TRANSPOWER

Upper North Island Reactive Support Investigation Project

Attachment B

Summary of approach used in SKM motor load survey

Consultation Document

June 2009

Contents

1 Introduction

This document describes the approach used by SKM in collecting data about motor loads from electricity lines businesses in the UNI region.

This document is largely based on a 2006 EEA paper "Voltage Stability of the Upper North Island, Stuart Macdonald, Transpower, Wellington, Kelvin Yee, Sinclair Knight Merz, Auckland, et al".

2 Abstract

In the Auckland and Northern Isthmus, i.e. the Upper North Island (UNI) region, dynamic voltage performance is known to be sensitive to the amount and composition of motor loads in the region. Hence assessment and confirmation of motor load performance is of critical importance for verification of voltage stability limits of the network.

An information collation exercise, by Sinclair Knight Merz, collected suitable data about the motor loads from electricity lines businesses in the UNI region. The method of data collection is presented. For each Grid Exit Point (GXP) the percentage of motor load and the split between large and small types is determined. The motors are also categorised by their expected protection behaviour during and after a grid fault is cleared.

Based on the load survey data, the dynamic voltage stability of the UNI region was assessed by Transpower. The load modelling assumptions, proposed planning guidelines, and proposed voltage performance criteria, used for analysis and assessment of the dynamic voltage stability are described.

The need for additional reactive power support devices in the UNI region is established for winter N-1 conditions. Analysis has shown that, depending on the behaviour of motor loads, the region may experience unacceptably low voltages as well as undesirable over voltages. A reactive compensation scheme for improving the voltage performance is proposed.

3 Background

Transpower has indicated for a number of years that the supply security to the Upper North Island (UNI), which includes Auckland and Northland (Zone 1), will be constrained by Voltage Stability issues. It has undertaken studies to gain a clear indication of how close the region is to voltage collapse and for instigating suitable measures for improving the stability.

Initial studies completed in 2002 indicated that the UNI region is exposed to a risk of voltage collapse under certain operating conditions within the required N-1 security criteria, especially during the summer peak period when there is a high proportion of motor loads in the area. Further, the analysis indicated that the level of risk is very sensitive to the performance of the motor loads following a grid disturbance (e.g. a transmission fault). The key assumptions which have significant impacts on voltage stability limits include the amount of motor loads at each point of supply in the region, the number and locations of large motors (150kW and above), and the behaviour of protection under low voltage. Hence, assessment and confirmation of the motor load performance was considered of critical importance for verifying the initial study findings.

In 2003, SKM undertook an information collation exercise supporting this work. This included collection of suitable load data from the electricity lines businesses in the UNI region, analysis and categorisation of load data, and investigation into and determination of load protection behaviour during and after a grid fault (grid event). Counties Power, Vector, UnitedNetworks, Northpower and Top Energy provided significant effort assisting with the data collection.

Load data was obtained in the requested customer class categories of residential, commercial, industrial and agricultural, and load type categories of static, small motor (<150kW) and large motor. The survey obtained details such as motor type, motor starter/drive type, protection type and motor control philosophy.

Static load, motor and feeder behaviour were analysed to predict the amount of load that remains connected, disconnects and reconnects at various times during a grid event.

Based on the load survey data, the voltage stability of the power system supplying the UNI region was re-assessed. Analysis has shown that, depending on the behaviour of the motor loads during system disturbances, the region could experience low voltages leading to voltage collapse as well as undesirable over voltages in the network. Transpower proposes to mitigate voltage performance issues by augmenting the region’s reactive power support with a combination of synchronous condensers, fast acting Static Var Compensators (SVC), and capacitors.

This paper outlines the results of the load surveys and grid simulations that provided Transpower with the necessary information to define the extent of Var compensation required within the UNI region.

4 Method of data collation

4.1 Apportioning GXP load by Customer Class

This section describes the methodologies used for the Electricity line Businesses (ELB) in the UNI region to gather and organise load information to allocate peak Grid Exit Point (GXP) load to the four customer classes of *residential, commercial, industrial* and *agricultural*.

The ELBs and customers in the UNI region had raw information available in different forms, leading to different methodologies being employed for different data sources.

4.1.1 Availability of metering data

The task was made easy where ELBs have access to customer metering data, including time-of-use data for some of the larger customers. The methodology for allocation of load demand was as follows:

- Where feeders supplied customers of a single class, (eg residential), the average peak demand per customer was calculated from the feeder maximum demand and the known number of customers on the feeder. This calculation was made for residential and agricultural customers.
- Other feeders supplying only two customer classes, one of which was either residential or agricultural, were used in a similar manner to calculate average peak loads for commercial and industrial customers.
- Metering data for large customers, and averaged meter data for industrial and commercial customers were used to improve the accuracy of these calculations

The calculated total peak load for each substation was compared with actual values and found to be acceptably close.

4.1.2 Partial availability of customer class numbers

Some ELBs had no access to customer metering data, but had detailed or summary breakdown of customers for each zone substation. The breakdown included several residential categories, unmetered connections and several classes of so-called “commercial”, which included industrial, agricultural and true commercial.

Velander’s formula was used to estimate the average maximum demand (kW) per customer in each customer class.

The number of residential customers served by each zone substation was known by these line companies.

The number of large industrial customers, and aggregated number of small industrial and large commercial customers were also known by some ELBs.

Other information used to apportion the remaining zone substation’s loads into the three other customer classes of industrial, agricultural and commercial included asset management plan information, local knowledge, housing density maps, and Statistics NZ demographic information.

The calculated total peak load for each substation was compared with the actual values and found to be acceptably close.

4.1.3 Results

The following table outlines the final GXP apportionment for the UNI Region during winter. A summer apportionment was also made but is not presented here.

Customer Types as a % of Total MVA				
BUS#	**Residential**	**Commercial**	**Industrial**	**Agricultural**
1	67.6	23.5	5.3	3.6
2	71.5	20.3	8.3	0.0
3	36.5	11.2	44.0	8.3
4	34.2	29.4	30.2	6.2
5	66.7	9.7	11.2	12.4
6	61.6	11.4	7.2	19.9
7	57.0	19.9	11.4	11.7
8	0.0	0.0	100.0	0.0
9	0.0	0.0	100.0	0.0
10	73.5	16.2	5.8	4.4
11	69.4	16.1	11.5	3.0
12	43.1	5.0	51.9	0.0
13	50.0	20.0	15.0	15.0
14	45.0	10.0	35.0	10.0
15	72.3	20.6	1.7	5.4
16	48.5	27.8	15.2	8.4
17	0.0	0.0	100.0	0.0
18	46.9	8.4	34.6	10.1
19	64.9	9.5	4.2	21.4
20	66.0	28.9	5.1	0.0
21	23.5	72.7	3.8	0.0
22	64.8	22.0	11.0	2.3
23	54.5	23.7	20.0	1.8
24	44.0	30.0	26.0	0.0
25	49.1	35.1	15.8	0.0
26	11.0	74.6	14.4	0.0
27	73.7	14.7	6.4	5.2
28	60.1	19.6	3.9	16.4
29	37.5	38.8	23.7	0.0

Table 1: Apportionment of GXP load by Customer Sector

Winter Window (June – August, 1800-2000 hours)

4.2 Identification of Large Motors at each GXP

Large motors were defined as being greater than or equal to 150kW (200hp). This portion of the data-gathering exercise was split into two groups: large ELBs and smaller ELBs.

4.2.1 Small ELBs

Discussions with smaller ELBs supported the belief that it would be possible to gather information on every large motor.

4.2.2 Large ELBs

SKM approached selected customers within the large ELBs and interviewed them regarding the number, size and behaviour of their large motors. Interviews were restricted to technical discussions on motor protection settings, control system philosophies and customer experience with historical outages and voltage dips.

Although this methodology did not provide an exhaustive list of every large motor within the large ELB areas, it provided a sample of the large motors in the region and supported observations made from the information collated from the smaller ELBs.

4.3 Apportioning Customer Class Load by Load Type

Load types were defined as being static, small motor (less than 150kW) and large motor (equal to or greater than 150kW).

In order to derive a representative breakdown of each customer class's load into static / small motor / large motor types, it was necessary to carry out detailed analysis on a selected sample and apply the findings over the entire UNI region.

One ELB was selected to assist with this item of investigation because of two reasons:

the ELB supplies a wide range of customer classes and sizes, and could therefore be considered a representative cross-section of the UNI region.

the ELB has access to customer metering data, and could therefore contribute real maximum demands for different classes of customers.

In summary, the real power analysis for each selected customer was as follows:

i) Determine the total peak load in kW from meter data

ii) Determine the large motor load in kW from the large motor survey

iii) Calculate static kW using building services / energy audit methods

iv) Assume that small motor kW = total kW - large motor kW - static kW

This produced a breakdown of load types by static, small motor and large motor load, and was carried out for each customer group in the sample for a winter window and a summer window. The findings were grouped into commercial, industrial and agricultural customer classes using weighted averages. Residential loads were not studied in this exercise, as the breakdown of residential load into small motor load and static load is better understood.

5 Response of motor load

The following factors influence motor behaviour during and after a grid fault when supply voltages are low:

- Motor type

- Starter/drive type
- Protection device
- Control system philosophy

Induction motors were found to be so prevalent in the UNI that other motor types were ignored as their effect was negligible. The following sections outline the study findings in relation to motor response.

5.1 Motor Starter/Drive Type

The following sections outline the major starter/drive types and their characteristics.

5.1.1 AC Contactors

AC contactors are used for the direct-on-line (DOL) starting and stopping of the vast majority of industrial motors. If the control voltage (one phase) momentarily falls below a certain value the contactor will drop out, disconnecting the motor from its supply. Investigations undertaken indicated that a three phase fault of 120 ms duration on the Otahuhu 220kV bus would cause widespread dropout of contactors.

Moreover, when the supply voltage is restored, motor restart may occur but would depend on the overall motor control system requirement.

5.1.2 Soft starters

For a sudden severe sag of 120 ms duration, soft starters will trip and most will automatically reset. Again, motor restart will depend on the overall control system.

5.1.3 Variable Speed Drives

In the event of a trip, VSDs can automatically reset and be ready to restart, depending on the overall control system.

5.2 Protection Devices

5.2.1 Thermal overload relay

The majority of motors less than 45kW are protected by a bimetallic type thermal overload relay with an approximate $I^2t = K$ characteristic. A bimetallic strip has a cold curve and a more sensitive hot curve. Class 10 relays are the most common in New Zealand.

If the motor stalls and draws a locked-rotor current (usually about 600% of rated value, but can be as high as 750%) the overload relay will trip in 2 seconds according to typical hot curve characteristics.

After a 220kV three phase fault is cleared in 120ms and the supply voltages begin to recover, motors used in non-sensitive processes such as water pumping stations will attempt to automatically restart. A typical re-acceleration current for a spinning motor with high inertia (around 300% full load current) will be allowed to flow for around 8 seconds for Class 10 relays. If the motor stalls in the attempt to restart due to insufficient supply voltage or a process-related high load, the thermal overload relay will trip after 2 seconds for Class 10 relays.

5.2.2 Motor management relays

Electronic motor management relays are used to protect large motors. The thermal overload protection will operate in a similar fashion to the bi-metallic strip overload relay.

Undervoltage protection is also provided in the motor management relay. Typical undervoltage trip settings would be for supply voltages less than 80% for 4 to 5 seconds.

5.3 Control system philosophy

Whether the motor is instructed to carry on, or trip off and go through its startup sequence, or trip off and request manual or system intervention will depend on the process with which the motor is involved.

Motors used in sensitive processes such as plastic moulding or food processing have little or no tolerance for power disturbances and will be instructed to trip off and await operator intervention (ie control restart = “no”).

Other cases were found where the motor will be commanded to simply carry on as if nothing had happened, such as in pumping stations or ventilation fans (ie control restart = “yes”).

5.4 Categorisation of motors according to expected behaviour

5.4.1 Initial Categories

By combining the above three factors into their feasible combinations, 20 distinct behavioural categories were identified and are described in Table 2.

TIMELINE OF EVENTS					**Time after Fault clearance**			
Item		**Protection**	**control restart**	**120ms 3ph 220kV fault**	**0 +**	**2-3 sec**	**4-5 sec**	**> 8sec**
1a	Large motors with circuit breakers or latched or DC contactors	U/V & O/L	yes	ride through	reacceleration		trip if V<80%	trip if I>300%
1b			no	ride through	trip			
1c		O/L	yes	ride through	reacceleration	trip if stalled		trip if I>300%
1d			no	ride through	trip			
2a	Large motors with AC contactors	U/V & O/L	yes	trip	reacceleration		trip if V<80%	trip if I>300%
2b			no	trip	stop			
2c		O/L	yes	trip	reacceleration	trip if stalled		trip if I>300%
2d			no	trip	stop			
3a	Small motors with AC contactors	O/L	yes	trip	reacceleration	trip if stalled		trip if I>300%
3b			no	trip	stop			
4a	VSD motors (large$small)	U/V & O/L	yes	ride through	reacceleration		trip if V<80%	trip if I>300%
4b			no	ride through	trip			
5a	Soft starter	U/V & O/L	yes	trip	reacceleration		trip if V<80%	trip if I>300%

5b	motors (large&small)		no	trip	stop			

Table 2 Motor behaviour – 20 categories

5.4.2 Category Population

In order to assign percentages of motor load to these 20 behavioural categories, the following assessments were made:

- **Large/small motor.** The split of large/small motor load was calculated from information gathered.
- **Starter/drive type and protection device.** The split of starter/drive type and protection devices was calculated/estimated based on large and small motor lists, meetings and discussions with ELBs, product vendors and end customers.
- **Control restart “yes” or “no”.** In order to calculate/estimate the split of control system philosophy, it was necessary to firstly estimate the distribution of motor-driven processes in the UNI region. For residential motors, it is known that there is no control system as such. The control philosophy for commercial motors was investigated. The NZ Energy Data File was used to derive a breakdown of sensitive / non-sensitive motor-driven processes for agricultural and industrial loads in the UNI region. It was necessary to make the general assumption that the annual energy consumption is approximately proportional to peak load. Applying knowledge of how the control systems for these motor-driven processes are typically arranged, SKM was able to derive a probability distribution on control system philosophy for industrial and agricultural motors in the UNI region.

The distributions were multiplied according to probability to produce percentages of total motor load assigned to the 20 behavioural groups for each of the four customer classes, as shown in Table 3.

TIMELINE OF EVENTS					% of total motor load			
Item		**Protection**	**control restart**	**120ms 3ph 220kV fault**	**Residential**	**Commercial**	**Industrial**	**Agricultural**
1a	Large motors with circuit breakers or latched or DC contactors	U/V & O/L	yes	ride through	0.0%	0.0%	1.2%	0.0%
1b			no	ride through	0.0%	0.0%	1.8%	0.0%
1c		O/L	yes	ride through	0.0%	0.0%	0.8%	0.0%
1d			no	ride through	0.0%	0.0%	1.2%	0.0%
2a	Large motors with AC contactors	U/V & O/L	yes	trip	0.0%	0.0%	7.2%	0.0%
2b			no	trip	0.0%	0.0%	10.8%	0.0%
2c		O/L	yes	trip	0.0%	0.0%	4.8%	0.0%
2d			no	trip	0.0%	0.0%	7.2%	0.0%
3a	Small motors with AC contactors	O/L	yes	trip	100.0%	26.0%	20.0%	34.0%
3b			no	trip	0.0%	14.0%	30.0%	51.0%
4a	VSD motors (large$small)	U/V & O/L	yes	ride through	0.0%	32.5%	4.0%	4.0%
4b			no	ride through	0.0%	17.5%	6.0%	6.0%
5a	Soft starter motors (large&small)	U/V & O/L	yes	trip	0.0%	6.5%	2.0%	2.0%
5b			no	trip	0.0%	3.5%	3.0%	3.0%

Table 3: Motor behaviour – representative quantities of the 20 categories

5.4.3 Grouping by behaviour in 30 second period after fault

For the purposes of modelling aggregated loads for voltage stability, it was found that in the 30 second period of critical interest immediately following clearance of a transmission fault, the 20 motor categories could be lumped into three groups (ie Groups 1, 2 and 3), based on their similar behaviour within short time slots.

The groupings are shown in Table 4, where items 1a – 5d refer to the 20 motor behavioural categories described in Table 2.

Grouping by behaviour in timeframe 30seconds after grid fault					
Group	**Conditional behaviour**	**Time after fault clearance**			
		0 +	**2-3 sec**	**4-5 sec**	**> 8sec**
Group 1: 1b, 1d, 2b, 2d, 3b, 4b, 5b	Trip	yes			
	Remain off	yes	yes	yes	yes
Group 2: 1c, 2c, 3a	Trip	yes			
	Reaccelerate if & when V>80%	yes			
	Trip if stalled		yes		
	Trip if I>300%				yes
Group 3: 1a, 2a, 4a, 5a	Trip	yes			
	Reaccelerate if & when V>80%	yes			
	Trip if stalled		yes		
	Trip if V<80%			yes	
	Trip if I>300%				yes

Table 4 Motor grouping according to behaviour following fault clearance

The following points summarise the expected behaviour of motors following a three phase grid fault when the voltage is low:

- A substantial percentage of motors will trip during the 120ms fault period because of contactor de-energisation.
- The small remaining percentage of motors that are connected by latched contactor, CB or other device may remain connected during the 120ms fault period, but as they will have no supply voltage (unless supported by local generation) until the fault is cleared, they will not draw any current. The 120ms fault period will produce a small loss in motor rotating inertia.
- A large proportion of all motors will be tripped and/or kept disconnected for at least 30 seconds by their control system. These are presented in Table 4 as **"Group 1"**.

- The remainder will attempt to re-connect or re-accelerate after the fault is cleared and the voltage recovers to above 70-80%. It is assumed that voltage recovery will initially be strong after fault clearance and contactors will re-energise very soon after fault clearance. Therefore for grouping purposes, “time after fault clearance” is used synonymously with “time after motor re-connection”.
- Of the motors that reconnect shortly after the fault or did not trip at all, overcurrent protection will operate if they draw starting current (about 600% times rated) for 2-3 seconds after re-connecting. These are presented in Table 4 as “**Group 2**”.
- Of the motors that reconnect shortly after the fault or did not trip at all, undervoltage protection will operate if the voltage remains under 80% for 4-5 seconds after the motor has re-connected. These motors also have overcurrent protection similar to Group 2. These are presented in Table 4 under “**Group 3**”.
- Finally, overcurrent protection will operate if motors draw reacceleration current (3 x rated) for 8 sec after fault cleared. These are presented in the results under “Group 2” and “Group 3”.

5.5 Feeder Protection Low Voltage Response

Feeder overcurrent protection is mainly of the inverse definite minimum time (IDMT) type.

Power system voltage instability causing momentary or sustained load overcurrent can in theory result in operation of feeder overcurrent protection. The most likely scenario for this to occur is on an industrial feeder with a high percentage of motor load attempting to restart simultaneously following a severe voltage dip and contactor dropout. It can be shown theoretically that this will be unlikely to occur.

Based on discussion with ELBs SKM could find no evidence that indicate that distribution feeders would (by feeder protection) as a result of Transpower faults or voltage depressions. Whilst the phenomenon is theoretically possible, the occurrence of industrial feeders with high percentages of motor load attempting to restart *simultaneously* with high re-acceleration current following a severe voltage dip and contactor dropout has been assessed to be very rare.

Therefore it was concluded that all static load should remain connected throughout the event period, and that motor load should be disconnected/reconnected according to the individual on motor set behaviour.

5.6 Summary Table

The results of Table1, Section 2.3, Table 3, and Table 4 are summarised for a select number of busses as the following tables, for Winter and Summer separately.

WINTER WINDOW (Jun - Aug, 1800-2000 hrs)							
BUS#	**Static (%)**	**Motor Load (% of total MVA)**					
		Group 1		Group 2		Group 3	
		Large	Small	Large	Small	Large	Small
1	72.2	0.9	8.3	0.2	12.3	0.5	5.6
4	49.7	5.3	18.6	1.2	15.1	2.3	7.8
5	67.4	2.0	12.2	0.5	13.8	0.9	3.2
7	63	2.0	13.9	0.5	14.3	0.9	5.4
10	74.6	1.0	7.5	0.2	12.2	0.5	4.0
11	50.8	9.1	17.0	2.2	14.1	4.0	2.8
13	57.7	2.6	16.9	0.6	15.3	1.2	5.7
14	52.3	6.2	18.3	1.5	15.2	2.7	3.8
15	74.6	0.3	7.6	0.2	12.3	0.1	4.9
16	59.2	2.7	14.9	0.6	14.3	1.2	7.1
18	53.3	6.1	17.9	1.4	15.1	2.7	3.5
21	53.1	0.7	15.7	0.1	13.8	0.3	16.3
22	70	1.9	9.0	0.4	12.4	0.9	5.4
23	63.2	3.5	11.9	0.8	13.0	1.6	6.0
25	62.3	2.8	11.9	0.6	12.9	1.2	8.3
27	74.3	1.1	7.8	0.3	12.2	0.5	3.8
28	64.6	0.7	14.1	0.2	14.7	0.3	5.4
29	55	4.2	15.1	1.0	13.6	1.7	9.4
Total	**61.9**	**3.8**	**11.8**	**0.9**	**13.1**	**1.7**	**7.0**

Table 5 Static and Motor Load Model by GXP for winter

SUMMER WINDOW (Mid Jan - Mid Mar, 1200-1400 hrs)							
BUS#	**Static (%)**	**Motor Load (% of total MVA)**					
		Group 1		Group 2		Group 3	
		Large	Small	Large	Small	Large	Small
1	45.8	2.7	16.4	0.6	22.5	1.2	10.8
4	35.0	5.5	23.2	1.3	21.7	2.4	11.0
5	39.8	5.6	20.9	1.3	22.2	2.5	7.7
7	64.3	17.2	4.2	3.9	2.4	7.6	0.4
10	49.3	3.0	14.9	0.7	23.0	1.3	7.9
11	27.8	14.0	26.0	3.2	18.8	6.2	4.0
13	33.4	4.6	25.2	1.0	22.4	2.0	11.4
14	31.4	10.7	25.8	2.4	20.9	4.7	4.1
15	44.6	0.9	16.8	0.2	22.6	0.4	14.4
16	31.0	5.5	25.3	1.3	21.3	2.4	13.2
18	28.7	11.5	26.4	2.6	19.9	5.1	5.9
21	27.4	1.3	24.8	0.3	20.4	0.6	25.4
22	35.1	6.2	21.8	1.4	20.8	2.7	11.9
23	37.5	7.1	20.6	1.6	20.9	3.1	9.3
25	33.1	6.2	22.4	1.4	20.3	2.7	13.9
27	43.7	2.5	17.9	0.6	22.6	1.1	11.7
28	41.1	1.8	22.1	0.4	24.2	0.8	9.6
29	28.5	7.5	24.9	1.7	19.7	3.3	14.4
Total	**36.0**	**6.5**	**20.4**	**1.5**	**20.3**	**2.9**	**12.5**

Table 6 Static and Motor Load Model by GXP for summer