RECLAMATION
Managing Water in the West

ANALYSIS OF SYNCHRONOUS MACHINES WITH BYPASSED COILS USING FEM-BASED MODELING SOFTWARE

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14. ABSTRACT *(Maximum 200 words)*
In this report, defined operating points of an existing hydro-electric generator with bypassed coils are simulated using Finite Element Method (FEM)-based modeling software using a 2-D model of the generator consisting of the rotor and stator core, rotor poles, field winding, damper bars, and stator coils. Separate electrical circuits for the field winding, the damper winding, and the stator circuits are also defined to simplify the model. The resulting model is then used to simulate a machine at rated operating conditions without bypassed coils and then at various operating conditions with bypassed coils. The results for the model are further analyzed and compared to corresponding measured field data to assess the accuracy of the model.

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Executive Summary

There are two hydro units at the Glen Canyon power plant which have had temporary bypass work performed on their stator windings after sustaining significant damage. While performing load tests on unit G2, Reclamation's Diagnostics Team measured the parallel winding currents flowing in this unit at various operating points. A numerical model was then developed in Finite Element Method (FEM) modeling software to represent the bypass work performed on the unit. With this model, the operating points measured by the Diagnostics Team were simulated, and the resulting currents calculated in the winding were compared to the corresponding field data to assess the model's accuracy.

The simulations performed at the operating points with either a unity power factor (excluding the low loading operating point) or a lagging power factor produced currents that were within a 7% margin of error. The simulations performed at the operating points with a leading power factor produced currents that were less accurate, with the worst case margin of error at roughly 18%. Overall, while the majority of simulations performed for this unit produced results within an acceptable margin of error, the inputs and assumptions could be refined to obtain more accurate results for operating points with a leading power factor.

Contents

1.0 Introduction

This report outlines the history of unit G2 at Glen Canyon power plant from when its winding sustained damaged to when the unit was rewound, details the measurement results, describes the inputs and assumptions used to create the numerical model, and shows the simulation results and compares them to the field measurements.

2.0 Unit G2 Data

2.1 Unit G2 Damage & Repair History

The stator winding of unit G2 sustained damage on December 1, 2001, as it was being manually brought online [2]. When water from cooling equipment located one floor above the unit leaked into the unit's air housing deck and into the machine, it caused a ground fault to occur in the A-phase of the winding. This was detected by the unit's ground fault relay, which tripped the unit offline before the unit breaker was closed.

During multiple visits to the plant, Reclamation's Diagnostics Team worked with plant personnel to assess G2's electrical and physical condition and dried the stator winding by operating the unit into a bolted terminal short. They then located the two stator coils where the fault occurred and electrically isolated them by bypassing the entire parallel circuit that contained them. The unit was then successfully brought back online on February 20, 2002, and was subsequently operated at reduced capacity until the unit was rewound in November of that year.

Before the unit was rewound in November 2002, G2's winding was rated for 165 MVA at 13.8 kV and a lagging power factor of 0.95. After it was rewound, the rating was increased to 174 MVA at the same voltage and power factor.

2.2 Unit G2 Field Measurements

Prior to unit G2's rewind, the Diagnostic Team recorded data on the unit's temporarily repaired winding to examine the effects of electrically bypassing an entire parallel circuit. The measurements consisted of the current flowing in each of the unit's parallel circuits (excluding the one that was electrically removed), as well as the total current flowing out of each phase of the machine.

The measurements made on G2 were collected at six different operating points, as shown in Figure 1. For four of these points, no MVARs were generated or absorbed by the unit (unity power factor) while the maximum loading limit was being determined; for the other two points, MVARs were generated and absorbed by the unit at a MW loading just below the maximum limit previously determined.

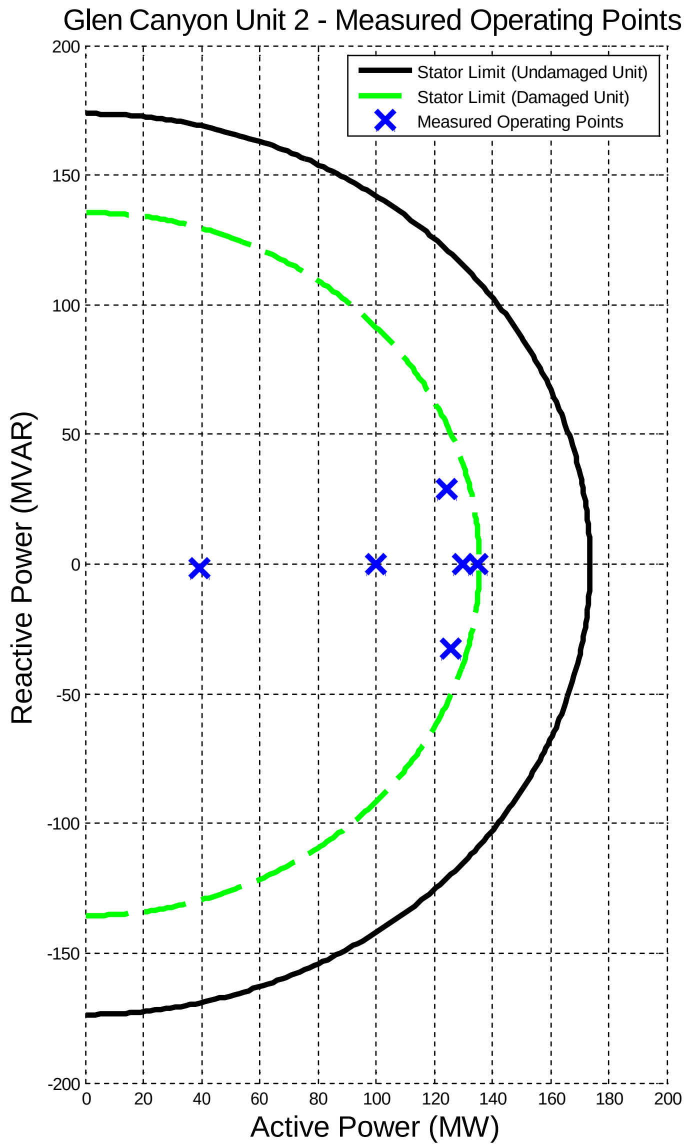

Figure 1: Glen Canyon Unit G2 – Measured Operating Points

The following tables detail the resulting currents measured from G2. Table 1 shows the field and line currents measured for each operating point. Tables 2, 3, and 4 show the parallel circuit currents for phases A, B, and C, respectively, as well as the percentage of total line current each circuit generates. Note that there are no measurements for circuit A5, as this was the circuit electrically removed from G2's winding. There are also no measurements for circuit B7, since the clamp CT placed on this circuit's jumper failed during testing.

Table 1: Glen Canyon Unit G2 – Measured Field Current and Phase Currents

MW	MVAR	If (A)	Ia (A)	Ib (A)	Ic (A)	Average Current (A)
39.4	-1.3	466	1552	1648	1776	1659
100	0	580	4032	4240	4336	4203
130	0	650	5216	5536	5600	5451
135	0	662	5488	5760	5800	5683
124.5	29	772	5088	5312	5456	5285
125.8	-32.6	500	5264	5584	5696	5515

Table 2: Glen Canyon Unit G2 – Measured A-Phase Circuit Currents

Unit Loading		T4-26		T10-71		T4-116		T10-161	
MW	MVAR	A1 (A)	% of Ia	A2 (A)	% of Ia	A3 (A)	% of Ia	A4 (A)	% of Ia
39.4	-1.3	230	14.80%	168	10.80%	212	13.70%	211	13.60%
100	0	582	14.40%	570	14.10%	564	14.00%	565	14.00%
130	0	753	14.40%	740	14.20%	732	14.00%	730	14.00%
135	0	785	14.30%	774	14.10%	768	14.00%	765	13.90%
124.5	29	735	14.40%	721	14.20%	715	14.10%	713	14.00%
125.8	-32.6	759	14.40%	740	14.10%	734	13.90%	740	14.10%

Unit Loading		T4-206		T10-251		T4-296		T10-341	
MW	MVAR	*A5 (A)	% of Ia	A6 (A)	% of Ia	A7 (A)	% of Ia	A8 (A)	% of Ia
39.4	-1.3	N/A	N/A	236	15.20%	230	14.80%	222	14.30%
100	0	N/A	N/A	608	15.10%	584	14.50%	575	14.30%
130	0	N/A	N/A	788	15.10%	756	14.50%	747	14.30%
135	0	N/A	N/A	824	15.00%	790	14.40%	780	14.20%
124.5	29	N/A	N/A	768	15.10%	735	14.40%	727	14.30%
125.8	-32.6	N/A	N/A	792	15.00%	765	14.50%	756	14.40%

*Circuit electrically removed

Table 3: Glen Canyon Unit G2 – Measured B-Phase Circuit Currents

Unit Loading		T5-40		T11-85		T5-130		T11-175	
MW	MVAR	B1 (A)	% of Ib	B2 (A)	% of Ib	B3 (A)	% of Ib	B4 (A)	% of Ib
39.4	-1.3	209	12.70%	186	11.30%	179	10.90%	200	12.10%
100	0	532	12.50%	500	11.80%	490	11.60%	528	12.50%
130	0	692	12.50%	652	11.80%	642	11.60%	681	12.30%
135	0	698	12.10%	684	11.90%	674	11.70%	715	12.40%
124.5	29	642	12.10%	632	11.90%	627	11.80%	657	12.40%
125.8	-32.6	675	12.10%	660	11.80%	756	13.50%	695	12.40%
Unit Loading		T5-220		T11-265		T5-310		T11-355	
MW	MVAR	B5 (A)	% of Ib	B6 (A)	% of Ib	**B7(A)	% of Ib	B8 (A)	% of Ib
39.4	-1.3	242	14.70%	214	13.00%	N/A	N/A	202	12.30%
100	0	624	14.70%	538	12.70%	N/A	N/A	517	12.20%
130	0	805	14.50%	692	12.50%	N/A	N/A	667	12.00%
135	0	843	14.60%	723	12.60%	N/A	N/A	696	12.10%
124.5	29	777	14.60%	667	12.60%	N/A	N/A	641	12.10%
125.8	-32.6	817	14.60%	705	12.60%	N/A	N/A	681	12.20%

**Clamp-on CT failed, no data recorded

Table 4: Glen Canyon Unit G2 – Measured C-Phase Circuit Currents

Unit Loading		T6-51		T12-96		T6-141		T12-186	
MW	MVAR	C1 (A)	% of Ic	C2 (A)	% of Ic	C3 (A)	% of Ic	C4 (A)	% of Ic
39.4	-1.3	214	12.00%	205	11.50%	201	11.30%	233	13.10%
100	0	518	11.90%	515	11.90%	515	11.90%	585	13.50%
130	0	672	12.00%	667	11.90%	672	12.00%	756	13.50%
135	0	695	12.00%	690	11.90%	692	11.90%	780	13.40%
124.5	29	656	12.00%	650	11.90%	652	12.00%	737	13.50%
125.8	-32.6	678	11.90%	678	11.90%	680	11.90%	765	13.40%
Unit Loading		T6-231		T12-276		T6-321		T12-6	
MW	MVAR	C5 (A)	% of Ic	C6 (A)	% of Ic	C7 (A)	% of Ic	C8 (A)	% of Ic
39.4	-1.3	258	14.50%	226	12.70%	221	12.40%	217	12.20%
100	0	634	14.60%	538	12.40%	525	12.10%	524	12.10%
130	0	822	14.70%	691	12.30%	678	12.10%	675	12.10%
135	0	850	14.70%	715	12.30%	697	12.00%	696	12.00%
124.5	29	802	14.70%	672	12.30%	657	12.00%	654	12.00%
125.8	-32.6	828	14.50%	704	12.40%	695	12.20%	686	12.00%

The maximum load limit from the measurements shown above was determined to be 135 MVA, or roughly 82% of the rated operating limit for G2 prior to sustaining damage. Overall, this meant an 18% reduction in loading from the rated operating limit for G2. The reduction in loading recommended based on EPRI report EL-4983 was only half of this (9%), which would have put the loading limit at 91% of the rated operating limit.

From these measurements, the effect of removing an entire parallel circuit from G2's stator winding can be seen. Since circuit A5 was removed, the magnetic flux from the rotor induced higher voltages (and thus higher currents) in the corresponding circuits B5 and C5. The highest parallel circuit current measured in G2's stator winding at the maximum load limit was 850A in circuit C5, which is just below the rated current per circuit, 865A. This value was 20% higher than what the current would have been in a similar undamaged winding.

3.0 Unit G2 FEM Model

A 2-D symmetrical model, shown in Figure 2, was created for unit 2 at Glen Canyon using the FEM-based software, MagNet. This model was developed primarily using Reclamation drawings and machine data, which included nameplate ratings, physical dimensions, and winding coil connections. The numerical model was used to run simulations of both the damaged winding from 2002 and the current undamaged winding, and the results were compared to the previously mentioned field data to assess the accuracy of the model.

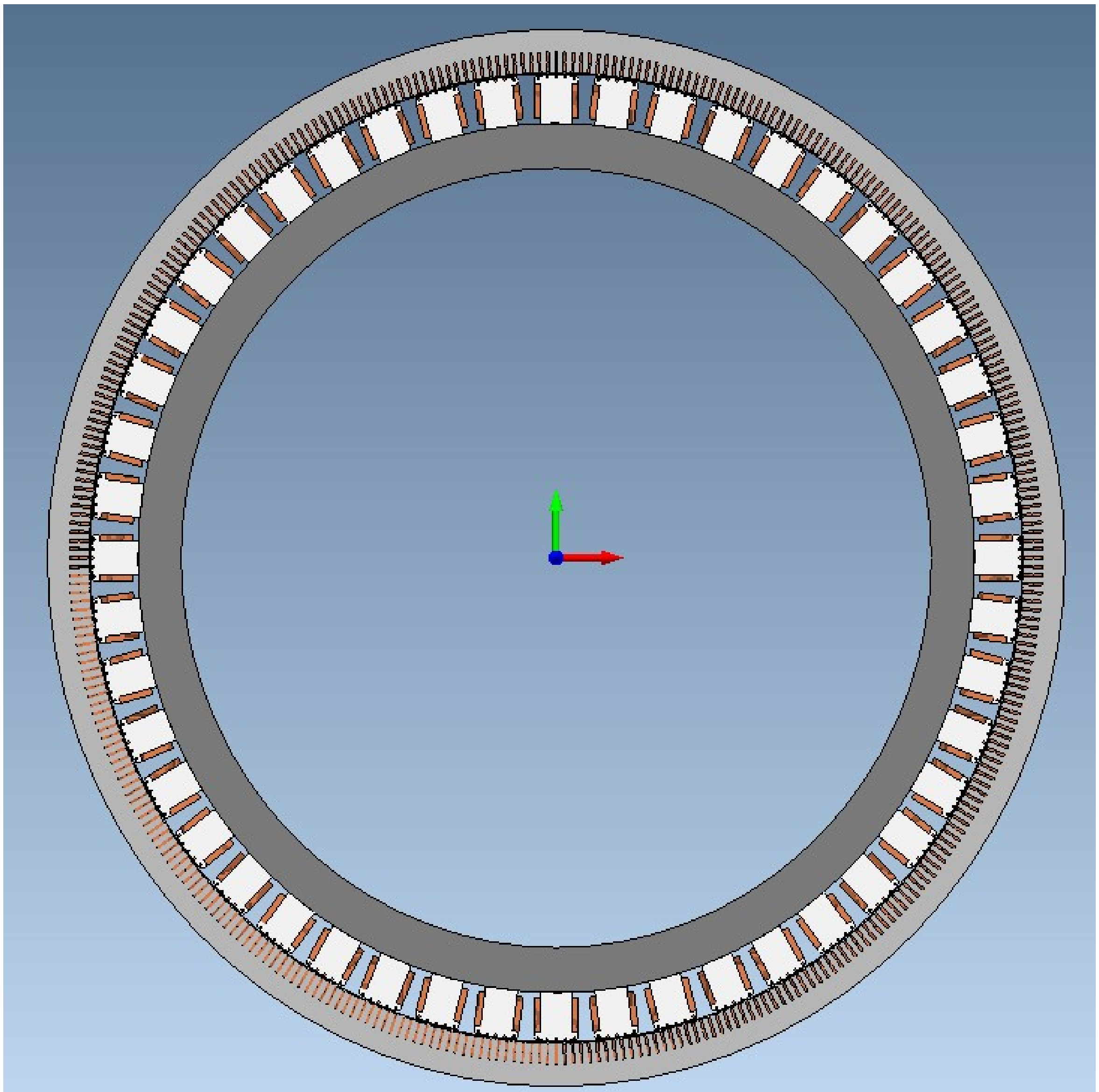

Figure 2: Glen Canyon Unit G2 – Synchronous Machine Model

3.1 Model Inputs & Assumptions

The general information that was used to create the 2-D synchronous machine model in MagNet included information on the number of poles and stator coils, the number of turns per coil (rotor and stator coils), the stator coil pitch, the air gap thickness, and the depth of the core material (which was used to define the depth of the entire model). These inputs are listed in Table 5.

Table 5: Glen Canyon Unit G2 – General Information

General Parameters	Value
Number of Poles	48
Number of Rotor Coil Turns (per pole)	33
Number of Stator Coils	360
Number of Stator Coil Turns (per coil)	3
Stator Coil Pitch	1 to 8
Air Gap Thickness (inches)	0.58
Model Depth (inches; based on core depth)	83.5
Number of Stator Circuits (per phase)	8

The physical dimensions used to develop the model for G2 were divided among those for the stator, those for the rotor, and those for the damper bars. Table 6 shows these dimensions, which were used to create the outlines for the rotor core, poles and coils, the stator core and coils, and the damper bars.

Once the model outline was finished, each of the components was created using the model depth specified in Table 5. The damper bars, rotor coils, and stator coils were modeled as solid pieces (including insulation) using the pre-defined model material 'Copper: 101% IACS (ETP)' from MagNet's material library. Both cores and all 48 poles were modeled with user defined materials. The magnetic permeability and loss data for these materials were referenced from a similar CEATI study, whose report is titled *Operation of Hydro Generators with Bypassed Stator Coils.* The mass density for these materials was provided by USBR.

Table 6: Glen Canyon Unit G2 – Physical Dimensions

Stator Parameters	Value (inches)
Stator Inner Radius	155
Stator Outer Radius	168.875
Wedge Offset	0.015
Wedge Length (radial)	0.188
Wedge Width	0.1085
Stator Coil Length	3.2185
Stator Coil Width	0.907
Rotor Parameters	**Value (inches)**
Core Inner Radius	124.5
Core Outer Radius (w/out poles)	139.045
Core + Poles Outer Radius	154.42
Coil Length	11.022
Coil Width	2.085
Pole Length w/out Tooth	13
Tooth Inner Width	10.75
Tooth Outer Width	14.75
Pole Face Radius - Center	42.6473
Pole Face Radius - Side	0.9884
Damper Winding Parameters	**Value (inches)**
Damper Bar Diameter	0.75
Damper Bar Radius	0.375
Pole Face Edge (Center) to Center Bar	0.5857
Pole Face Edge (Center) to 1 Bar out	0.6589
Pole Face Edge (Center) to 2 Bars Out	1.025
Center Bar to 1 Bar out	2.9286
Center Bar to 2 Bars out	5.9304

3.2 Modeling Coil Connections

To model the coil connections for the field winding, stator winding, and damper bars, the coil components were grouped together and defined as coils which created corresponding electrical components for them in the circuit window. An example of this is shown in Figure 3.

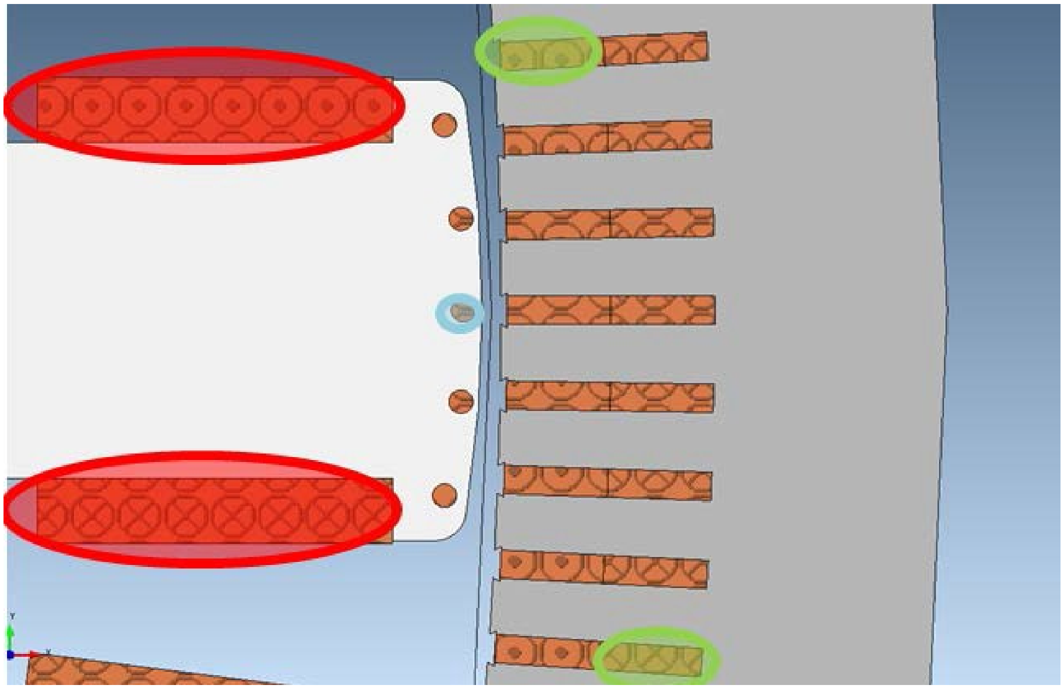

Figure 3: Coil Components Example (Taken from Unit G2 Model)

Since the field winding was not altered during the bypass work, all 48 coils were grouped together to form a single component in the circuit window, which was connected to an independent current source that supplied the DC field current. This current was updated with the measured field currents from Table 1. The damper bar components in the circuit window were all shorted together on both ends, just like the actual damper bars on unit G2. The resulting field and damper windings are shown in Figures 4 and 5, respectively.

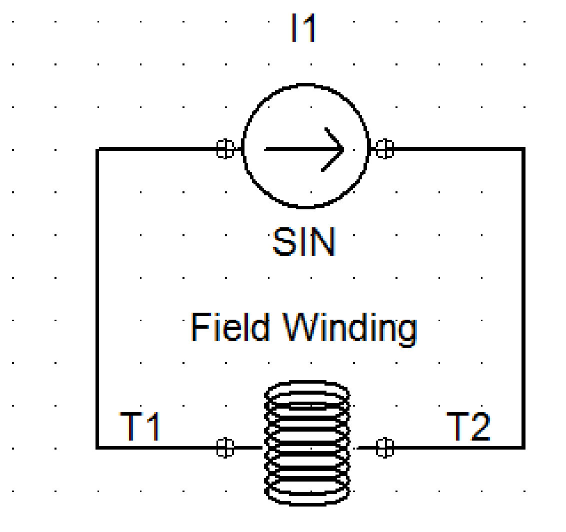

Figure 4: Glen Canyon Unit G2 Circuit Window - Field Winding

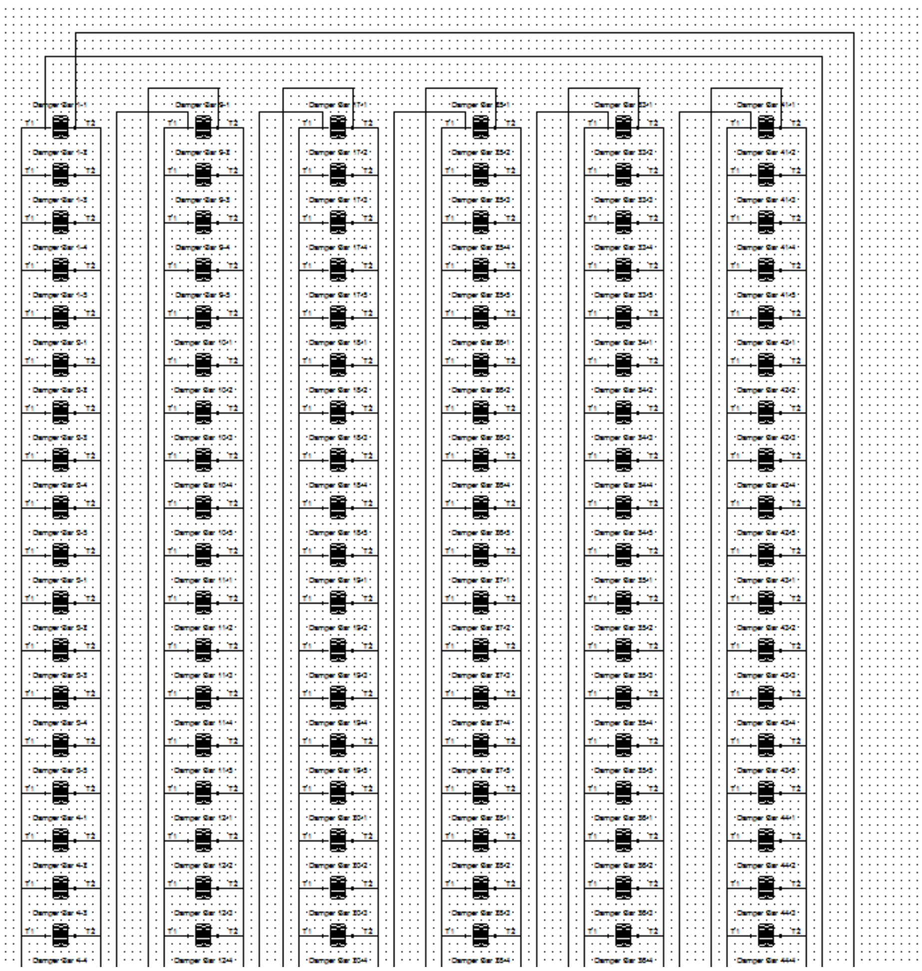

Figure 5: Glen Canyon Unit G2 Circuit Window - Damper Winding

The stator coils for G2 are connected together in alternating groups of two and three coils in series going around the stator. Each stator circuit consists of six coil groups, or fifteen individual coils, and there are eight circuits paralleled together per phase (24 circuits total). Since the end windings were not modeled in the main window, they were modeled in the circuit window as a single resistor and inductor for each parallel circuit, which represented the total resistance and leakage reactance of all 15 coils per circuit lumped together. The values used for the end winding resistance and leakage reactance were referenced from the CEATI study mentioned in section 3.1. To represent the loading of the unit, a simple three-phase impedance was connected to each phase of the stator winding. The value of this impedance was changed with loading, and was calculated using equations 1 through 4. Figure 6 shows the resulting circuit of one phase of the winding connections (including the load impedance). To model the bypass work performed on G2, circuit A5 was disconnected from the rest of the A-phase circuit; the circuit removed is circled in Figure 6.

$$Z_{load} = \frac{V_t^2}{\sqrt{MW^2 + MVAR^2}} \quad (1)$$

$$R_{load} = Z_{load} * PF \quad (2)$$

$$L_{load} = \frac{\sqrt{Z_{load}^2 - R_{load}^2}}{120 * \pi} \quad (3)$$

$$C_{load} = \frac{1}{120 * \pi \sqrt{Z_{load}^2 - R_{load}^2}} \quad (4)$$

Where:

- V_t – Terminal Voltage
- Z_{load} – Load Impedance
- R_{load} – Load Resistance
- PF – Power Factor
- L_{load} – Load Inductance (Lagging PF Load Only)
- C_{load} – Load Capacitance (Leading PF Load Only)

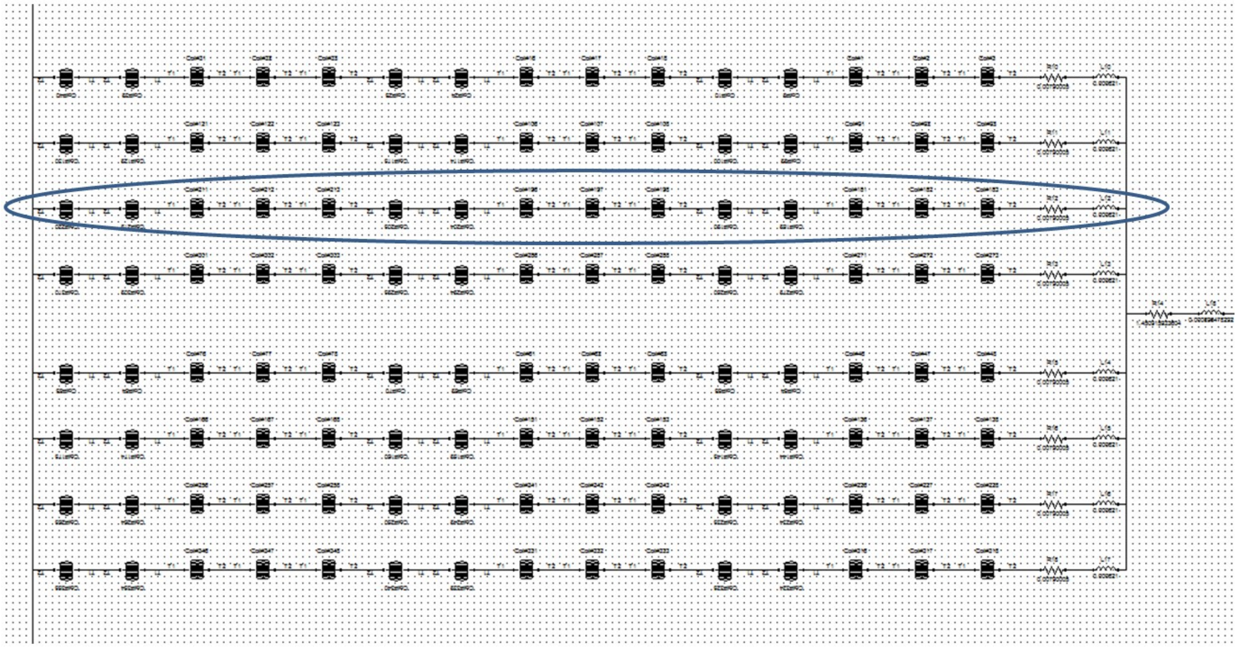

Figure 6: Glen Canyon Unit G2 Circuit Window – Stator Winding Including Load Impedance

4.0 Simulation Results

Using the model developed for Glen Canyon Unit G2, transient simulations were performed at seven different operating points: one at the rated conditions of the existing unit, and six at the operating points described in section 2.2. The solver parameters used for these simulations are detailed in Table 7.

Table 7: Glen Canyon Unit G2 – Solver Parameters

Parameter	Value
Maximum Newton Iterations	50
Newton Tolerance	1%
Polynomial Order	2
CG Tolerance	0.01%
Transient Simulation Stop Time	450ms
Transient Simulation Time Step	1ms

To assess the accuracy of the simulated voltages and currents, the simulation results were compared to the machine ratings and the field measurements in the following tables. Since MagNet produces time domain currents and voltages, the RMS of these values were calculated using MATLAB code. The simulated voltages were each expressed in kV and as a per unit value of the machine's rated phase voltage. For the phase and parallel circuit currents, the percentage difference between the simulated and measured currents were displayed below the simulated and measured values. The percentage difference for each simulated current was calculated using equation 5. Table 8 shows the terminal voltages and machine line currents calculated for the existing unit operating under rated conditions. Tables 9-20 cover the terminal voltages, machine line currents, and parallel circuit currents calculated for each simulation.

$$\text{Margin of Error} = \left(\frac{II_{ssssssssllllttssll}}{II_{sssslls sssmmssll}} - 1\right)*100\% \qquad (5)$$

Table 8: Unit G2 Model Simulation Results (Phase Voltages & Currents) – Existing Ratings

Measured Output			
S (MVA)	173.7		
P (MW)	165.0		
Q (MVAR)	54.2		
Terminal Voltage (kV)	13.8		
Field Current (A)	1040		
Simulation Results			
Phase	A	B	C
Simulated Phase Voltage (kV)	8.31	8.29	8.31
Per Unit Voltage (p.u.)	**1.04**	**1.04**	**1.04**
Simulated Current (A)	7514	7512	7511
Measured Current (A)	7267	7267	7267
Margin of Error (%)	**3.40**	**3.37**	**3.36**

*All results are rms, symmetrical

Table 9: Unit G2 Simulation Results (Phase Voltages & Currents) – 23% Load, PF = 1.0

Measured Output			
S (MVA)	39.4		
P (MW)	39.4		
Q (MVAR)	-1.3		
Terminal Voltage (kV)	13.8		
Field Current (A)	466		
Simulation Results			
Phase	A	B	C
Simulated Phase Voltage (kV)	7.53	7.5	7.56
Per Unit Voltage (p.u.)	**0.95**	**0.94**	**0.95**
Simulated Current (A)	1560	1555	1568
Measured Current (A)	1552	1648	1776
Margin of Error (%)	**0.52**	**-5.64**	**-11.71**

*All results are rms, symmetrical

Table 10: Unit G2 Simulation Results (Parallel Circuit Currents) – 23% Load, PF = 1.0

A-Phase	A1	A2	A3	A4	A5	A6	A7	A8
Simulated Current (A)	221.3	220.8	220.5	221.4	0	229.3	224.3	222.7
Measured Current (A)	230	168	212	211	0	236	230	222
Margin of Error (%)	**-3.78**	**31.43**	**4.01**	**4.93**	**N/A**	**-2.84**	**-2.48**	**0.32**
B-Phase	B1	B2	B3	B4	B5	B6	B7	B8
Simulated Current (A)	194.2	193.6	193	200	220	200.7	197.1	195.4
Measured Current (A)	209	186	179	200	242	214	N/A	202
Margin of Error (%)	**-7.08**	**4.09**	**7.82**	**0.00**	**-9.09**	**-6.21**	**N/A**	**-3.27**
C-Phase	C1	C2	C3	C4	C5	C6	C7	C8
Simulated Current (A)	193.6	192.6	192.7	209.3	217.3	197.2	195.9	194.1
Measured Current (A)	214	205	201	233	258	226	221	217
Margin of Error (%)	**-9.53**	**-6.05**	**-4.13**	**-10.17**	**-15.78**	**-12.74**	**-11.36**	**-10.55**

*All results are rms, symmetrical

Table 11: Unit G2 Simulation Results (Phase Voltages & Currents) – 58% Load, PF = 1.0

Measured Output			
S (MVA)	100.0		
P (MW)	100.0		
Q (MVAR)	0.0		
Terminal Voltage (kV)	13.8		
Field Current (A)	580		
Simulation Results			
Phase	A	B	C
Simulated Phase Voltage (kV)	7.81	7.78	7.98
Per Unit Voltage (p.u.)	**0.98**	**0.98**	**1.00**
Simulated Current (A)	4102	4084	4126
Measured Current (A)	4032	4240	4336
Margin of Error (%)	**1.74**	**-3.68**	**-4.84**

*All results are rms, symmetrical

Table 12: Unit G2 Simulation Results (Parallel Circuit Currents) – 58% Load, PF = 1.0

A-Phase	A1	A2	A3	A4	A5	A6	A7	A8
Simulated Current (A)	584.8	583.2	581.5	577.4	0	599.5	589	586.9
Measured Current (A)	582	570	564	565	0	608	584	575
Margin of Error (%)	**0.48**	**2.32**	**3.10**	**2.19**	**N/A**	**-1.40**	**0.86**	**2.07**
B-Phase	B1	B2	B3	B4	B5	B6	B7	B8
Simulated Current (A)	499.2	497.2	494.7	522.9	582.9	509.1	502.7	501.1
Measured Current (A)	532	500	490	528	624	538	N/A	517
Margin of Error (%)	**-6.17**	**-0.56**	**0.96**	**-0.97**	**-6.59**	**-5.37**	**N/A**	**-3.08**
C-Phase	C1	C2	C3	C4	C5	C6	C7	C8
Simulated Current (A)	513.4	510.3	508.6	576.9	593.8	517.1	516.5	514
Measured Current (A)	518	515	515	585	634	538	525	524
Margin of Error (%)	**-0.89**	**-0.91**	**-1.24**	**-1.38**	**-6.34**	**-3.88**	**-1.62**	**-1.91**

*All results are rms, symmetrical

Table 13: Unit G2 Simulation Results (Phase Voltages & Currents) – 75% Load, PF = 1.0

Measured Output			
S (MVA)	130.0		
P (MW)	130.0		
Q (MVAR)	0.0		
Terminal Voltage (kV)	13.8		
Field Current (A)	650		
Simulation Results			
Phase	A	B	C
Simulated Phase Voltage (kV)	7.92	7.87	7.97
Per Unit Voltage (p.u.)	**0.99**	**0.99**	**1.00**
Simulated Current (A)	5403	5374	5439
Measured Current (A)	5216	5536	5600
Margin of Error (%)	**3.59**	**-2.93**	**-2.88**

*All results are rms, symmetrical

Table 14: Unit G2 Simulation Results (Parallel Circuit Currents) – 75% Load, PF – 1.0

A-Phase	A1	A2	A3	A4	A5	A6	A7	A8
Simulated Current (A)	767.1	766.1	765.7	761.4	0	797.3	775.6	769.9
Measured Current (A)	753	740	732	730	0	788	756	747
Margin of Error (%)	**1.87**	**3.53**	**4.60**	**4.30**	**N/A**	**1.18**	**2.59**	**3.07**
B-Phase	B1	B2	B3	B4	B5	B6	B7	B8
Simulated Current (A)	651.1	650	648	680.4	764.8	670	657.2	653.4
Measured Current (A)	692	652	642	681	805	692	N/A	667
Margin of Error (%)	**-5.91**	**-0.31**	**0.93**	**-0.09**	**-4.99**	**-3.18**	**N/A**	**-2.04**
C-Phase	C1	C2	C3	C4	C5	C6	C7	C8
Simulated Current (A)	675.3	673.4	671.9	761.9	793.6	685.8	680.4	675.6
Measured Current (A)	672	667	672	756	822	691	678	675
Margin of Error (%)	**0.49**	**0.96**	**-0.01**	**0.78**	**-3.45**	**-0.75**	**0.35**	**0.09**

*All results are rms, symmetrical

Table 15: Unit G2 Simulation Results (Phase Voltages & Currents) – 78% Load, PF = 1.0

Measured Output			
S (MVA)	135.0		
P (MW)	135.0		
Q (MVAR)	0.0		
Terminal Voltage (kV)	13.8		
Field Current (A)	662		
Simulation Results			
Phase	A	B	C
Simulated Phase Voltage (kV)	7.92	7.88	7.98
Per Unit Voltage (p.u.)	**0.99**	**0.99**	**1.00**
Simulated Current (A)	5616	5585	5655
Measured Current (A)	5488	5760	5800
Margin of Error (%)	**2.33**	**-3.04**	**-2.50**

*All results are rms, symmetrical

Table 16: Unit G2 Simulation Results (Parallel Circuit Currents) – 78% Load, PF – 1.0

A-Phase	A1	A2	A3	A4	A5	A6	A7	A8
Simulated Current (A)	797	796	795.7	791.3	0	829.6	806.3	800
Measured Current (A)	785	774	768	765	0	824	790	780
Margin of Error (%)	**1.53**	**2.84**	**3.61**	**3.44**	**N/A**	**0.68**	**2.06**	**2.56**
B-Phase	B1	B2	B3	B4	B5	B6	B7	B8
Simulated Current (A)	675.9	674.8	672.8	705.9	794.2	696.3	682.6	678.4
Measured Current (A)	698	684	674	715	843	723	N/A	696
Margin of Error (%)	**-3.17**	**-1.35**	**-0.18**	**-1.27**	**-5.79**	**-3.69**	**N/A**	**-2.53**
C-Phase	C1	C2	C3	C4	C5	C6	C7	C8
Simulated Current (A)	701.8	699.9	698.6	792.4	826.8	713.6	707.4	702.3
Measured Current (A)	695	690	692	780	850	715	697	696
Margin of Error (%)	**0.98**	**1.43**	**0.95**	**1.59**	**-2.73**	**-0.20**	**1.49**	**0.91**

*All results are rms, symmetrical

Table 17: Unit G2 Simulation Results (Phase Voltages & Currents) – 74% Load, PF = 0.97 Lag

Measured Output			
S (MVA)	127.8		
P (MW)	124.5		
Q (MVAR)	29.0		
Terminal Voltage (kV)	13.8		
Field Current (A)	772		
Simulation Results			
Phase	A	B	C
Simulated Phase Voltage (kV)	8.13	8.09	8.2
Per Unit Voltage (p.u.)	**1.02**	**1.02**	**1.03**
Simulated Current (A)	5395	5383	5439
Measured Current (A)	5088	5312	5456
Margin of Error (%)	**6.03**	**1.34**	**-0.31**

*All results are rms, symmetrical

Table 18: Unit G2 Simulation Results (Parallel Circuit Currents) – 74% Load, PF – 0.97 Lag

A-Phase	A1	A2	A3	A4	A5	A6	A7	A8
Simulated Current (A)	766.1	765.1	764.8	759.1	0	796.7	774.6	768.6
Measured Current (A)	735	721	715	713	0	768	735	727
Margin of Error (%)	**4.23**	**6.12**	**6.97**	**6.47**	**N/A**	**3.74**	**5.39**	**5.72**
B-Phase	B1	B2	B3	B4	B5	B6	B7	B8
Simulated Current (A)	644.9	643.8	641.9	672.7	755.1	664.2	650.7	647.1
Measured Current (A)	642	632	627	657	777	667	N/A	641
Margin of Error (%)	**0.45**	**1.87**	**2.38**	**2.39**	**-2.82**	**-0.42**	**N/A**	**0.95**
C-Phase	C1	C2	C3	C4	C5	C6	C7	C8
Simulated Current (A)	676.9	675	674	765.7	801.8	687.9	682	677.2
Measured Current (A)	656	650	652	737	802	672	657	654
Margin of Error (%)	**3.19**	**3.85**	**3.37**	**3.89**	**-0.02**	**2.37**	**3.81**	**3.55**

*All results are rms, symmetrical

Table 19: Unit G2 Simulation Results (Phase Voltages & Currents) – 58% Load, PF = 0.97Lead

Measured Output			
S (MVA)	130		
P (MW)	125.8		
Q (MVAR)	-32.6		
Terminal Voltage (kV)	13.8		
Field Current (A)	500		
Simulation Results			
Phase	A	B	C
Simulated Phase Voltage (kV)	7.45	7.39	7.49
Per Unit Voltage (p.u.)	**0.94**	**0.93**	**0.94**
Simulated Current (A)	5104	5065	5133
Measured Current (A)	5264	5584	5696
Margin of Error (%)	**-3.04**	**-9.29**	**-9.88**

*All results are rms, symmetrical

Table 20: Unit G2 Simulation Results (Parallel Circuit Currents) – 75% Load, PF – 0.97 Lead

A-Phase	A1	A2	A3	A4	A5	A6	A7	A8
Simulated Current (A)	725.1	723.7	722.7	721	0	751.7	732.1	727.8
Measured Current (A)	759	740	734	740	0	792	765	756
Margin of Error (%)	**-4.47**	**-2.20**	**-1.54**	**-2.57**	**N/A**	**-5.09**	**-4.30**	**-3.73**
B-Phase	B1	B2	B3	B4	B5	B6	B7	B8
Simulated Current (A)	623.3	621.9	619.4	649.5	719.9	640.4	628.8	625.7
Measured Current (A)	675	660	756	695	817	705	N/A	681
Margin of Error (%)	**-7.66**	**-5.77**	**-18.07**	**-6.55**	**-11.88**	**-9.16**	**N/A**	**-8.12**
C-Phase	C1	C2	C3	C4	C5	C6	C7	C8
Simulated Current (A)	635.7	633.6	631.5	707.9	731.8	643.3	640	636.5
Measured Current (A)	678	678	680	765	828	704	695	686
Margin of Error (%)	**-6.24**	**-6.55**	**-7.13**	**-7.46**	**-11.62**	**-8.62**	**-7.91**	**-7.22**

*All results are rms, symmetrical

While the simulation performed at a loading of 23% (Tables 9 & 10) was effectively a unity power factor operating point, there was a small amount of MVAR absorbed by the unit when the corresponding field measurements were made, and it was thus modeled with a leading power factor to account for this. The resulting currents from this simulation also appear to vary greatly from the corresponding measured currents, with the greatest margin of error being calculated at over 30%. However, since the loading per circuit was measured at lower levels around 200A, the deviation between simulated and measured current levels is exaggerated. A difference in magnitude of 60A at this loading would result in a margin of error of about 30%, whereas the same difference at a loading of roughly 700A per circuit would result in a less than 10% margin of error.

The simulation run at the machine's existing ratings produced line currents that were within a 3.4% margin of error. The simulations run at unity power factor (excluding the simulation run at 23% loading) produced line currents that were within a 4.84% margin of error, and circuit currents that were within a 6.59% margin of error. The simulation run at a lagging factor produced line currents that were within a 6.03% margin of error, and circuit currents that were within a 6.97% margin of error. The simulation run at a leading factor produced line currents that were within a 9.88% margin of error, and circuit currents that were within a 18.07% margin of error.

5.0 References

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