13-980704-CLN-01

TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: OH GROUND PLANE BEHAVIOR

When the OH power supplies are energized, the voltage applied to the OH coil rises rapidly to up to as much as 6kV. The waveform of the voltage rise is determined by the R-C snubber circuits connected across each thyristor in each power supply. Prior to any of the thyristors being fired, the snubber capacitors are charged to a voltage equal and opposite to that from the AC source, so the voltage across the load is approximately zero. Once the thyristors are fired, the snubber capacitors discharge into the thyristor through the snubber resistors and the voltage seen by the load rises exponentially according to the time constant of the RC snubbers. This time constant is $15\Omega * 1\mu F = 15\mu S$.

Ignoring initial fast transients, the 6kV is more or less equally divided amongst the OH coil turns. The voltage of each turn with respect to ground is set, nominally, by the grounding resistors connected from each power supply terminal to ground, such that one coil terminal goes to (+) 3kV and the other to (-) 3kV. Should a ground fault occur on one terminal, or perhaps exist at the moment that the power supplies are turned on, one terminal would stay at ground and the other would go to +/- 6kV.

Whenever the voltage of the OH coil turns to ground changes, capacitive charging currents flow through the insulation capacitance, and return through the ground plane, to ground.

The OH coil is a 4 layer coil, wound 2 in hand. Thus each layer has two windings and the turns in those windings, depending on the series connection of the total 8 windings, have a particular voltage to ground. The inner layer faces the ground plane formed by the tension tube on the ID of the coil. The outer layer faces the ground plane formed by conducting paint on the OD of the coil. The two layers in between indirectly face the ID and OD ground planes.

Thus the capacitance to ground per unit length of each winding consists of capacitance to the ID ground plane, and to the OD ground plane. The outer layer will have the highest capacitance to the OD ground plane, since $C \sim 1/d$, and the thickness of insulation layers separating the outer layer from the OD ground plane is the least. Similarly the inner layer will have the highest capacitance to the ID ground plane.

During normal operations, the start and finish leads of the OH coil are nominally at (+) and (-) equal voltages. If the OH winding pattern was fully symmetric, meaning that it started, e.g., at the top of the outer layer, progressed downward, inward, upward, inward, downward, inward, reached the inner layer, and then progressed outward following the same pattern and ended at the top of the outer layer, then the capacitance to would be symmetrically distributed about the midpoint of the coil. In this case, during normal operations, with the coil terminals at (+) and (-) V, adjacent turns in the outer layer of the coil would be at equal but opposite voltages. Capacitive currents, due to voltage derivatives, would flow locally only. There would be no net capacitive current through ground.

On the other hand, even with the symmetric coil, if (due to a ground fault), one coil terminal stays at ground and the other goes to a voltage V, there will exist net capacitive currents which must flow through ground. Conversely, if the voltage is symmetric, but the coil is asymmetric, net capacitive currents will flow.

To the extent that the ground plane, through which the capacitive currents must return to ground, is resistive, surface potentials will develop due to I*R drop as that current reaches "solid" ground. This is undesirable for several reasons:

- corona, partial discharge, and eventual degradation of the ground plane and ground insulation can occur leading to flashover and/or insulation breakdown;
- any instrumentation electrically connected to the ground plane will be subject to the surface potential of the ground plane;
- the electrical insulation associated with any instrumentation electrically separated but physically in contact with the ground plane must withstand the surface potential of the ground plane.

To simulate (EAD03, neumeyer/PSCAD/fileman/NSTX/OHX) this situation on the NSTX OH coil, a simplified model was assumed whereby:

- the outer layer consists of 1/4 of the total (≈ 1000) turns, wound such that turn 1 begins at one end and turn 250 at the other end of the coil. Per the discussions above, this should be worst case since, in practice, the voltages to ground on the adjacent turns will be different, perhaps even opposite in polarity, leading to something less than additive charging currents as in the case assumed;

- the remaining 3/4 of the turns do not return currents through the OD ground plane. This is not necessarily a conservative assumption, but certainly a simplifying one;

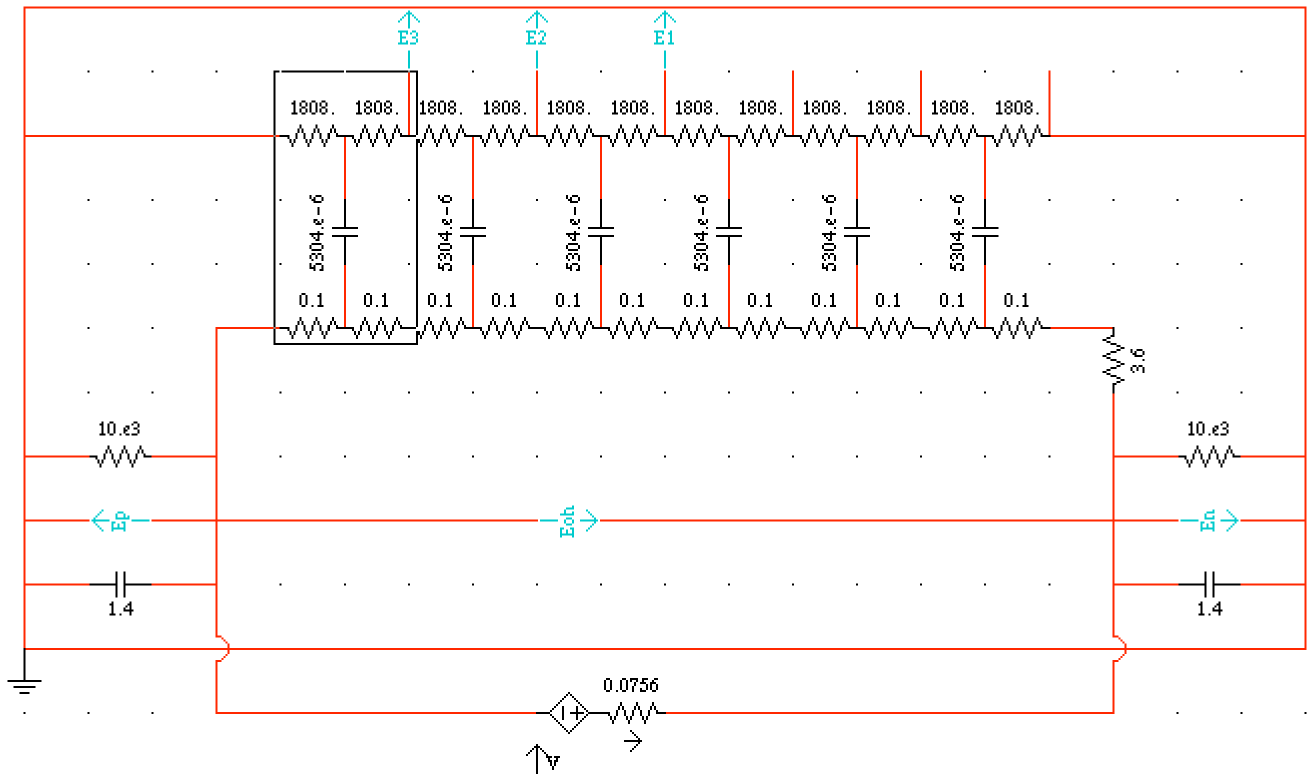
- the OD ground plane extends the full length of the coil, and is connected to solid ground at each end;

- the ground plane resistivity is 2000 Ω/square (per T. Meighan);

- OH power supply grounded through 10kΩ resistors at each terminal, and connected via cabling with 1.4μF capacitance to ground;

- coil insulation capacitance, etc., calculated per the following spreadsheet.

Coil Groundwall OD	6.162	in
Coil Copper OD	6.076	in
Groundwall Thickness	0.086	in
Coil Length	210.000	in
Dielectric Constant	3.000	
Coil Capacitance	1818.8	pf/ft
	31829.3	pf
Surface Resistivity	2000.0	ohms/square
Circumference	19.4	in
Surface Resistance	1239.8	Ω/ft
	21695.9	Ω
#Coil elements	6	
Capacitance/element	5304.9	
#Ground plane element	12	
Resistance/element	1808.0	
Snubber R	15	Ω
Snubber C	1.0	μF
Snubber tau	15.0	μS
PS OC Voltage	1012.85	Volt
Series Snubber	4	
Snubber Vo	253.2	Volt
Snubber Io	16.9	amp
Snubber dVo/dt	16.9	V/μS
#series PSS	6	
#Series snubber	24	
∑dVo/dt	405.14	V/μS

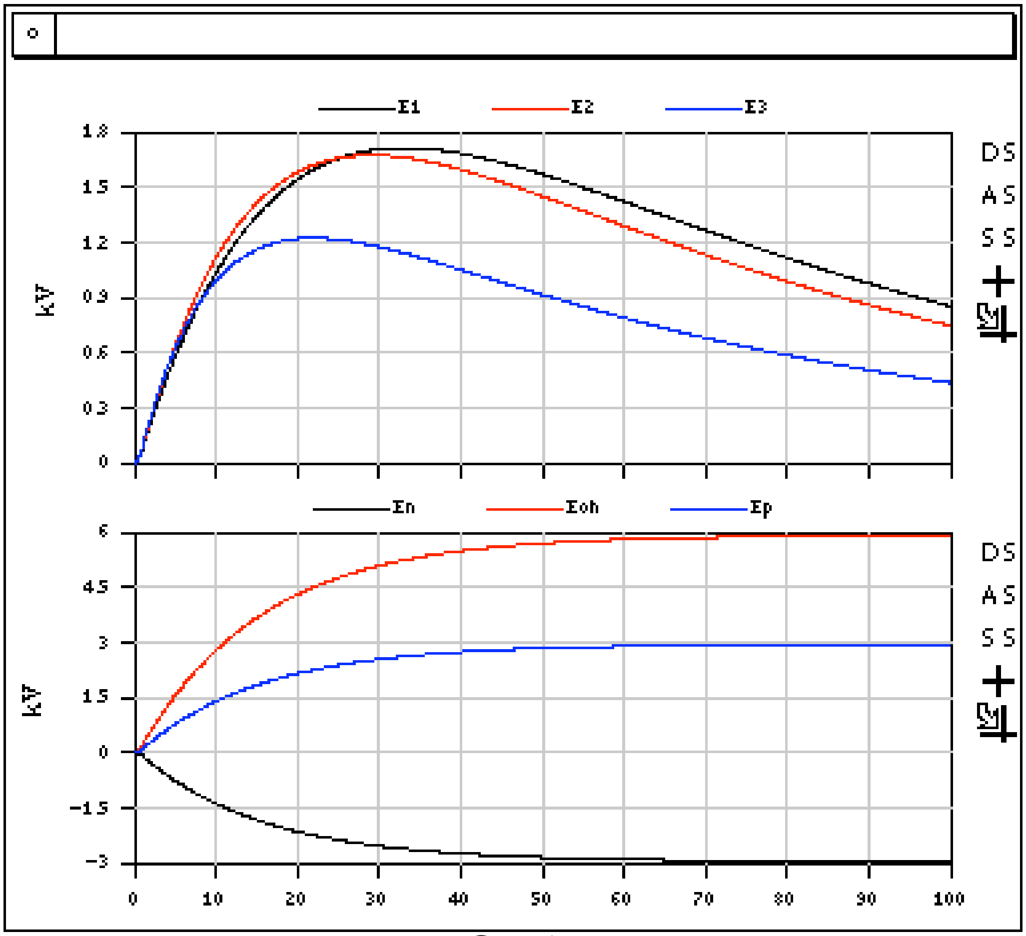


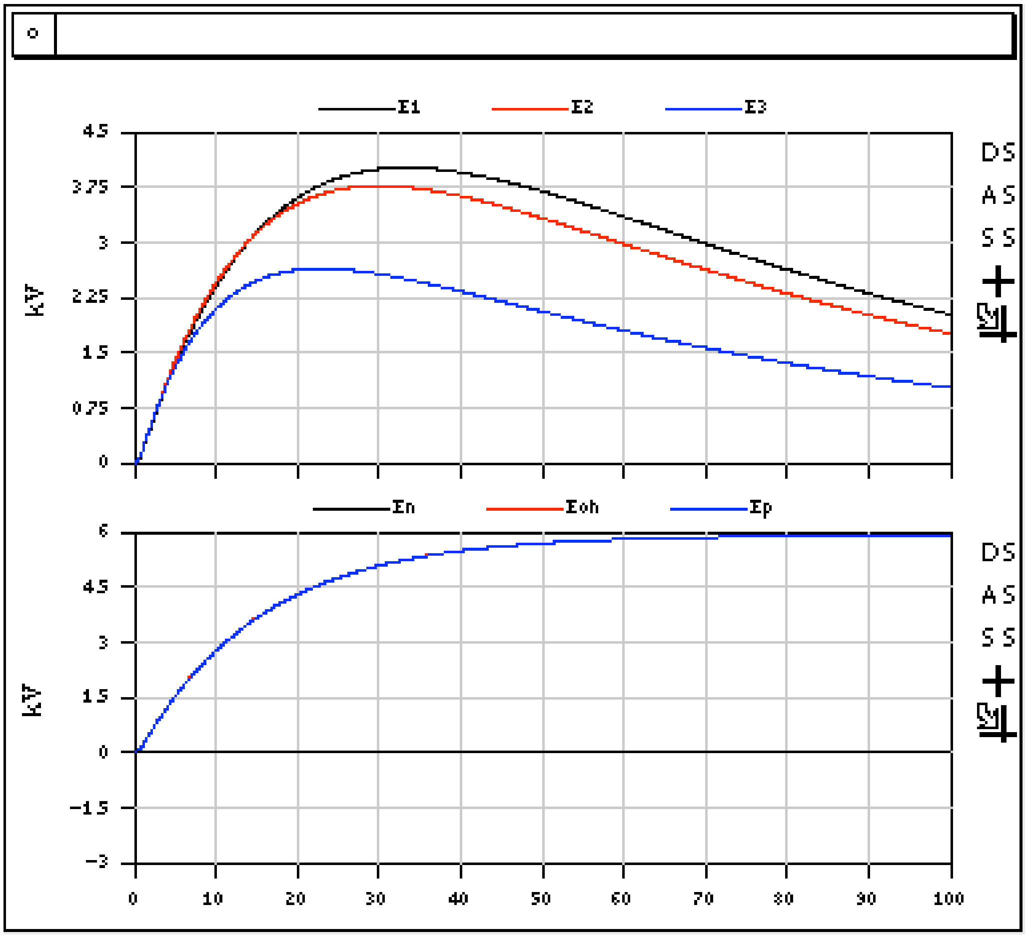
PSCAD Model

It is noted that the voltage drop across the coil is achieved by series connection of 48 resistors each of 0.1Ω, and 12 of which are involved in the outer layer. This results in a few kA of current flow out of the power supply, and is a simplified way to get to the desired answer. The voltages E1, E2, and E3 are measures of the surface potential on the OD ground plane.

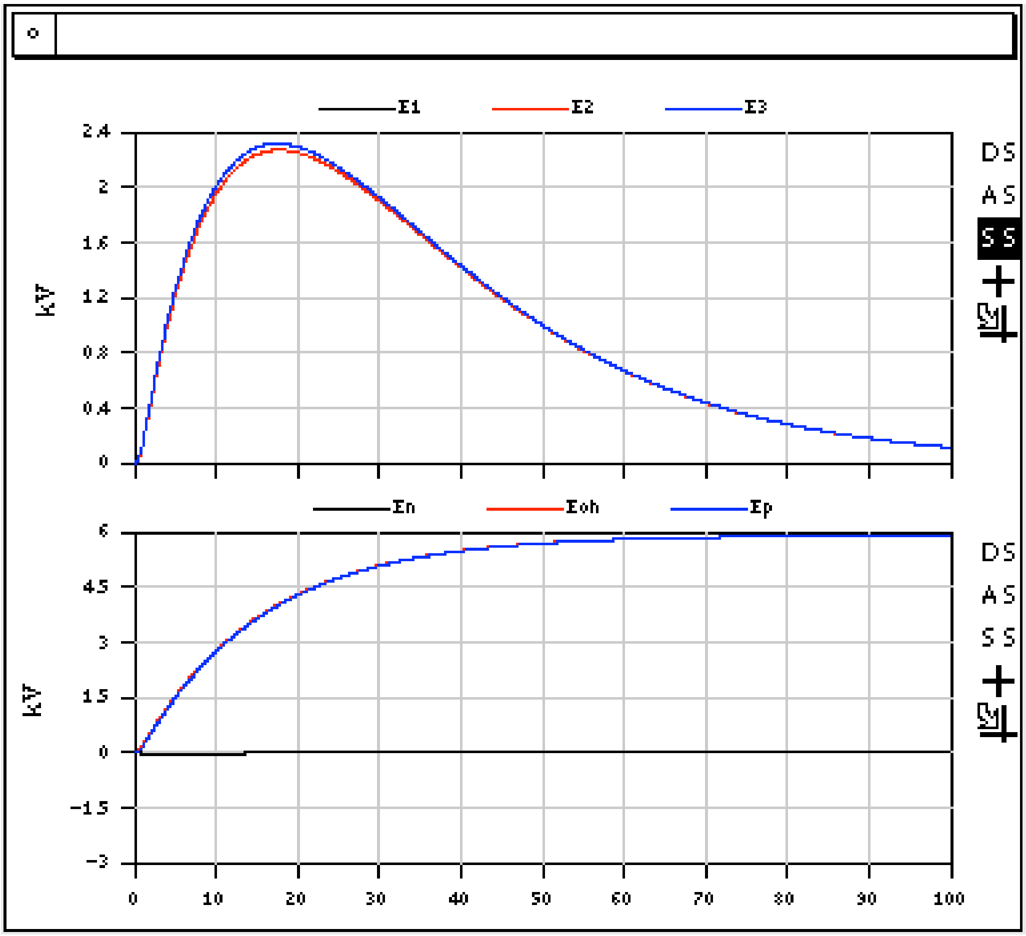
Four cases were run as described in the table and figures following.

Case	Ground Plane	Fault Status	E1 peak (kV)	E2 peak (kV)	E3 peak (kV)
1	Nominal	None	1.75	1.7	1.23
2	Nominal	Ground on (-) terminal	4.0	3.8	2.65
3	Added ground connection at middle (z=0)	Ground on (-) terminal	0	2.2	2.3
4	1/10 resistivity	Ground on (-) terminal	1.5	1.4	0.8


E1
E2
E3
kV
1.8
1.5
1.2
0.9
0.6
0.3
0
DS
AS
SS
En
Eoh
Ep
6
4.5
3
1.5
-1.5
-3
0
10
20
30
40
50
60
70
80
90
100
Case 1

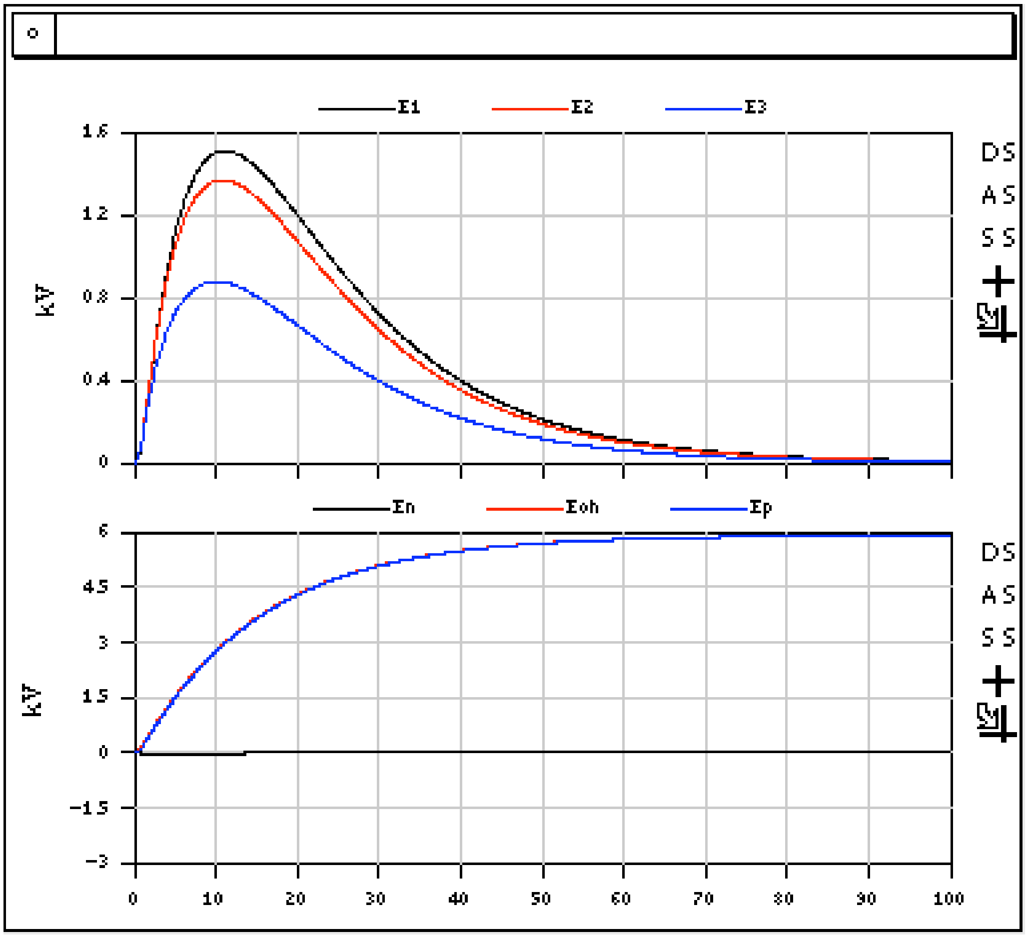

E1
E2
E3
4.5
3.75
3
2.25
1.5
0.75
0
kV
DS
AS
SS
En
Eoh
Ep
6
4.5
3
1.5
0
-1.5
-3
kV
DS
AS
SS
0
10
20
30
40
50
60
70
80
90
100

Case 2



E1
E2
E3
2.4
2
1.6
1.2
0.8
0.4
0
kV
DS
AS
SS
En
Eoh
Ep
6
4.5
3
1.5
0
-1.5
-3
kV
0
10
20
30
40
50
60
70
80
90
100

Case 3



Case 4

From the results shown the voltage on the OD ground plane is too high with the 2000Ω/square resistivity (cases 1 and 2). The situation can be improved upon if an additional "solid" ground connection can be made at the midplane (z=0) case 3. However, the voltage is still too high. In case 4, 200Ω/square resistivity was assumed. In this case the RC time ($R_{ground\ plane} * C_{insulation}$) becomes << the rise time of the applied voltage, and the large surface potential tends not to build up.

Assuming that the OH coil, at the present time, has been painted with the 2000Ω/square paint, and overcoated with a sealer, the following courses of action are recommended for consideration:

1) Paint an additional ground plane, and sealer, of lower resistivity (ideally ≈ 100Ω/square, or less*) than the present coating either a) over the present coatings, or b) after removing the present coatings, if that is feasible via solvents and/or abrasion. In case of a), it is not necessary to provide a connection to the original underlying ground plane; it will be capacitivly coupled. The additional ground plane may consist of less than 100% coverage, e.g. azimuthal stripes, or other pattern, such that low resistance (lower than 2000Ω/square, perhaps much lower than the above 100Ω/square (e.g. fully conducting) as long as no loops are formed toroidally or poloidally) is available all along the length of the coil.

2) Thermocouples and other instrumentation on the center stack should be electrically insulated from the ground plane, i.e. not galvanically coupled, unless a trace ground wire is provided to ensure that the potential of the ground plane at the point of connection does not rise to high level.

3) Ground plane connections to "solid ground" should extend as far inwards toward the miplane as is feasible. This serves to minimize the length over which the capacitive currents flow before reaching ground.

* Note: the lower resistivity will lead to more toroidal current during the $\leq$ 5mS plasma initiation interval. However, 100Ω/square paint, around the $\approx$ 19 inches of coil circumference, would only result in a toroidal current around 6kV/1000turn/19in/100Ω/sq = 3 mA/inch. Presumably this would not endanger the paint.

cc:

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NSTX File