confirmed that the surge arresters chosen were adequate.

Figures 10 and 11 show a representative simulation result following application of the surge arresters. Figure 10 shows the transient voltage level across the 3rd tuned harmonic capacitor bank, and Figure 11 shows the surge arrester conduction current.

Figure 12 shows the surge arrester current and energy for the case when a 10 kA lightning strike hits the filter busbars and the filter disconnecter is open. The two traces in the graph indicate the current into a surge arrester between each phase and ground. The surge on the busbar that is struck conducts a large current but it is interesting to note that the surge arrester on the phase that was not struck also conducts a small current.

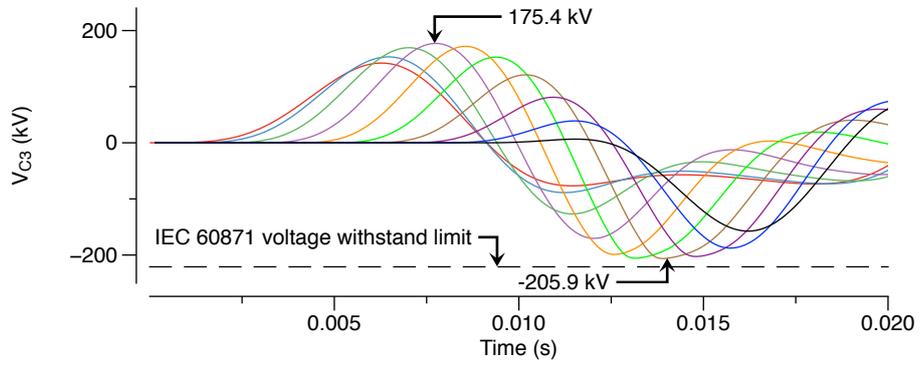


Figure 10: Tuned 3rd harmonic branch capacitor bank voltage – 1 ms point on wave switching scenarios

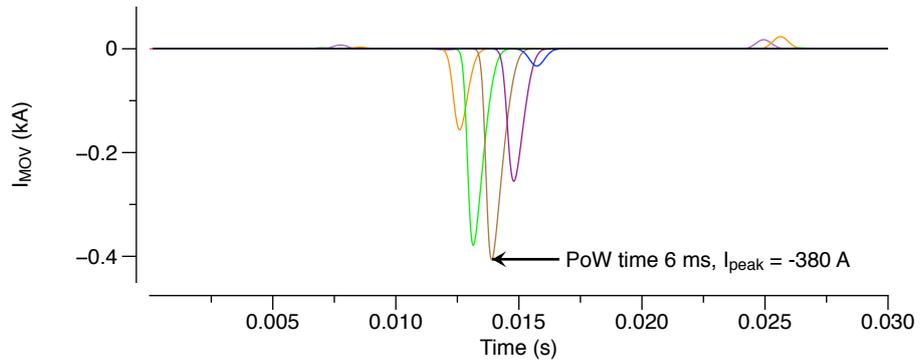


Figure 11: Point on wave switching surge arrester conduction current

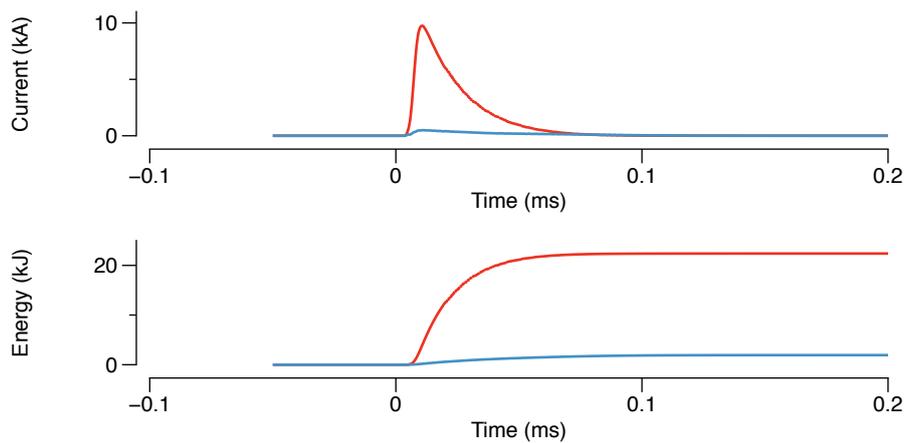


Figure 12: Bus surge arrester current and absorbed energy, direct strike to disconnected filter

3.6 Protection coordination

The protection system for the Aurizon Wotonga harmonic filter was designed to assure fast and selective trip and alarm functionality. A protection system with fast overall voltage and frequency protection was developed. This was further supported with dedicated restricted earth fault (REF), over-current and harmonic thermal overload protection for each leg of the filter bank. Each capacitor bank was also equipped with unbalance protection.

The PowerFactory EMT simulations were used to confirm the stability of the protection scheme during energisation. The following outcomes were a result of the protection coordination study:

1. PowerFactory was used to calculate the prospective fault current for single phase to ground and phase to phase faults on the filter equipment.
2. Some of the filter branch overcurrent settings were increased to avoid nuisance tripping during worst case switching conditions.
3. Other protection settings were calculated to allow for normal operation of the filter whilst ensuring fast detection of possible fault conditions

4 Conclusion

The design of harmonic filters for the railway feeder station provided an opportunity to develop a model in DigSILENT PowerFactory and carry out all the necessary work in a single integrated approach to:

1. Investigate compliance with emission limits,
2. Synthesis of an optimised solution to achieve compliance,
3. Determining the necessary steady state ratings of filter components,
4. Augment the design and ratings by carrying out electromagnetic transient analysis,
5. Establish a robust protection scheme for the filters, and test the protection scheme under steady state and transient conditions.

The inherent ability of the analysis system to perform many hundreds of operating scenarios by means of study case and scripted automation ensures that all possible operating conditions can be tested to ensure compliance and safe operation can be assured.