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Building 865 Hypersonic Wind Tunnel Power System Analysis

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Abstract

This report documents the characterization and analysis of a high current power supply for the building 865 Hypersonic Wind Tunnel at Sandia National Laboratories. The system described in this report became operational in 2013, replacing the original 1968 system which employed an induction voltage regulator. This analysis and testing was completed to help the parent organization understand why an updated and redesigned power system was not delivering adequate power to resistive heater elements in the HWT. This analysis led to an improved understanding of the design and operation of the revised 2013 power supply system and identifies several reasons the revised system failed to achieve the performance of the original power supply installation. Design modifications to improve the performance of this system are discussed.

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NOMENCLATURE

HWT	Hypersonic Wind Tunnel
I	Amperes
KV	kilovolts
KVAR	KiloVolt-Ampere-Reactive
PFC	Power Factor Control
RMS	Root Mean Square
SCR	Silicon Controlled Rectifier
SNL	Sandia National Laboratories
V	Volts
X	Reactance (Ohms)
Z	Impedance (Ohms)

1. INTRODUCTION

This report documents the characterization and analysis of a high current power supply for the building 865 Hypersonic Wind Tunnel (HWT) at Sandia National Laboratories. The system described in this report became operational in 2013, replacing the original 1968 system which employed an induction voltage regulator to control the power delivered to resistive heater elements in the HWT. This analysis and testing was completed to help the parent organization understand why an updated and redesigned power system was not delivering adequate power to the heater elements. The HWT uses several sets of heater elements to add enthalpy to the air flow in order to reach varying flight conditions in the Mach 5 to Mach 14 regime. The analysis is in this report will focus on the heater set used during Mach 8 operations as this was viewed as a worst-case load for the power system. This analysis led to an improved understanding of the design and operation of the revised 2013 power supply system and identifies several reasons the revised system failed to achieve the performance of the original power supply installation. Design modifications to improve the performance of this system are discussed.

1.1 Original 1968 Power System Configuration

The original power supply for the building 865 Hypersonic Wind Tunnel (HWT) consisted of a 2500 kVA, 3ϕ, 12.47kV/4160V transformer which drove a 4160V, 3ϕ, inductive voltage regulator capable of 2787V to 5533V operation (+/- 33% V_o). The output of the inductive voltage regulator drove a custom 1000 kVA, 3ϕ, 5433V to 75V step down transformer which was drove a set of delta connected heater elements. This system also contained a 450 kVAR, 4160 V, 3ϕ capacitor bank which was installed to improve the low Power Factor (PF) caused by the heater load. The PF in the previous system was likely in the 0.6 range, lagging.

It is important to note that it is very likely that the original power system designer and HWT facility operators did not have a precise understanding of the power system requirements to achieve the desired range of flight conditions in this unique test facility. The broad voltage range on the inductive regulator offered significant control of power into the heater system up to a maximum of +66% over the nominal 4160V operating point. This significant operating margin covered the uncertainty in the heater system power requirements. It also allowed for the mitigation of voltage drops across conductors and transformers in the system. It is important to note that this design also used an oil-filled 4160/75 V step down transformer. It is likely that this step down transformer had a nominal 5% series impedance, similar to other transformers in this system. Since this system employed a simple induction voltage regulator, the system operated at 60Hz regardless of the set point.

A one-line diagram of the original inductive voltage regulation system is shown in figure 1.

1.2 Revised 2013 Power System Configuration

The present 2013 design involved replacement of all the hardware connecting to the 12.47 kV area distribution system. The voltage regulator was replaced by a bi-directional SCR switching system to allow for full system voltage control. The designers employed an existing SCR switch module design which was based on a 575 volt operating point and a listed maximum operating current of 3000 Amps. A 12.47kV to 575V step down transformer was installed to feed the SCR switching module. The output of the SCR module is connected to a 575V to 4160V step up transformer. The output of this transformer drives a set of 4/0 feeder cables which connect to an *air-insulated* 4160V/75V step down transformer adjacent to the HWT. The output of the 75 volt transformer can be wired to supply three different heater configurations. Two configurations, for Mach 5 and Mach 14 operation, connect the output of the transformer directly to the heater terminals using large cables. A third configuration for Mach 8 operation connects the output of the HWT transformer to a set of rectangular copper bus bars which extend approximately 11.5 ft. before they connect to the heaters. A one-line diagram of the present power system is shown in Figure 2.

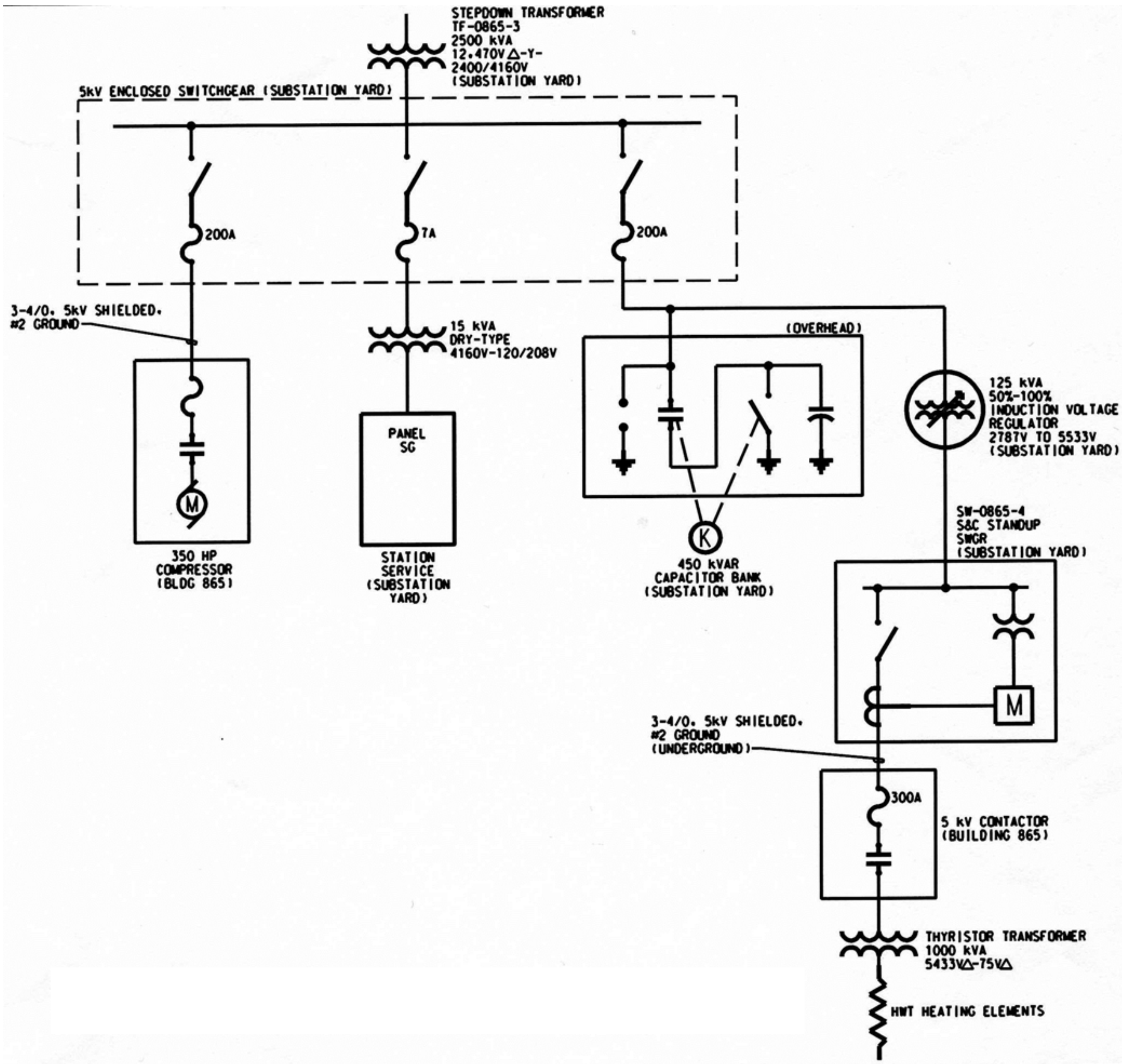


Figure 1. Original 1968 HWT power supply system.

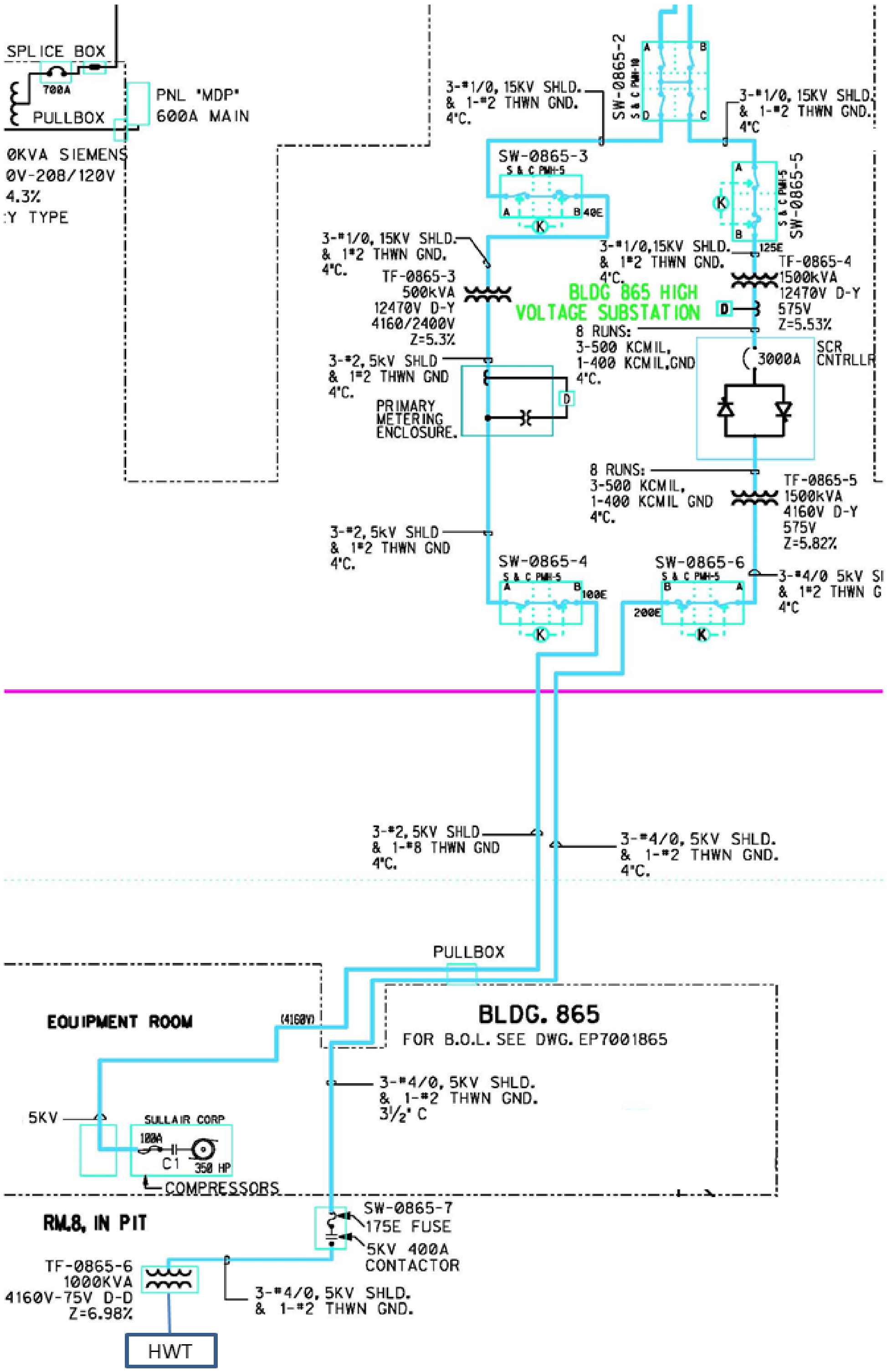


Figure 2. Present HWT power supply system (2013 design).

A review of the design criteria for this system produced a single reference to the need to supply approximately 20 kA at 75 volts to the heater load in the HWT. Unfortunately, there were no direct heater measurements to indicate power requirements over the performance envelope of the HWT. To my knowledge, the heater load characteristics which vary dramatically over the Mach 5, 8, and Mach 14 operating configurations, were neither supplied to the designer nor characterized by the designer. Given the low impedance nature of the heater load, system analysis needed to account for inductive elements throughout the system to understand the impact of voltage drops across transformers and conductors. Apparently, this did not occur to the extent necessary to assure that the new design was comparable to the previous system design in its ability to generate adequate load current for the range of operations at the HWT.
The redesign introduced performance constraints which have prevented this system from reaching the performance of the previous inductive voltage regulator system. These include:

1. The system cannot operate above the nominal 4160 V operating voltage. This eliminated the potential to overcome significant voltage drops across system transformers.

2. The SCR module had a maximum rated current of 3000 Amps/phase. Due to the high degree of reactive current flowing in this system, real power to the HWT heater load was limited by this SCR module current rating.

3. The HWT step down transformer was changed from oil-insulated to air-insulated. This increased the transformer series reactance to 7%, a likely 1.5-2% increase in series reactance from the previous design. This likely increased the full system inductance by approximately 20%, further aggravating system voltage drops.

Additionally, at SCR operating points other than full conduction, significant switching harmonics are introduced into the system. Although this higher frequency content increases the reactive voltage drop across the 575V and 75V transformers, it does not impact the maximum attainable power flow into the heater at full conduction. *However, this harmonic content will need to be carefully considered as solutions are considered, especially if power factor correction capacitors are added and they remain in the circuit when the SCRs are not fully conducting.*

2. POWER SYSTEM MODELING AND ANALYSIS

2.1 Power System Model and HWT Heater Load Characterization

Existing power system components (transformers, cables, switches, bus bar and heater load, etc.) were analyzed or measured to construct an equivalent circuit model. Nominal model components are shown in Figure 3.

Analysis of cable runs and the SCR switch module showed that the impact of these impedances were not significant when compared to the series reactance of the three system transformers, bus bars and heater elements. These impedances were not included in the system model to improve model convergence. Elements not included were L_{scr}, R_f, L_f, shown in Figure 1, and other miscellaneous cables or bus work.

The Mach 8 HWT heater load and bus bars were measured in a cold state (no current flow). Resistance values in the heater were adjusted to match load measurements during high power operation using data from current and voltage monitors at the heater load terminals. Since the cold state inductance of the heater would not likely change during full power operation, only the resistance was changed in the model to match test measurements. Not surprisingly, the resistive value of the tungsten heaters increased dramatically from cold state measurements to high current operation due to the temperature coefficient of the tungsten elements.

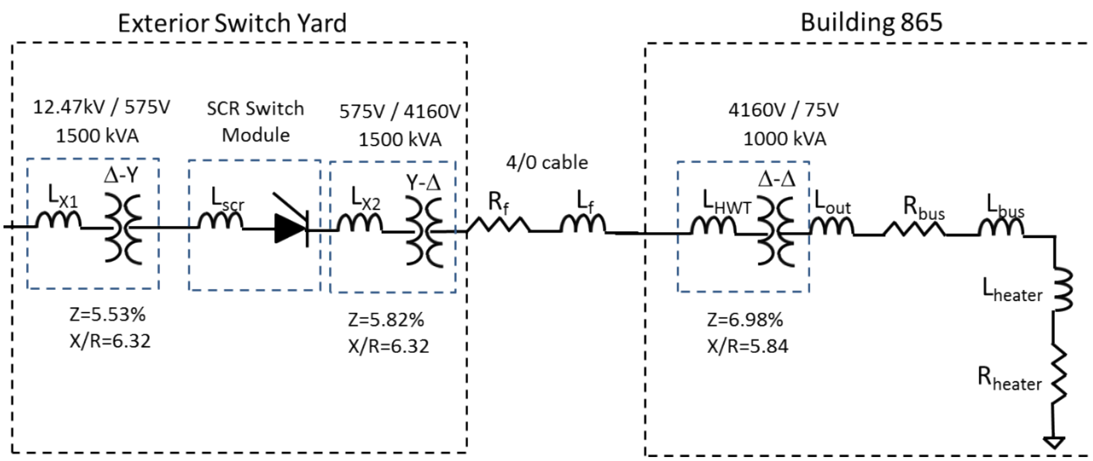
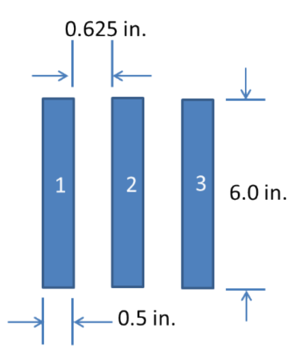


Figure 3. Nominal model components for present system (2013 design).

The Mach 8 HWT heater consists of a 3-phase, delta connected assembly of tungsten heater screens. Access to individual heater phase elements was not possible. Heater terminals are connected to the power system by 2 1/8 inch diameter, 58 inch long flexible cables that attach to an approximate 11.5 ft. section of copper bus bars. The cross sectional dimensions and layout of the bus bars are shown in Figure 4. Bus bar thickness, height and spacing are identical from bus 1 to 2 and bus 2 to 3. The flexible cables and their attachment to the horizontal bus bars are shown in Figure 5. It should be noted that the layout of the flexible cables are highly inductive, adding considerably to the total inductance of the bus bar/cable assembly.



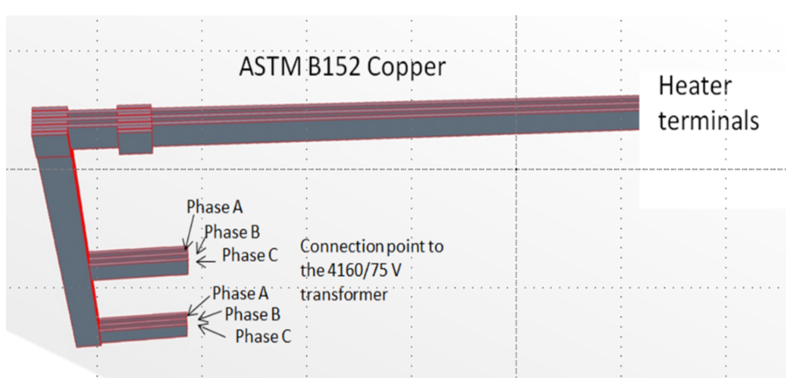


Figure 4. Copper bus bar assembly used during the Mach 8 experiments. LEFT: End-view of bus bars. RIGHT: Vertical bus at the left attaches to the 4169/75 V transformer output. Top horizontal bus connects to flexible cables which attach to the heater elements.

Figure 5. Flexible cable connection to the bus bars in the Mach 8 heater load configuration. Left: Cable connection from heater terminals to the horizontal bus bars at the floor. Right: Cable connection to the bus bars. Note the large spacing between the cables. This is a highly inductive configuration.

Load measurements were taken at the input to the horizontal bus bar/cables at the top of the transformer output and directly at the heater terminals with the bus bar/cables disconnected from the heater terminals. Bus/heater and heater measurements are shown in Tables 1-3. All measurements were taken using a 60Hz source.

Table 1. Cold state bus and heater impedance measurements (no current flow).

Phase	Resistance (Ω)	Inductance (H)
1-2	1.7m	2.7μ
1-3	1.6m	3.5μ
2-3	1.8m	2.6μ

Table 2. Cold state heater only impedance measurements (no current flow, disconnected from the bus bar).

Phase	Resistance (Ω)	Inductance (H)	Impedance (Ω/angle)		*Balanced Load Approximation* Z_{LL} *(line-to-line)*
1-2	0.86m	0.48μ	$0.88m\angle 12^{o}$		$0.9m\angle 11^{o} = 0.88m + j0.17m$
1-3	0.90m	0.38μ	$0.91m\angle 9.0^{o}$		$0.9m\angle 11^{o} = 0.88m + j0.17m$
2-3	0.89m	0.46μ	$0.91m\angle 11^{o}$		$0.9m\angle 11^{o} = 0.88m + j0.17m$

Table 3. Implied horizontal bus bar/cable only impedance (Table 1 minus Table 2).

Phase	Resistance (Ω)	Inductance (H)
1-2	0.84m	2.20μ
1-3	0.70m	3.12μ
2-3	0.91m	2.14μ

The bus resistance values shown in Table 3 seem unreasonably high. It is likely that contact resistance effected these low current measurements.

Additional vertical bus work attaches the horizontal bus to the output of the 75V transformer. The vertical section is approximately 45 inches long. The approximate inductance of this vertical section was added to the model between the output of the 4160/75 V transformer and the input to the horizontal bus bar assembly.

Based on the measurements in Tables 1-3, each leg of the delta configured load model was calculated based on the line-to-line *Balanced Load Approximation shown* in Table 2. The results are shown in Figure 6. A balanced load model was selected due to issues with the tracking of phase numbers throughout the physical system. Since the goal was to determine *gross* system characteristics and to explore design modification options, this approach was viewed as sufficient to meet these objectives.

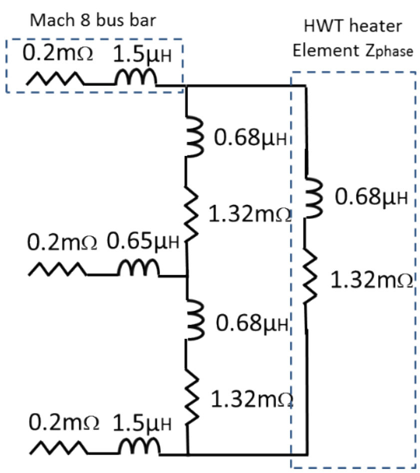


Figure 6. A*pproximate* balanced delta load model for the Mach 8 heater assembly (cold state). A single HWT heater element is shown in the dashed outline to the right of the figure. Z_{phase}= 3/2 (Z_{LL}).

A PSpice system model was constructed from the 12.47 kV distribution transformer to the HWT heater load. Transformer impedances in this model were calculated from transformer test reports which listed the %Z series impedance and X/R ratios of the transformers. These values are shown in Fig 3.

2.2 Full System Circuit Model and Comparison to Field Measurement Data

Several HWT system experiments were conducted in the Mach 8 configuration which was determined to be a worst-case load for the HWT power supply. A few elements of the circuit model were fine-tuned to match model values to measured voltages and currents in the system. This was done during a maximum power run with the SCRs gated in the full on position to eliminate the effects of harmonics on voltage drops across system inductances.

Heater load resistances were adjusted to match model values and measurements at the input to the bus bar and at the heater terminal. As mentioned earlier, it was anticipated that the heater resistances would need to be adjusted from the cold state measurements at low current to full current operation due to the extreme operating temperature of the tungsten screen heaters. Since it is not possible to measure the temperature of the tungsten heater screens, the value of heater resistance was adjusted in the model to best fit the measurements. A reasonable fit between the model and data was obtained with a heater resistance value of 2.6 mΩ. This compares to the cold-state measured value of approximately 1.32 m. This is not an unreasonable increase in resistance based on the temperature coefficient of tungsten.

This equilibrium value is a function of I^2R heating and cooling of the screens by the mass flow rate of air through the screens during tunnel operation. The three phase PSpice circuit model for the Mach 8 RUN #85 experiment on 8/14/14 is shown in Figure 7.

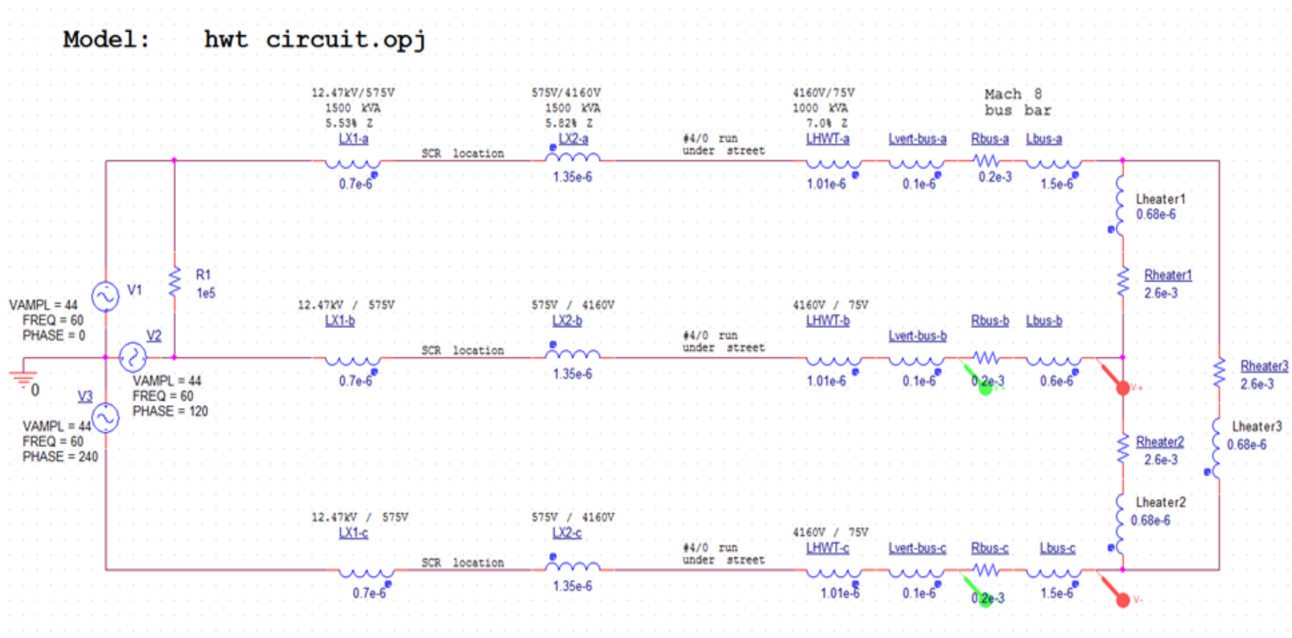


Figure 7. Three phase PSpice model of RUN #85 on 8/14/14. This was a Mach 8 experiments with a fully conducting SCR module. The input voltage in the Wye source in Fig. 5 was set to match measurements at the output of the 12.47kV/575 V transformer under no-load conditions. The heater resistance was adjusted to best fit measurement data. All other values are based on calculations or measurement as described previously.

Table 4 shows a comparison of model predictions and measurements during the Mach 8 full power experiment. Given the balanced heater load approximation, nominal +/-5 to 10% accuracy of the measurements, and the complexity of this system, the model values match the measurements fairly well. The model under predicts average current into the load by approximately 5%.

The model clearly shows the impact of inductive voltage drops on the ability of this system to deliver current to the HWT heater load. The model also predicted that the SCRs would exceed their nameplate current rating during full voltage operation into the Mach 8 heater load. In reviewing the design of the SCR module, it was determined that the nameplate rating was extremely conservative. The SCR module uses phase control thyristors (Powerex TDS5 series) which are rated for 5000 Amps and 1800 V steady-state operation. Armed with this knowledge, the decision was made to conduct this system experiment into the Mach 8 heater load with the SCRs set to full conduction. A decision was also made to also conduct an additional test with the 12.47kV/575 V transformer set at a 5% higher tap setting. The no-load voltage on the SCRs during this experiment were projected to reach 615-620 volts, approximately 8% over the nameplate voltage rating. The snubber circuit for the SCR module, which contains MOV surge protectors, was rated at 660 volts, more than adequate margin for this over voltage experiment. The results of this 5% over-voltage experiment are shown in Table 5. Although this experiment produced the highest available power to the load, it still fell well short of the needed heater power to fully capture the desired HWT performance space.

Table 4. Mach 8 full power experiment.

Date/Time: Thursday, 8/14/14, RUN #85
HWT Configuration: Mach 8 heater with bus. SCR command at 10.0 volts, P0=678, T0cal=1122.
Comments: 20 second power supply operation. All voltage data are line-to-line.

Test Data

Comments: FLEX-kit current monitor calibration not verified. *FLEX-kit current monitors limit exceeded at this SCR setting.*
Instrumentation: Dranetz meter on 575V. Fluke Multimeter(s) at Xfmr Secondary and at load; 3 phase FLEX-kit current probe setting at 20kA.

	12.47kV/575V Transformer	575V SCR Module					Load		
Phase	Output *NO LOAD* Volts/Amps (RMS)	Input SCR Volts (RMS)	Output SCR Volts/Amps (RMS)		V_{IN}/V_{OUT} Ratio (%)	Power Factor	Bus Input$^{\xi}$ Volts (RMS)	Heater Terminal Volts/Amps (RMS)	
A-B	585	516	514	2958	99	0.6	44	31	>20kA
B-C	585	513	511	2918	99	0.7	48	41	>20kA
C-A	588	510	505	3233	99	0.7	44	33	>20kA

$^{\xi}$ At input to horizontal bus

Test data reflected to 75V system basis

A-B	76		67	22700			44	31	22700
B-C	76		67	22400			48	41	22400
C-A	77		66	24800			44	33	24800

Model Values - 75 Volt system basis

Model version: hwt circuit.opj (8/14/14, RUN#85 comparison, SCRs=10 V, full open)
Date: 7/15/14
Comments: Balanced delta load using average heater load measurements. Vsource=44 V line-neutral (76 V line-to-line), Lx1=0.7uH, Lx2=1.35µH, Lhwt=1.01uH, Lvert-bus=0.1uH, Rbus=0.2mΩ, Lbus1,3=1.5uH, Lbus2=0.65uH, Rl=2.6mΩ, Ll=0.68 µH

A-B	76		67				43	34	22000
B-C	76		67				47	33	23000
C-A	76		67				44	32	21000

Table 5. Mach 8 full power experiment with 5% tap increased voltage on 12.47kV/575V transformer.

Date/Time: Thursday, 8/21/14, RUN #90
HWT Configuration: Mach 8 heater with bus. SCR command at 10.0 volts, P0=709, T0cal=1195.
Comments: 12.47V/575 V transformer taps set to +5%. 20 second power supply operation. All voltage data are line-to-line.

Test Data

Comments:
Instrumentation: Dranetz meters used in 575V circuit. Fluke Multimeters used at load.

	12.47kV/575V Transformer	575V SCR Module					Load		
Phase	Output *NO LOAD* Volts/Amps (RMS)	Input SCR Volts (RMS)	Output SCR Volts/Amps (RMS)		V_{IN}/V_{OUT} Ratio (%)	Power Factor	Bus Input$^{\xi}$ Volts (RMS)	Heater Terminal Volts/Amps (RMS)	
A-B	617	549	544	3065	99	0.6	47.5	34.6	
B-C	617	547	542	3040	99	0.7	52.1	45.4	
C-A	619	543	535	3343	99	0.7	47.5	36.8	

$^{\xi}$ At input to horizontal bus

Test data reflected to 75V system basis

A-B	80		71	23500			48	35	23500
B-C	80		71	23300			52	45	23300
C-A	81		70	25600			48	37	25600

Model Values - 75 Volt system basis

Model version: hwt circuit.opj (8/14/14, RUN#90 comparison, SCRs=10 V, full open)
Date: 8/121/14
Comments: Balanced delta load using average heater load measurements. Vsource=46 V line-neutral, Lx1=0.7uH, Lx2=1.35μH, Lhwt=1.01uH,
Lvert-bus=0.1uH, Rbus=0.2mΩ, Lbus1,3=1.5uH, Lbus2=0.65uH, Rl=2.6mΩ, Ll=0.68 μH.

A-B	80		71				45	36	23000
B-C	80		71				50	35	24000
C-A	80		71				48	34	22000

3. PATH FORWARD AND RECOMMENDATONS TO INCREASE POWER FLOW

The model developed for the HWT power supply system matches the measured performance of this system well enough for use in design studies to improve the performance of the HWT power supply. However, the actual load current requirement for full operation across the HWT phase space is unknown. We can review this statement as redesign options are pursued in the future.

A reasonable worst-case prediction would be to use a circuit prediction with the drive voltage set to replicate the upper setting of the old induction voltage regulation. If we increase the drive voltage in the model developed during this analysis by 33% (upper range on the old inductive regulator), a load current of 27-30 kA would be generated. This corresponds to 42-45 volts at the heater terminals. This extrapolation assumes the heater resistance does not change substantially.

In reviewing options to increase current through the heater load to the range of 30 kA, a power factor correction (PFC) bank seems like a reasonable choice. It may be possible to generate the projected required currents with only the addition of a PFC bank. This bank can be placed downstream of the SCR module to limit the increase in current through the SCRs. However, given the apparent 5000 Amp rating of the SCR module, the PFC bank can likely also be placed upstream of the SCRs. Any significant changes in the operating conditions of the SCR module should be discussed with the design engineers/manufacturers. Although these SCRs have an extremely high surge current rating (10's kA for several cycles), the addition of a PFC back will likely create surge currents and oscillations that will need to be examined carefully. Additionally, any PFC bank design will need to consider operation of the SCRs at less than full conduction. This will introduce significant harmonics into the system which can produce excessively high currents in the PFC bank. *One option to avoid this situation is to only engage the PFC bank during full conduction operations when higher heater power values are required.*

The design of a PFC bank for this system may not be straight-forward as the goal is not necessary to improve the system power factor but to drive more current into the unbalanced delta heater load. To reduce system modification costs, it should be possible to generate significantly more load current without exceeding cable run and/or transformer damage thresholds due to overheating. Given the extremely short duty cycle of this system, current and power ratings can be substantially exceeded with minimal impact on the lifetime of components. This analysis will need to be to be completed and documented as NEC code based limits and suggested manufacturer current and power ratings may be significantly exceeded.

Given the short operating duration of this system, over-current/power operation is primarily a heating and component lifetime issue. The projected operating lifetime of the HWT heater system is approximately 500 hours, orders of magnitude below the lifetime design basis of the cables, switchgear and transformers involved in this system. In a worst case scenario, the wind tunnel would operate for 60-70 seconds with a one hour cool down period. This would be repeated for a maximum of 8 operations per day. This represents a worst-case duty cycle of only 2%. Even a significant degradation of component lifetimes would not likely be an issue in a system with an expected 500 hour lifetime.

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