ELECTRICAL SUPPLY MODELLING OF THE BLACKWATER COAL HAULAGE SYSTEM

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1 SUMMARY

The Blackwater heavy haul rail network in Central Queensland is electrified via a 50/25kV auto-transformer distribution system. The traction system is fed from the Central Queensland 132kV transmission network at several locations. The primary objective of this project is to provide decision making tools to explore short-term operational strategies and produce recommendations for long term traction supply augmentations, which enable increased coal haulage, whilst maintaining adequate traction supply system performance and compliance with power quality standards.

To achieve the degree of accuracy required and to have confidence in the output of the decision making tools an early decision was made by QRNetwork to construct a comprehensive model of the Blackwater system. This model necessarily encompassed: accurate modelling of the network infrastructure, realistic train performance, and accurate electrical behaviour of QR’s power system infrastructure and the Central Queensland generating and transmission network.

Construction of the model required the selection of multiple software products, interfacing of the outputs and inputs of these products and the sourcing of specific railway, power systems and modelling skills.

The developed models have to date been used for assessing system capacity, energy consumption, power quality outcomes and the effects of engineering design changes under a variety of scenarios, including: varying train size & number of locomotives, effects of running AC traction with unity Power Factor and regenerative braking, reduced power operation, increased/reduced headway, electrical contingency events, driver methodology changes, short circuit protection studies, harmonic filter design and augmentation options. During the simulations timetable robustness & the effect of random equipment failures are easily explored.

2 INTRODUCTION

The Blackwater coal transportation system is a large heavy-haul electrified railway, powered by a 50/25kV auto-transformer fed traction supply system. There are presently six 50kV feeder stations which supply the rail system from the Central Queensland 132kV transmission network. The system was originally designed and built in the early to mid 1980’s. Due to the relatively weak 132kV network, Harmonic Filters and Static VAR Compensators (SVC) were essential to address power quality issues, including Harmonic Voltage Distortion and Negative Phase Sequence voltages [1]. The three phase electrical waveforms regulated by the transmission utility become distorted due to the railway load which is unbalanced across phases and rich in harmonic currents.

QRNetwork is required to support prudent investment to increase haulage throughput in accordance with the Coal Rail Infrastructure Master Plan (CRIMP) [2]. Increased electric traffic places increased demand on the Power Supply System, exacerbating Power Quality issues. In order to assess the effects of increased traffic and evaluate upgrade options, integrated modelling of the 132kV/275kV supply network, QR traction supply system, and the traction load is necessary. The objective is to explore the limitations of the existing system, and determine what power system augmentations would be required, to support growth consistent with the CRIMP. Variables including Feeder Station MW/MVAr loading, Contact/Catenary voltage drop, SVC performance and Harmonic Filter performance are assessed. The power quality is assessed in terms of the Australian National Electricity Rules (NER) for customer connections, and AS61000.

3 OVERVIEW OF THE BLACKWATER NETWORK

The Central Queensland Coal Network is comprised of four systems as shown in Figure 1.
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The Blackwater Coal Network servicing the Bowen Basin is the largest and carries the second highest tonnages on the QR network, after the Goonyella system.

The Blackwater network consists of 994 km of bi-directional track, of which approximately 300 km are duplicated. Although construction of the major part of the electrification occurred in the mid 1980s substantial additions for track duplication and new mines have continued to the present day. Today’s network has 823 kms of electrified track. Figure 2 shows the extent of the electrified sections of the Blackwater corridor.

Figure 1 Central Queensland Coal Network

Figure 2 Blackwater Network Electrified Lines

Coal is carried from 11 electrified and 2 non-electrified coal loaders to the two export terminals at the Port of Gladstone; RG Tanna Coal Terminal, and Barney Point Coal Terminal. The Blackwater system also services a number of domestic users including Gladstone Power Station, Stanwell Power Station, and QCL Fisherman’s Landing.

The Blackwater Line operates both electric and diesel electric consists. A typical Blackwater electric train consists of 4 x 35/3600 class, 3000kW, locomotives and approximately 88 x 106t (26.5tal) coal wagons. A typical diesel electric train consists of 3 x 4000 class diesel electric, 2240 kW, locomotives and 88 x 106t (26.5tal) coal wagons.

4 POWER QUALITY ISSUES WITH AN ELECTRIFIED RAILWAY

The undesirable effects of the electrified railway load on the supply network are considerable. The railway load has the following characteristics:

- it is an intermittent and fluctuating load with high peak levels (Up to 180%) in relation to its continuous rating and periods when there is no load at all. It has the potential to introduce flicker,
- it is a single phase load and therefore represents an unbalance in a 3 phase system which results in Negative Phase Sequence voltages (NPS),
- the railway vehicles utilise power electronic converters which cause harmonic currents to flow in the power network,
- it can represent a significant lagging power factor.

All these characteristics are detrimental to power quality which has attracted increased levels of regulation in recent years.

In Australia the following Standards and Guidelines will apply to power quality:

- National Electricity Rules
- EN 50121-5 Emission and Immunity of Fixed Power Supply Installations
- AS 61000.3.6 Limits Assessment of emission limits for distorting loads in MV&HV power systems (Maximum Harmonic Levels)
- AS 61000.3.7 Limits Assessment of emission limits for fluctuating loads in MV & HV power systems (Maximum Levels of Intermittent High Load)
- HB-264 Power quality manual - Recommendations for the application of AS/NZS 61000.3.6 and AS/NZS 61000.3.7

The National Electricity Rules specifies the maximum acceptable NPS voltage level allowable at connection points to the interconnected network. The Network Service Provider (NSP) will allocate the customer a maximum level at the Point of Common Coupling (PCC). The main reason for the restriction on the NPS voltage levels at the point of common coupling is to protect other consumers. Excessive levels of NPS can damage...
rotating machinery. The negative phase sequence voltage when applied to a rotating electrical machine will cause reverse rotating magnetic fluxes. The induced currents in the rotor will result in substantial heating [3]. The high frequency causes substantial skin effect and therefore losses become very high.

The transmission utility ensures acceptable NPS and harmonic distortion levels using the procedures outlined in AS 61000.3.6 and the HB-264 Manual. The procedure apportions maximum distortion limits to arrive at the NPS and harmonic voltage levels to be allocated to the electrified railway and every other consumer connected to the PCC [4]. The effect of the total distorting load should not cause the harmonic levels at any frequency or the NPS voltage to exceed the ‘Planning Levels’. The flow of harmonic currents in the power system can cause failure of capacitor banks, interference to the operation of electronic equipment and additional power loss in rotating machinery.

5 OBJECTIVES OF THE SYSTEMS MODEL

The primary objective of the project is to provide short-term operational strategies and recommendations for long term traction supply augmentations, which enable increased coal haulage, whilst maintaining adequate traction supply system performance and compliance with power quality standards. The recommendations were built around the regulator’s framework of just-in-time, maximum cost-effective solutions. Additionally, investment trigger points will be identified in accordance with the QR Network Coal Infrastructure Master Plan.

6 STRUCTURE OF THE MODEL

An unbalanced load-flow model of the Blackwater electrified railway system and the HV transmission system was developed using the DiSILENT PowerFactory software [5].

Train mechanical data is generated using a detailed RailPlan operational model [6]. The Railplan model takes into account track gradient/curvature, locomotive and train mechanical characteristics, and the timetable supporting the throughput.

This mechanical data, at the wheel, is converted to electrical parameters at the pantograph using a detailed model of the locomotive. SimPowerSystems is used to calculate the active and reactive components of the locomotives power demand at varying speeds and loads [7]. It is also used to generate the electrical harmonic profile of the rollingstock.

The generated locomotive characteristics are then embedded in the PowerFactory software so that the mechanical data can be directly input and converted to dynamic electrical loads. The loads are moved through the system using a scripted algorithm, resulting in realistic Real & Reactive power loading continuously along the track, voltage levels at the pantographs and loading of feeder station equipment. Due to the integrated nature of the model, power quality variables at the points of common coupling could also be realistically determined. The power quality variables are assessed over a 24hr period using statistical analysis.

7 RAILPLAN SOFTWARE DESCRIPTION

Railplan, developed by Funkwerk-IT, is an event driven simulation system based on a traction performance calculation module. This uses the route characteristics and capabilities of the traction units to model the movement of individual trains. Train running times can be captured as an input to developing a robust timetable. Once a timetable has been entered and details of the track layout, signalling, interlocking, operational rules, and driving methodology are completed, RailPlan allows a complete system to be simulated to verify that the timetable will perform as planned.

8 SIMPOWERSYSTEMS SOFTWARE DESCRIPTION

SimPowerSystems extends Simulink with tools for modeling and simulating the generation, transmission, distribution, and consumption of electrical power. It provides models of many components used in these systems, including three-phase machines, power electronic drives, and libraries of application-specific models. Transformers, converters and DC machines can be discretized and efficiently modelled. By coupling the discrete elements together key electrical system parameters, such as, active and reactive power, power factor (PF), current harmonics, Total Harmonic Distortion (THD), efficiency and load flow may be determined.

9 POWERFACTORY SOFTWARE DESCRIPTION

PowerFactory is an unbalanced load flow program developed by DiSILENT in Germany. This program is capable of conducting load flow simulations on very large power system networks. In an unbalanced load flow program the phase quantities remain independent which is a requirement due to the unequal loading provided by the railway. Transformer Automatic Tap Changers must be able to respond in a realistic manner to the unbalanced loading [8]. Also the Static VAr Compensators located at each Feeder Station will respond in an unbalanced manner in terms of VAr compensation on each phase. The
SVC’s are also unbalanced in terms of their MVAr phase ratings.

10 RAILPLAN MODEL DESCRIPTION

The Blackwater rail network was modelled using the layout editor of RailPlan. Figure 3 shows a section of the bi-directional track layout including feeder station, signals, turnouts and yards. Grades, curvature and civil speed limits are uploaded from spreadsheets. The grade profile, civil speed limits and location of feeder stations & Track Sectioning Cabins (TSC) from Callemondah to Burngrove are shown in Figure 4.

Figure 4 Grade profile and civil speed limits Callemondah to Burngrove

To realistically develop the mechanical loading on the system the entire Blackwater network is modelled including the non-electrified branches to Minerva and Rolleston and the Goonyella system electrified loader at Oaky Creek which is expected to ship coal using the Blackwater corridor. All services required to complete the total forecast haulage task are incorporated in the simulation.

The rollingstock is comprehensively detailed using a combination of curves and absolute values. Curves included are: locomotive Tractive Effort (TE) curves, Rake Resistance curves [9] and Braking curves. Absolute values include parameters, such as, the braking characteristics [10], mass, length, maximum speed, rotational inertia, payload, jerk rate, reaction time, power build up and electrical rake data.

The rollingstock are then configured into operational train consists and the model of each train is applied to the simulation as a distributed parameter model along the length of the train.

11 SIMPOWERSYSTEMS 3500/3600 CLASS LOCOMOTIVE MODEL DESCRIPTION

The symmetry of the locomotive two module, two bridge, traction package can be seen in Figure 5 below.

Figure 5 Detailed Locomotive Electrical Model

SimPowerSystems is used to model the electrical system of the worst case electrical load locomotive intended for use on the Blackwater corridor, the 3500 class Clyde ASEA Walkers locomotive. This 1980s generation locomotive incorporates a 4MVA single phase main traction transformer feeding two double bridge phase controlled rectifiers supplying armature current to six DC traction motors. In addition the traction motor fields are fed from field converters (rectifiers). The 250 kVA peak auxiliary three phase load is fed from a converter which includes a controlled rectifier, filtered DC link and inverter.

The locomotive was built with four power factor correction banks which include in each bank capacitance of 1000 μF rated at 910 Vrms, 280 A. These are installed to improve the power factor of the inductive locomotive loading. The locomotive does not carry onboard power filters to reduce the effect that generated current harmonics have on distorting the supply voltage.

Regenerative braking is not a feature of this locomotive. The energy generated by the traction motors during braking is fed directly to an onboard 2MW resistor bank.

From the model, tables are constructed using small increments in speed and tractive effort to describe the electrical loading. By using interpolation still further refinement in the look-up methodology is achieved. A graphical representation of the look-up table is shown in
Figure 6. With the PF correction active and the locomotive operating at the continuous rating of; Speed 40 km/h and Tractive Effort 260 kN, the locomotive has the following electrical characteristics:

- Input Active Power - 3,526 kW,
- Input Reactive Power - 1,134 kVAr,
- Power Factor (PF) - 0.95,
- Efficiency - 81.9%,
- Mechanical power at the wheels - 2,900 kW.

The QR electrification model includes: traction transformers, auto-transformers, isolators, circuit breakers, neutral sections, earth connections, rail and overhead cabling. Switches and isolators can be operated to run the model under contingency conditions with a transformer or feeder station out of service or individual track sections can be isolated.

The impedance parameters of the QR overhead line sections are broken into 2 km sections. The line impedances in each section utilise lumped parameters, however the characteristics approach those of a distributed model due to their short length. Within these sections the train can be positioned with infinite resolution.

An accurate model of the supply network as well as an accurate representation of the railway electrical infrastructure is necessary to obtain a meaningful simulation of the load flow, NPS levels and the level of harmonic disturbance at the points of common coupling.

Figure 7 Example of a QR electrical section in the PowerFactory model

Figure 8 A section of the Central Queensland electricity supply network

External to the railway network the model includes; generators, transformers, transmission lines, distribution lines, Static VAR Compensators, capacitor banks and substations.

The electrical loading of the system is achieved by repositioning the traction load every three seconds and calculating the load flow for the entire system. Depending on the requirements of the simulation these calculations are generally performed for a 24 hour period.

13 MODEL INTEGRATION PROCESS

Each train in an operational simulation conducted using RailPlan Software generates an excel
spreadsheet file of approximately 60,000 rows by 20 columns of data. This data through analysis and the use of macros is reduced to approximately half the size.

The mechanical results are then processed by intermediate algorithms to make the data suitable for input to the Electrical Model. The RailPlan event driven data must be converted into equal time slots. For a 24 hour simulation each train consist will have 28,800 three second rows of data which may be spread over two or three train services. The PowerFactory electrical model must then determine how many locomotives are on the train, divide the input tractive effort by the number of locomotives, look up the locomotive electrical characteristics at this speed and tractive effort, and apply them in the load flow calculation.

The PowerFactory software must solve the supply network electrical loading and voltages at every point in the system. The action of SVC’s tap changing transformers and generation plant in response to load variation is taken into account in an outer calculation loop to the main load flow. Therefore at every time step several converging load flows are solved until a final solution is achieved. The swing bus generator, at which the magnitude and phase angle of the voltage are specified, makes up the difference between the scheduled loads and the generated power that is required to supply the network losses and the time and spatially varying loads from the railway.

For each iteration the initial conditions of the electrical simulation are set by the algorithms working on the mechanical data and the forecast seasonal loading. The initial conditions for each iteration of the mechanical data are necessarily input from the previous step. To simulate a full 24 hours the simulation requires extensive computing resources.

14 MODEL LOADING, VOLTAGE AND POWER QUALITY RESULTS

The model can be used to calculate the voltage appearing at the locomotive pantograph at every simulation step. Figures 9 & 10 show typical output from the simulator for a moving train.

The results in Figure 9 show the position, speed, tractive effort, pantograph voltage for a service from Ensham Mine to the Port of Gladstone. Periods of high tractive effort correspond to the train lifting from standstill or negotiating the two ruling grades. Pantograph voltage fluctuation due to other trains operating in the system are evident. The simulator accurately assesses the effects on pantograph voltage due to trains in the same and adjacent sections, the voltage regulating and balancing function of the SVC’s, and the voltage regulating function of 132kV and 275kV transformer on-load tap changes.

In Figure 10 the coasting effect between Westwood and Stanwell is evident between 14:30 and 15:00 as this loaded train moves towards Callemondah.

By using the train output the instantaneous loading at each Feeder Station transformer can be found taking into account:

- MW and MVAr consumption of all trains in each supplied electrical section
- the aggregate effect of transmission on MW and MVAr

The feeder station loading on the PCC is then determined by taking into account:
- MW and MVAr consumption of all transformers at each feeder station.
- the aggregate effect of transmission on MW and MVAr

Figure 11 shows the MW, MVAr and MVA loading at the 132kV terminals of one of the Feeder Station transformers during a scenario that included the operation of 16 electric train consists.

Figure 11 Typical Feeder Station transformer loading results

It should be noted that the model includes the 50kV harmonic filters. The effect of these on the fundamental quantities is to give a negative 10MVAr flow at times when there is no train loads in the section. At intermediate loading the MVAr level approaches zero and therefore the power factor goes to unity. At peak loading the power factor becomes slightly lagging. The loading can be assessed over a 24hr period with the 1 min, 10 min and 30 min averages being calculated. This assists in determining suitable ratings for the transformers.

A further feature of the simulator is that the total system power demand may be assessed over a 24hr period for the purposes of determining energy usage for a given coal throughput.

Figure 12 Total system power demand over a 24hr period

Figure 12 shows the instantaneous power consumption graph for one particular scenario. The result accurately accounts for railway system transmission losses due to:

- 25kV/50kV Line Losses,
- Transformer losses
- Harmonic Filter losses

The Negative Phase Sequence (NPS) results can be assessed at any location in the electricity network. The levels at the designated points of common coupling are important from a compliance perspective. Figure 13 shows typical NPS results for a 132kV bus under one traffic scenario.

The NPS results at any particular location are the aggregate effect of unbalanced loading from a number of railway sections. The simulator accurately models the combined effect to give realistic results which can be compared with compliance limits.

Figure 13 Negative Phase Sequence results for a transmission system 132kV bus.

15 CONCLUSION

A comprehensive mechanical and electrical model of the Blackwater Coal Transportation railway has been developed. This includes a highly accurate representation of the track gradients and mechanical losses in determining the power, Tractive Effort and speed at the rail.

A detailed electro-mechanical model of the railway locomotive has been constructed to enable realistic calculation of real and reactive electrical power as a function of speed and tractive effort. This data is used as a lookup table in a specially developed load flow algorithm which allows the train loads to be moved throughout the whole rail network. The load flow model includes the associated 132kV and 275kV transmission and generation systems which supply the power.

This comprehensive model allows accurate assessment of all system engineering quantities including:
- Train tractive effort
- Train speed
- Train position
- Pantograph voltage, current and PF
- Feeder Station MW and MVAr loading,
- SVC operating points
- Negative phase sequence voltage at the PCC’s
- Harmonic voltages at the PCC’s
- Total system loading.

This sophisticated modelling allows the many system interactions which exist in an electrified railway/electricity transmission system to be studied in relation to different throughput scenarios. It also allows the accurate assessment of compliance with power quality standards. Based on these results the system augmentation requirements to obtain future throughput levels can be assessed.

The developed models have been used for assessing:
- the present system capacity
- energy consumption
- power quality outcomes as a result of various scenarios
- effect on the electrical system of varying train size & the number of locos per train
- effects of operating AC traction with unity Power Factor and regenerative braking
- effect of operating the locomotives in reduced power mode
- effect of increasing or reducing headway
- electrical system characteristics using contingency events
- effect of changing driver methodology
- short circuit behaviour of the electrical system for protection studies
- harmonic filter design
- augmentation options

16 REFERENCES
[4] HB-264-Power quality manual - Recommendations for the application of AS/NZS 61000.3.6 and AS/NZS 61000.3.7