53-960809-CLN-01

TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: PRELIMINARY DESIGN OF MONOLITHIC OH COIL

This memo presents the results of a preliminary assessment of a monolithic OH coil design and a power supply to match.

The main parameters of the coil are as follows:

Parameter	**Value**	**Units**
Conductor Width	1.0	cm
Conductor Height	1.5	cm
Conductor Hole Diameter*	3/16	in
Conductor Corner Radius	0.1	cm
Conductor Hole Elongation	0.0	cm
Turn-Turn & Layer-Layer Spacing	0.04	inch
#Layers	4	
#Turn Spaces/Layer	224	
#Turns/Layer	222	
#Turns	888	
R(center)	12.654	cm
Height (over turn insulation)	355.6	cm
Height above midplane (over turn insulation)	177.77	cm
Cooling path length (outer layer)*	199.5	m
Inductance	12.4	mH
Conductor Initial Temperature	20	deg C
20C Coil Resistance	92.9	mΩ

* conductor is wound with one path per layer, i.e. "one-in-hand"

A simulation was developed which models the power supply and coil.

Features of the coil model include the following:

- coil inductance based on section of length "l" of an infinite solenoid, with "n" turns, and with effective area "A" based on geometric mean radius of centers of coil layers:

$$L = \mu_o n^2 A / l$$

- "G" function of copper modeled using:

$$G(T) = 6.295e13+2.093e14*T-2.871e11*T^2$$

$$T(G) = 0.1361+4.550e-15*G+5.331e-32*G^2$$

- copper temperature coefficient of resistance equal 0.0041/deg C

Features of the power supply model (to represent two Transrex units fed from XST transformer) include:

- equivalent resistance "R_{eq}" of rectifiers at "f" = 60Hz, with commutating inductance "L_c" and resistance "R_c" modeled using:

$$R_{eq} = 6*f*L_c + 2*R_c$$

- commutating inductance and resistance include converter transformer, 138/13.8kV substation transformer, 138kV transmission lines to Brunswick and Trenton substations, and equivalent impedance of the grid[1]. Impedances common to multiple bridges are multiplied by the number of loading bridges in the computation of the single bridge equivalent resistance.

- power supply system DC bus/cable resistance allowance of 2.5mΩ

- AC system voltage drop computations based on fundamental frequency component "I_1" resulting from rectifier load current "I_d":

$$I_1 = \sqrt{6}/\pi * I_d$$

[1]"Analysis of TPX Pulsing of Utility Grid", TPX Memo 41-940502-PPPL/CNeumeyer-01

Features <u>not</u> modeled in the simulation include:

- passive structures & plasma

- mutually coupled PF coils

- OH flux not coupled by plasma due to finite solenoid height

- presence/flow of water in conductor cooling passage

- ratcheting of temperature in any power supply or coil elements

- sequential or buck-boost power supply control strategy to reduce reactive power (which would be possible after plasma initiation, when power supply voltage margin ≥ 0)

The main objectives in sizing the coil and constraining the power supply operation are as follows:

- produce same flux swing as earlier OH design

- utilize same coil radius as earlier OH design

- maximize height of coil

- limit coil temperature to $\leq$ 100C

- maximize plasma initiation loop voltage

- limit voltage drop in grid at Brunswick & Trenton to $\leq 1\%$, and voltage drop incoming to PPPL to $\leq 3\%$

- allow margin for additional power loads due to HHFW heating and other PF power supplies during plasma current flat top

For design study a scenario with the following features was used:

- transition from precharge to initiation phase with zero delay

- 20mS initiation pulse

- longest required plasma current ramp (0.4 sec)

- longest required plasma current flat top (0.5 sec)

- L/R decay of OH current after the end of flat top

In performing the analysis it was found that, given the parameters of the Transrex rectifier and the impedances which feed it, the maximum DC current which can be taken at thyristor phase control angle $\alpha = 0$ degrees (rectifier fully on) is 24kA, based on the constraint that the voltage drops in the grid be limited to the aforementioned values. In all cases therefore the precharge current was therefore set to 24kA, and the current at the end of flat top was set to the value needed to give the required flux swing. Thus the fields and forces are asymmetric. But the advantages gained by this approach are as follows:

- the power supply is fully exploited for precharge

- a power margin exists at the end of flat top to allow for the other loads even when the coil temperature is maximum

- maximum stresses (during prechage) occur when the coil is cool

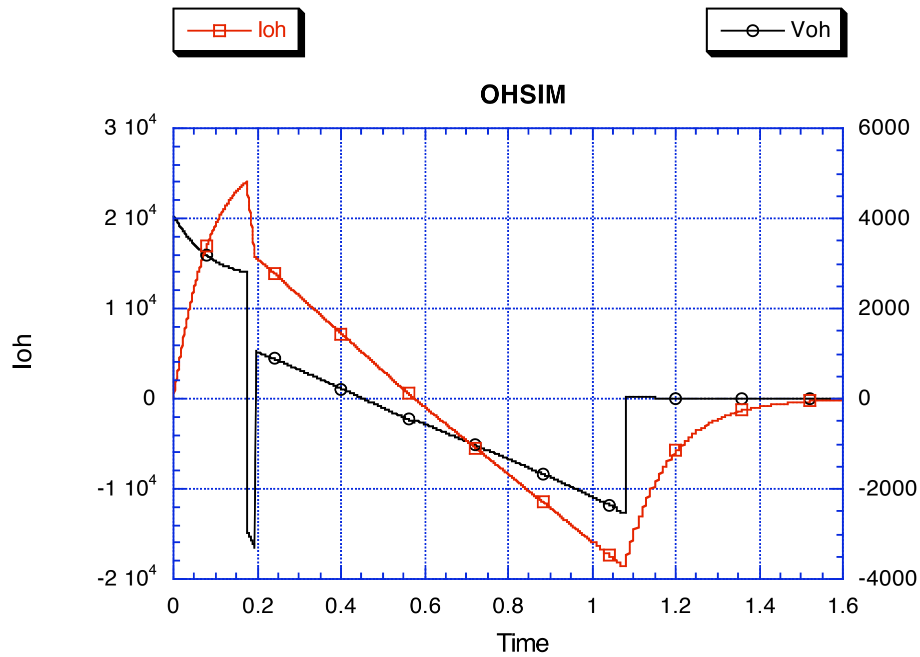
- for the partial inductive (single swing) case, more than 1/2 of the double swing volt seconds will be available

- for pulses without HHFW, assuming that the stresses are acceptable, the flux swing can be made nearly symmetric (depending on the margin required for the other PF power supplies) and the flat top can be extended

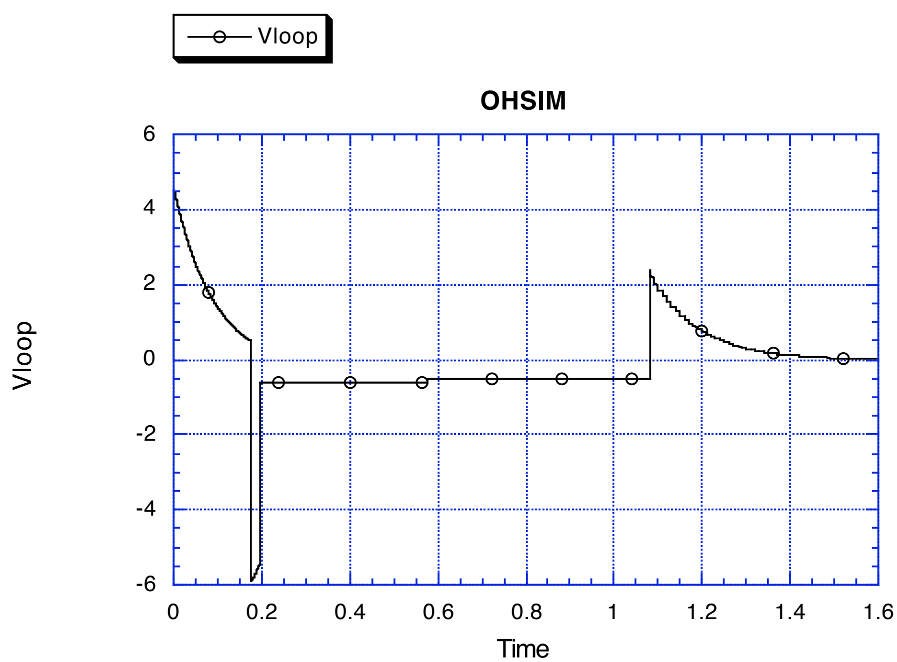
The following table summarizes the simulation results:

Parameter	**Value**	**Units**
Precharge Current	24.0	kA
Central B	7.5	Tesla
End of Flat Top Current	-18.65	kA
Flux Swing	0.6	Volt-Sec
Initiation Loop Voltage	5.9	Volts/Turn
Initiation Interval	20.0	mS
Plasma Ramp Time	400.0	mS
Plasma Flat Top Time	500.0	mS
ESW @ Iprecharge	0.3	sec
T_{max}	73.0	deg C
P_{max}	73.1	MW
Q_{max}	68.3	MVAR
S_{max}	94.3	MVA
ΔV_{max} (PPPL)	3.0	%
ΔV_{max} (Brunswick)	0.98	%
ΔV_{max} (Trenton)	0.65	%

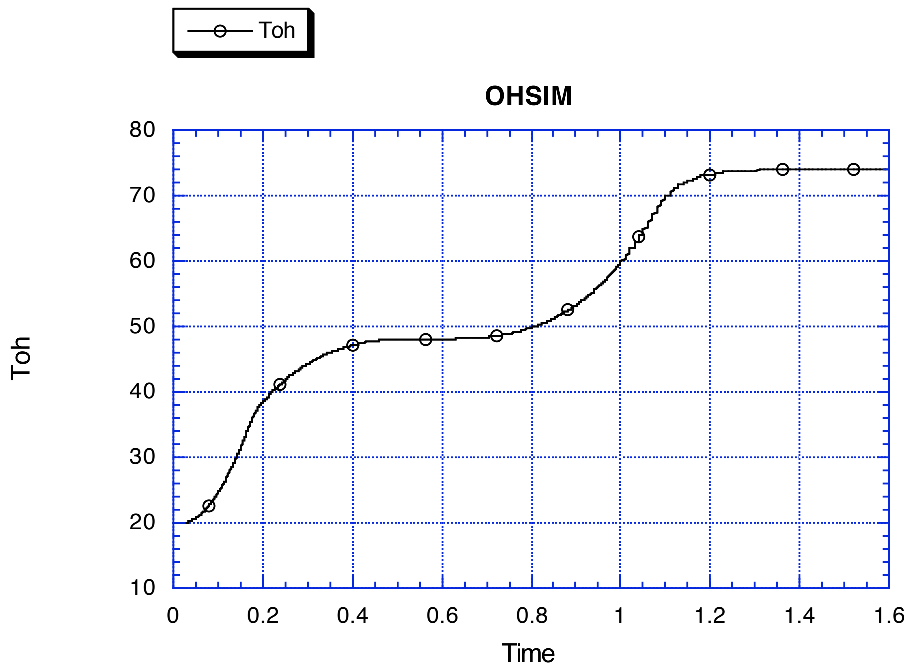
Simulation results are depicted in the following figures.



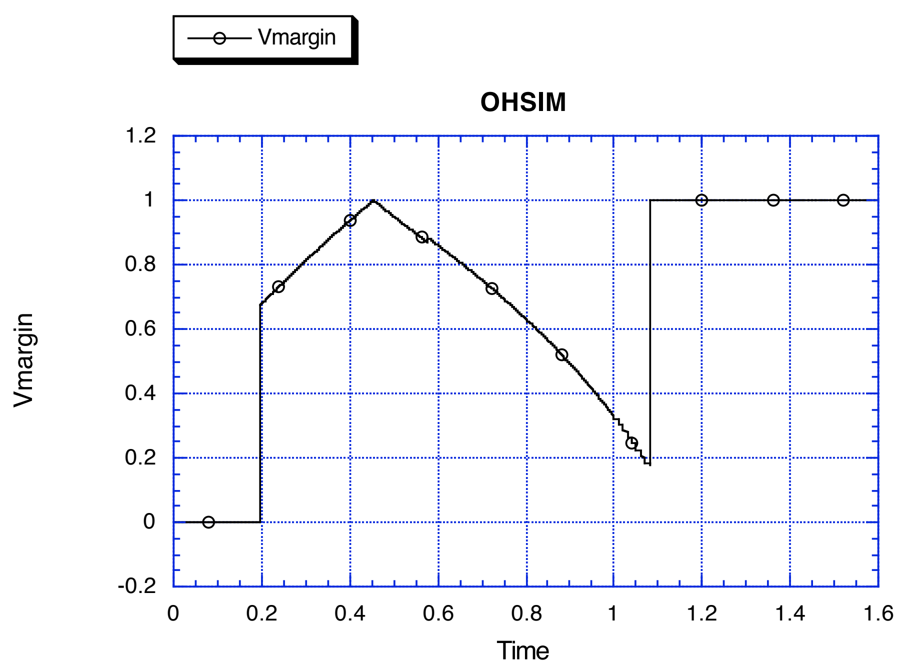
OH Coil Terminal Voltage & Current



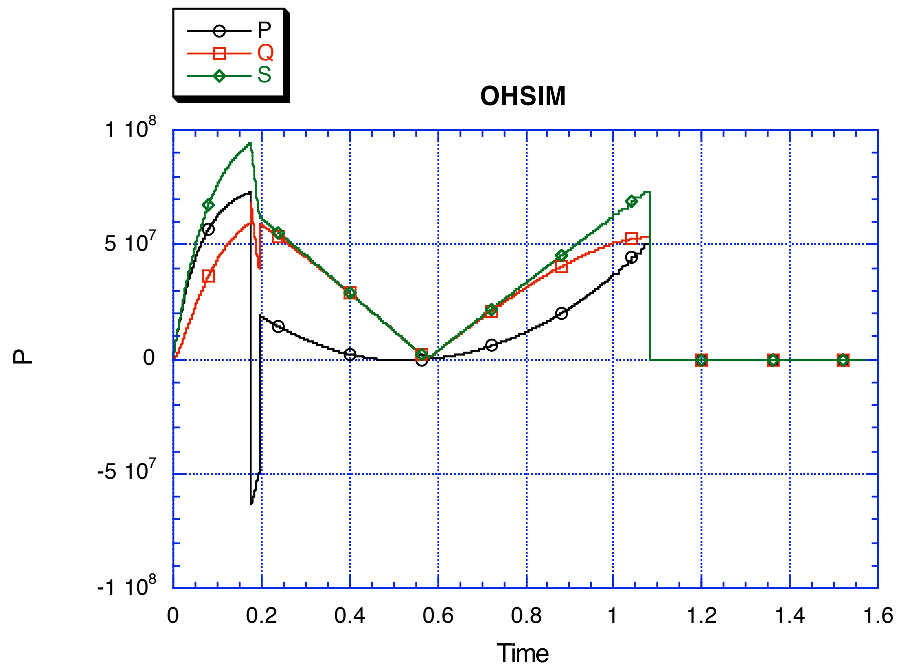
Plasma Loop Voltage



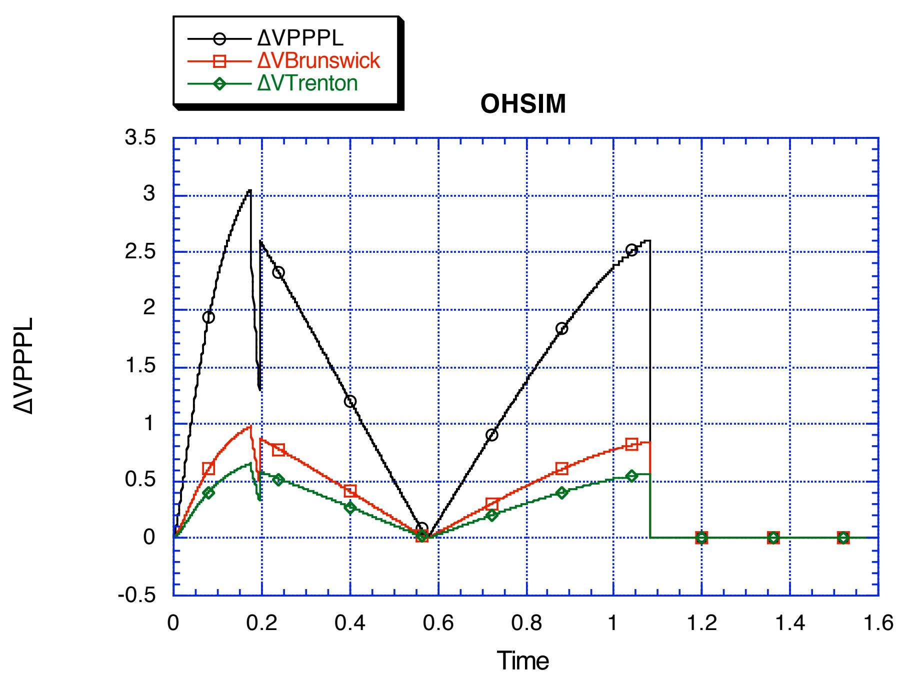
Coil Temperature



Power Supply Voltage Margin (per unit)



Active, Reactive, and Apparent Power (measured at PPPL 138kV bus)



Voltage Drops in Grid (%)

Concerning the use of utility grid power, there are several factors which complicate the analysis and need to be anticipated. The grid is not a constant in terms of impedance, voltage, and response to a changing load. The voltage incoming to PPPL varies on the order of +/- 3% over a 24 hour period, even without variation in the PPPL load. The "synchronous" impedance of the grid varies with time of day and day of year, as different generators and transmission lines are connected in different configurations, etc.. The base load on the grid (which releases itself to some degree as the voltage drops) varies with time of day and day of year. The "transient" impedance of the grid (time duration ≈ a few seconds) is somewhat less than the "synchronous" impedance. The response of VAR sources in the grid to changes in reactive load (time duration ≈ a few seconds) depends on generator excitation/VAR compensator response. The response of the grid to changes in active power load is rapid and results from the inertia of the generators and the release of other loads due to reduced voltage and frequency.

The utility grid impedances were derived from load flow studies performed by PSE&G for TPX for the projected grid configuration in the year 2000, with the grid in a relatively "soft" configuration (the impedances provided for short circuit calculations are much lower). However, the use of a simple impedance model has its shortcomings, considering the complexity of the power system.

To account for uncertainties in the grid model, as well as the simplifications used in the power supply model, and the variation of grid voltage over a 24 hour period, a small margin was maintained in the precharge phase such that (according to the simulation) the precharge to 24kA can be accomplished with the grid voltage 7.5% lower than nominal. Beyond this, with lower AC input voltage the coil resistance increases sufficiently toward the end of precharge such that the 24kA cannot be reached.

In case the margins allowed are not sufficient to account for the uncertainties the options available would be:

- reduce the initial coil temperature below 20C

- move the tap on the XST transformer to boost the voltage by 5%

- add reactive power compensation (shunt capacitor power factor correction) to reduce the voltage drop during precharge and allow a shift of the flux swing bias to a more symmetric case

- power the OH rectifier using a D-site motor-generator

In summary, reasonable margins have been included to cover the uncertainties, and recovery options exist if the margins prove to be inadequate. More detailed analysis (using more sophisticated power supply models, including the other PF coils, power supplies, heating loads, etc.) will be performed at a later phase of the design.

Concerning the cooling of the OH coil, preliminary calculations are based on a simple lumped thermal resistance and thermal capacitance model of the OH coil. The thermal resistance is based on the mass flow of the water and the thermal capacitance on the mass of copper. Two options were considered. First, sufficient pressure is applied to the cooling path so that the resultant flow and thermal time constant is less than 1/3 of the desired repetition period (600 sec). Second, the use of 10C inlet water temperature is assumed, while the required initial (bulk average) coil temperature is held at 20C.

In the first case, given the cooling path length of the outer layer (the longest path), the required pressure and flow would be 650 psi and 0.76 GPM.

In the second case, the required pressure and flow would be 284 psi and 0.47 GPM.

In the second case, there could be a concern regarding dew point and condensation on the leads of the coil (I assume that there would not be a problem in the gaps inside and outside of the coil within the stack), since part of the coil would go below 20C in order to reach a bulk average temperature of 20C. The dew point temperature which can be maintained in the test cell is not known at this time. I suppose that, if there is a problem it could be solved by thermal insulation around the leads.

As a compromise, the 10C water could be introduced only until the coolest part of the coil (at the inlet) reached the dew point temperature, at which time the inlet water temperature would be increased to the dew point temperature. A pressure and flow somewhere in between the above two cases would be required.

Comments/suggestions regarding this coil design are requested.

cc:

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