INVESTIGATION INTO
HARMONICS AND SWITCHING TRANSIENTS
AT SUBSTATIONS EQUIPPED WITH CAPACITOR BANKS
USING ATP SOFTWARE

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1 ABSTRACT

This project titled *Investigation into harmonics and switching transients at substations equipped with Capacitor banks using ATP software* was initiated during a Bachelor of Engineering (Co-op) work placement with Ergon Energy. The project includes two main interests to Ergon Energy. Firstly Ergon Energy is interested in utilising ATP software for transient and harmonic modelling and wish to access its suitability. Secondly Ergon Energy has possibly had some issues with switching transients as a result of capacitor switching and harmonics at some of their substations and wishes to have them further investigated. Models have been developed and testing was carried out at Yeppoon Substation to verify the developed models' results.

2 INTRODUCTION

2.1 Scope

Investigation into the modelling of shunt capacitors when used for VAR or voltage level compensation on the Ergon Energy distribution system. The capacitors may also be accompanied by a series current limiting reactor and/or ripple signal blocking circuit. The main issues to be investigated are; high voltage/current spikes created during switching causing protection trips or over voltage issues, possible harmonic resonance states with various transformer/circuit configurations sinking the 225 Hz ripple control signal.

2.2 Test System

The system used for testing and verification of the developed models was the Yeppoon (66/22/11kV) Substation. Yeppoon was chosen as it has two 4 MVA capacitor banks and there have been unexplained trips in the past. A single line diagram is shown in *Figure 2-1*.

2.3 Objectives

1. Prove that ATP Software is valid for time domain and frequency domain analysis.
2. Create ATP models for the test system and verify with field testing.
3. Identify any current/voltage spikes during switching which has the potential of causing protection trips or over voltage issues.
4. Identify any harmonic resonance that has the potential of sinking the ripple control signal.
5. If the above issues are apparent then suggest possible solutions.
6. Provide a generic model that can be used for future capacitor studies by Ergon Energy Engineers.

This technical paper will concentrate on the ATP modelling aspects (objectives 1-2) of the project. For objectives 3-6 read the full report.

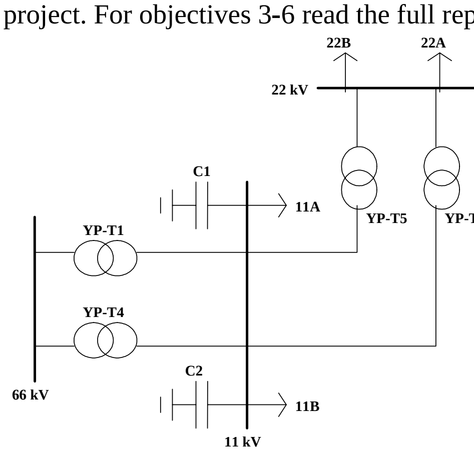

Figure 2-1 – Yeppoon Substation Single Line Diagram

3 ATP SOFTWARE

The software that has been used throughout this project for modelling and simulation is a combination of two separate programs. These programs are ATP Draw and ATP/EMTP (Alternative Transients Program/ Electromagnetic Transients Program).

ATP/EMTP is a well established and proven transients program originating from the times when data cards were inserted into computers for simulation. Although this legacy process still remains a number of GUI programs are now available to simplify the process for users. The GUI program that is used in this case is known as ATP Draw. ATP Draw provides a graphical interface where models can be constructed and then ATP Drawconstructs the data cards for use in ATP/EMTP, therefore simplifying the process for using ATP/EMTP.

The main reasons why ATP Draw and ATP/EMTP were used include:

- The software can be licenced for free.
- Proven and well established software that is continually updated through the ATP user group.
- Can be used for both transient and harmonic simulations.
- Ergon Energy is interested in using the software and this project is a way for them to be exposed to it.

4 ATP MODELLING VERIFICATION

In order to verify the modelling of ATP there is a need for a suitable baseline for comparison. This baseline was provided by performing manual calculations from first principles. *Figure 4-1* was used as the test circuit for transient and harmonic simulation.

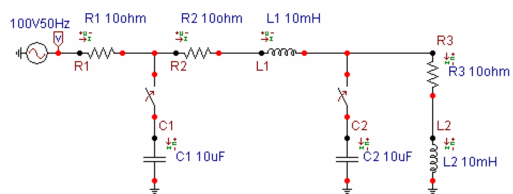

Figure 4-1 – Modelling Verification Circuit

4.1 Transient Modelling

Transient Modelling was conducted by closing the switch to capacitor C2, switch S1 was closed. The baseline of *Figure 4-2* and the ATP results of *Figure 4-3* are almost identical therefore showing that the simulation is valid.

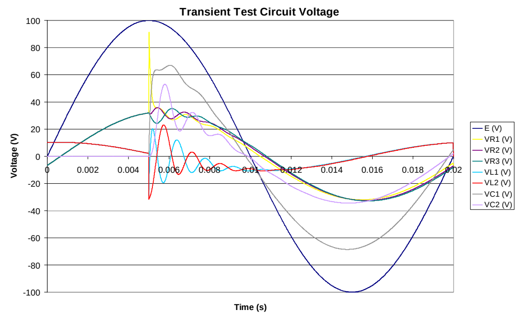

Figure 4-2 – Transient Simulation Baseline Results

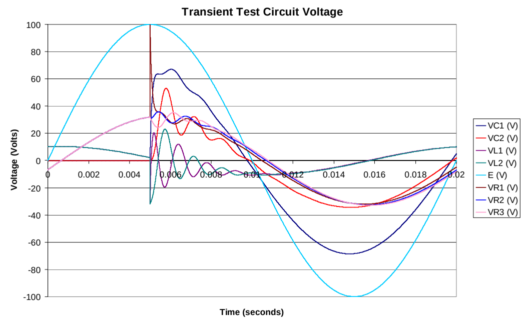

Figure 4-3 – Transient Simulation ATP Results

4.2 Harmonic Modelling

Harmonic Modelling was conducted with switches S1 and S2 closed. The baseline of *Figure 4-4* and the ATP results of *Figure 4-5* show that the simulation is valid.

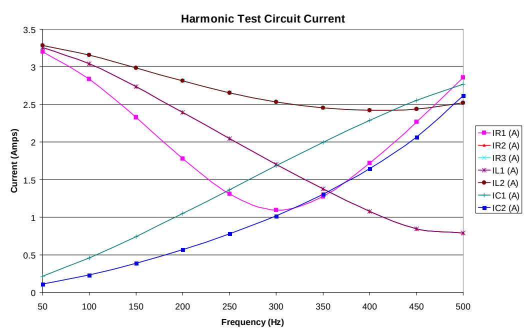

Figure 4-4 – Harmonic Simulation Baseline Results

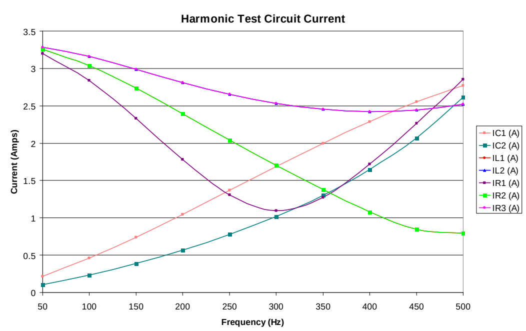

Figure 4-5 – Harmonic Simulation ATP Results

5 SWITCHING MODEL

The following section provides and overview of how the Yeppoon switching model was developed.

5.1 Source

The source that was used for the switching model is from the ATP library and is known as the *3ph Type 14 Source*. The magnitude was set at 55.719kV_{LNpeak} so that the voltage at the 66kV bus would be within acceptable limits.

The source impedance that was used was obtained from Ergon Energy's load flow models and is shown in *Table 5-1*.

R (Ω)	L (mH)
7.960604	43.81128

Table 5-1 – Source Impedance

5.2 Loads

The loads on the substation have been modelled through the use of grouped loads for all feeders on each bus section. Each grouped load has been modelled using two RLC star models connected in parallel. The first RLC model will model the active power of the load using a resistance and the second RLC model will model the reactive power of the load using an inductance. The magnitudes of the loads that were recorded during testing are shown in *Table 5-2* and the parameters for the RLC models are shown in *Table 5-3*.

Bus	Feeder	MW	MVAR
11A	Statue Bay	0.9783	0.4802
	Braithwaite St	1.1227	0.3005
	Arthur St	2.3827	1.6055
	Total	**4.4837**	**2.4826**
11B	Farnborough Rd	1.3715	0.3871
	Cooee Bay	1.4340	0.4698
	Rockhampton Rd	0.8935	0.2705
	Total	**3.6990**	**1.1296**
22A	Tanby	1.7598	0.8598
	Total	**1.7598**	**0.8598**
22B	Waterpark	0.3462	0.1592
	Total	**0.3462**	**0.1592**

Table 5-2 – Load Magnitudes

Bus	R/Phase (ohms)	L/Phase (mH)
11A	26.9867	155.1388
11B	32.7112	340.9680
22A	275.0305	1791.8875
22B	1397.9425	9680.1397

Table 5-3 – Load Parameters

5.3 Capacitor Banks

Figure 5-1 shows the connections of a single capacitor bank unit from Yeppoon. Each 4 MVA capacitor bank consists of six 666.7 kVA units. Of particular interest to the switching model are the inrush resistors and corresponding circuit breakers used for limiting switching transients.

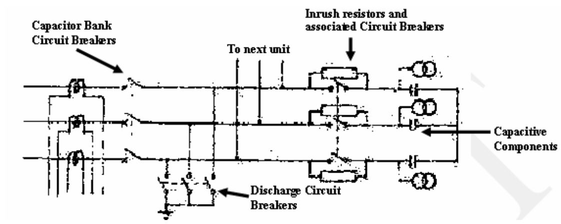

Figure 5-1 – Capacitor Bank Unit Connections

From the specifications of the Capacitor Bank Unit the switching procedure is defined as listed below.

- Connecting Capacitor Bank
  1. Discharge circuit breakers are opened.
  2. Capacitor bank circuit breakers close. Inrush current is limited by inrush resistors.
  3. 250ms later inrush circuit breakers are closed in order to bypass inrush resistors.
- Disconnecting Capacitor Bank
  1. Capacitor bank circuit breakers are opened.
  2. Inrush circuit breakers are opened.
  3. Discharge circuit breakers are closed. Capacitor bank is discharged through the inrush resistors to earth.

Each of the capacitor bank units are modelled as show in *Figure 5-2*. Note that for the final model this will be represented as one block.

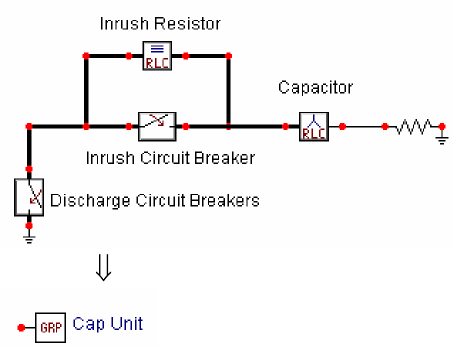

Figure 5-2 – Switching Capacitor Bank Unit Model

The final capacitor bank model (*Figure 5-3*) consists of the models for the six units, the capacitor bank circuit breaker and a series resistance which is used to prevent numerical oscillation in the result. The parameters used in the capacitor bank and unit models are given in *Table 5-4*.

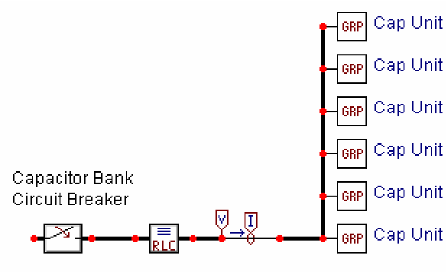

Figure 5-3 – Switching Capacitor Bank Model

Capacitance per Unit	S_{3ph} (MVA)	V_{LL} (kV)	Capacitance / Phase (uF)
	0.6667	13.5	**11.6437**
Inrush Resistors	1.8 ohms		
Series RLC	0.001Ω		

Table 5-4 – Capacitor Bank Model Parameters

5.4 Transformers

There are a total of four transformers in the Yeppoon substation. Each transformer is modelled using ATP Draw's *Saturable 3 Phase Transformer* as it is the only model in the library that is suitable for modelling a practical transformer.

The parameters to be used in the transformer model needed to be calculated from the transformer test data. Transformer test data and calculated ATP parameters are shown in *Table 5-5*.

Transformer Test Data				
Parameter	**Transformer**			
	YP-T5	**YP-T6**	**YP-T1**	**TP-T4**
Freq (Hz)	50	50	50	50
Rating (MVA)	10	10	100	100
Pri (kV)	11	11	66	66
Sec (kV)	22	22	11	11
Iron (kW)	4.41	4.24	11.52	11.52
Copper (kW)	41.246	40.633	73.497	73.497
R %	8.76	8.65	4.415	4.415
Z %	8.772	8.66	4.424	4.424
Vector Grp	Yd1	Yd1	Dy1	Dy1
ATP 3 Phase Saturable Transformer Model Parameters				
Parameter	**Value**			
	YP-T5	**YP-T6**	**YP-T1**	**TP-T4**
V_{RP} (kV)	6.3509	6.3509	66.0000	66.0000
V_{RS} (kV)	22.00	22.00	6.3509	6.3509
R_P (ohms)	0.0277	0.0252	0.0614	0.0614
L_P (mH)	0.1687	0.1666	0.3061	0.3061
R_S (ohms)	0.1110	0.1007	0.0017	0.0017
L_S (mH)	0.6748	0.6663	0.0085	0.0085
I_O (A)	2.3963	2.3552	0.4294	0.4294
F_O (Wb-T)	28.61	28.61	297.30	297.30
R_M (ohms)	27437	28537	1134375	1134375

Table 5-5 – Transformer Model Parameters

5.5 Complete Model

The complete switching model for Yeppoon substation is shown in *Figure 5-4*.

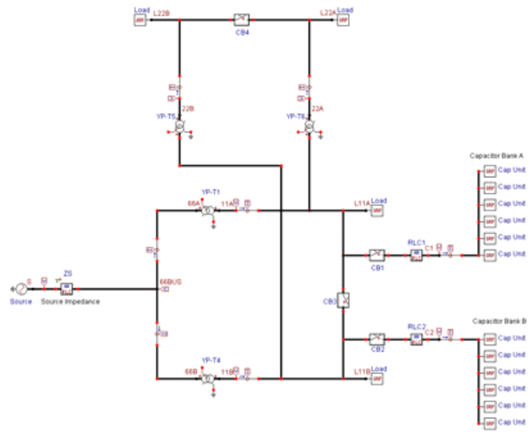

Figure 5-4 – Yeppoon Capacitor Switching Model

6 HARMONIC MODEL

The following section provides an overview of how the Yeppoon harmonic model was developed.

6.1 Source

As the ATP Draw library only includes a single phase harmonic source a three phase source has been modelled using three single phase sources each 120º out of phase in series with the source impedance from *Section 5.1*.

The parameters for the harmonic source were determined from field testing and are shown in *Table 6-1*.

Harmonic Number	Amplitude (RMS)	Harmonic Number	Amplitude (RMS)
1	39399	12	38.75417
2	60.3127	13	37.37538
3	54.21914	14	33.27833
4	29.06974	15	28.23399
5	836.2216	16	28.16842
6	36.42847	17	51.68195
7	412.7532	18	45.70397
8	53.27473	19	38.36003
9	64.16984	20	29.49669
10	32.18343	21	26.38917
11	70.04809		

Table 6-1 – Harmonic Source Parameters

6.2 Loads

ATP Draw includes a frequency dependant load in its library known as the Cigre load. It is a distribution load model based on tests by the Electricite de France [1]. This was found to be unsuitable for this application as it is only valid for harmonic orders 5 and above [2].

A comparison was conducted to find a suitable replacement. This was found to be a resistance and inductance in parallel as used in *Section 5.2*. The comparison of *Figure 6-1* shows close alignment with the Cigre load for harmonic orders 5 and above while also being valid for the fundamental.

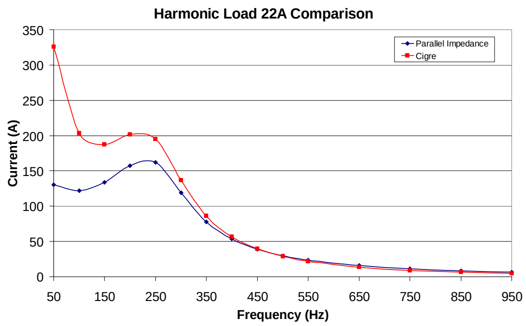

Figure 6-1 – Harmonic Load Comparison

6.3 Capacitor Banks

The capacitor bank models for the harmonic study will be similar to those used in the switching study (*Section 5.3*). The only difference will be the removal of the inrush resistors and associated circuit breakers, as they are not used at steady state.

6.4 Transformers

The transformer models will be the same for the harmonic study as they were for the switching study (*Section 5.4*).

6.5 Final Model

The complete harmonic model for Yeppoon substation is shown in *Figure 6-2*.

7 TESTING

Testing was completed at Yeppoon substation using two PowerMonic recorders, one for each capacitor bank. The recorders were set up to record the following:

1. 11 kV bus voltage transient and harmonics
2. Capacitor Bank 1 current transient and harmonics
3. Capacitor Bank 2 current transient and harmonics

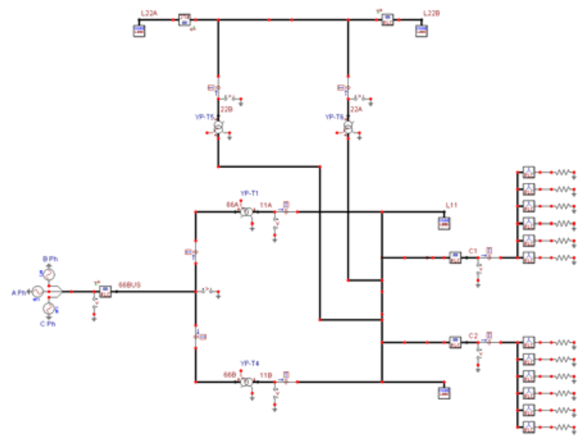

Figure 6-2 – Yeppoon Harmonic Model

The following switching procedure was repeated multiple times to ensure repeatability of the results. The feeder loads were also recorded so that the models can be correctly set up for comparison.

1. Close Capacitor Bank 2
2. Open Capacitor Bank 1
3. Open Capacitor Bank 2
4. Close Capacitor Bank 2
5. Close Capacitor Bank 1
6. Open Capacitor Bank 1
7. Open Capacitor Bank 2
8. Close Capacitor Bank 1

8 MODEL VERIFICATION

8.1 Switching

The results for the 11 kV bus voltage transient that occurs when a capacitor bank is switched in is shown in *Figure 8-1* from the model and *Figure 8-2* from testing. It can be seen that the results are almost identical proving the validity of the capacitor switching model. The results of the model and testing also showed no transient effect on the voltage when switching out the capacitor bank.

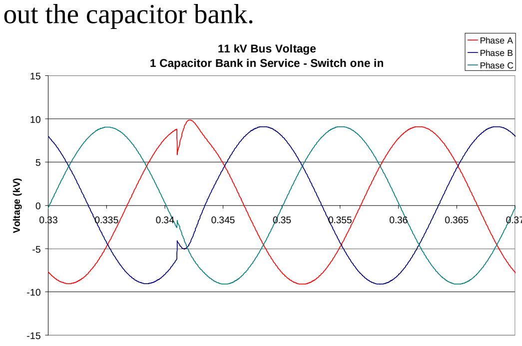

Figure 8-1 – Model Results – 11 kV Voltage

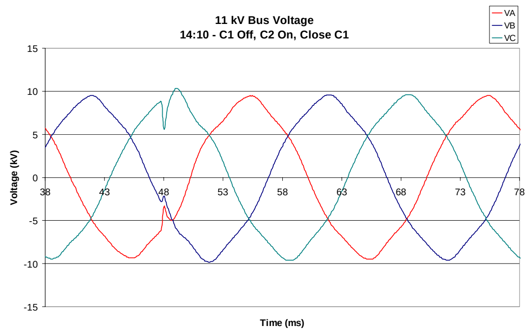

Figure 8-2 – Testing Results – 11 kV Voltage

There was a problem with the recording of the current transients during testing and therefore comparison could not be made in this way. The resulting magnitude of the current transient peak was however confirmed using *Equation 8-1* from [3] which resulted in 796A. The modelled current transient is shown in *Figure 8-3* and results in a similar peak current. The current transient from switching out the capacitor bank in the model was also similar to that recorded in testing.

$$I = \frac{V_{LN}}{X_c - X_L}\left(1 + \sqrt{\frac{X_C}{X_L}}\right) \qquad \textbf{\textit{Equation 8-1}}$$

Where,

V_{LN} = Line to ground operating voltage of capacitor bank

X_C = Phase to neutral capacitive reactance of capacitor bank in ohms

X_L = Phase inductive reactance of source

It can be seen in *Figures 8-1*, *8-2* and *8-3* that there are no instances of voltage or current spikes during switching that has the potential of causing protection trips or over voltage issues.

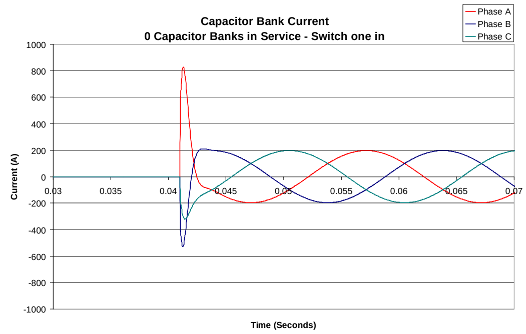

Figure 8-3 – Model Results – Capacitor Bank Current

8.2 Harmonics

The harmonic source parameters of *Table 6-1* were set up for the model using testing results when there were no capacitor banks in service. When there was a capacitor bank in service the results are shown in *Figure 8-4* from the model and *Figure 8-5* from testing. It can be seen that the results for the major harmonics and THD are similar. The model and testing results are also similar when there are two capacitor banks in service.

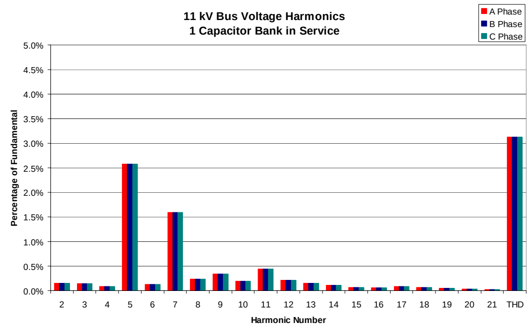

Figure 8-4 – Model Results – 11 kV Bus Harmonics

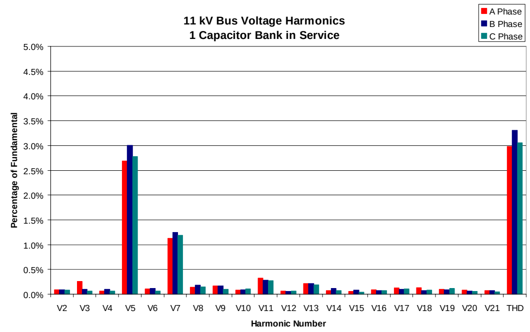

Figure 8-5 – Testing Results – 11 kV Bus Harmonics

9 CONCLUSIONS

- The ATP Software has been successfully validated for transient time domain analysis and steady state frequency domain analysis using first principles.
- ATP models have been created of Yeppoon substation for capacitor switching studies and harmonic studies. These ATP models have also been verified using field testing results from Yeppoon substation.

10 REFERENCES

[1] G. Furst, (1998) *ATP Harmonic Analysis with Harmonic Frequency Scan*. ATP Documentation, April 1998.

[2] ATP Rule Book.

[3] ABB Power T&D Company Inc. (1997) *Electrical Transmission and Distribution Reference Book*, 5th Ed., USA.