PREDESIGN OF A NEW OHT POWER SUPPLY FOR VERSATOR II

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0. Introduction.

A basic design of a new OHT power supply for VERSATOR II, is advanced.

A requirement on the design is to permit the operation of VERSATOR II in two modes: the double swing, in which a longer plasma pulse should be obtained; and the primary shut-off, when the plasma is not driven anymore by the OHT, but by RF waves (RF current drive mode).

The report was organized as follows:

In Section I the establishment of a current bias is examined.

In Section 2 the commutation phase is analyzed, restricted to the use of a saturable inductor.

Section 3 deals with the start-up phase, which break-downs the gas, creating the plasma.

Section 4 is devoted to the double swing drive, and....

Section 5 to the OHT shut-off.

In Section 6 a list of major components is written down.
1. **Current Buildup.**

   This is the first phase of the OH operation, with the aim of establishing a magnetic bias in the system, from which the swing of the OH current can follow. The maximum current reached during this phase, $I_m$, must be as large as compatible with the current capacity of the OHT primary in order to maximize the available external volt-seconds ($M_I m$) for plasma consumption. For Versator II, $M$, the mutual inductance between the primary and plasma equals $8\mu H$, and $I_m=15kA$. Therefore, volts-seconds $=0.12$, a 6% of these available in the Alcator C machine.

   One typical circuit for establishing the magnetic bias is shown in Fig. 2. Initially V1 is fired, and $I_{OH}$ starts to increase until reaching the maximum of 15kA, when V2 is fired, crowbarring the OH. The current builds up through the vacuum bottle (VB), which remains in the conducting state (closed), and through $L_{sat}$. These two components are necessary for commutating the OH current through the path AB, later on. In practice, VB and $L_{sat}$ may be three vacuum bottles and saturable inductors in the series parallel connection shown in Fig. 3, according to the current handling capacity of the VB's.

   According to the information given by the Alcator Group a single inductor varies its self-inductance from $\sim 300\mu H$ - in the low current regime, $<350A$ - to $20\mu H$ - in the high current regime, $>350A$. Its internal resistance is constant and $=3m\Omega$. Therefore, for the circuit shown in Fig. 2, $R_{sat}=1m\Omega$, and $L_{sat}=10\mu H$ (high current regime $>1kA$) or $L_{sat}=100\mu H$ (low current regime $<1kA$).
2. **Energy Calculations.**

To raise the current to the 1kA level where the inductors saturate little energy is needed, numerically, $\frac{1}{2}(710\mu\text{H})(1\text{kA})^2=355\text{J}$. A larger amount of energy is needed to reach the 15kA; for this case, $\frac{1}{2}(620\mu\text{H})(15\text{kA})^2=69750\text{J}$ are necessary. This energy comes from $W_1$ in Bank 1. Some energy is lost in heat in this process. The efficiency of this process is defined as

$$\eta = \frac{\frac{1}{2}L I_m^2}{\frac{1}{2}C_1 V_i^2} = \exp(-2\gamma \omega t_m)/(1-\gamma^2)$$

(1)

Equation (1) is a very good approximation for $\gamma^2=R^2C/4L\leq 10^{-3}$, $\omega$ is the radian frequency $=1/\sqrt{LC_1}$, and $t_m=1.57/\omega$ is the rise-time. In the present case $L=620\mu\text{H}$, and $R=12\text{m}\Omega$. For Bank 1 it is advisable to use 1mF, 4kV, 8kJ, unit capacitors, in order to maintain uniformity with the 700kJ toroidal bank already in use. For ten capacitors in a parallel connection, $C_1=10\text{mF}$, $W_1=80\text{kJ}$, and $\eta=92\%$, and therefore 73.6kJ are available for conversion into magnetic energy, and 6.4kJ are lost heating the conductors during each shot. Taking into account a 10% supply margin, Bank 1 can be specified as follows:

**BANK #1.**

**UNIT:** 1mF, 4kV, 8kJ

**TOTAL OF 11 CAPACITOR IN PARALLEL CONNECTION**

11mF, 4kV, 88kJ

$\eta = 92\%$
3. **Other Equipment**

The A-s rating of V1 must be larger than $Q_1 = C_1 V_1 = 44 C_1$ plus the charge passing through it during the crowbar action, (assume 15kA passing during 2ms before current commutation, in normal operation) 30C, plus the small amount leaking through it during commutation. Adding together the above numbers, V1 must be rated at 80A-s. For V2, 36 A-s are required. Both V1 and V2 must hold -4kV reversed voltage. Therefore:

V1: Tube GL/37207A    200A-s

V2: Same Tube.

One may consider larger GL8205 tubes for V1 and V2, in the case of failure (commutation not obtained).
Figure 2. Circuit configuration during the current buildup in OHT phase

Figure 3. Connection scheme of saturable inductors and vacuum bottles
2. Current Commutation

2.1. Circuit Operation

By the time when the OH current is maximum, Bank 1 has been crowbarred (at \( t_2 \)), and being a burning arc in VB (open state), V3 is fired at \( t=t_3 \) in order to provide a diverting path AB for the OH current, and to drive through zero the current in VB, the only way to get VB/do its job. Figure 4 shows the circuit at \( t_3 \). Bank 2 must be polarized as shown because it must oppose the current in the vacuum bottle, driving the current through zero. When this happens, \( L_{\text{sat}} \) increases its value, the period of oscillation increases and \( \text{di/dt} \) in the vacuum bottle decreases; and so current is commutated. An alternative operation may be the use of a SCR instead of the saturable inductor, as PRETEXT is operated.* In Fig. 4, \( C_3 \gg C_2 \), and so \( C_3 \) can be neglected in the analysis. Also shown is a spark gap and the pulse shaping network to be described below.

2.2. Analysis

The circuit model is shown in Fig. 5. Initial conditions are \( I_{\text{OH-SAT}} = I_m \), \( I_c = 0 \), and \( V_c = -V_2 \). The meaning of the above symbols are implicit in the Figure.

Neglecting all resistances:

\[ I_{OH}(t) = I_m + \left(\frac{V_2}{\omega L_{OH}}\right) \sin \omega(t-t_3) \]  
\[ I_{SAT}(t) = I_m - \left(\frac{V_2}{\omega L_{sat}}\right) \sin \omega(t-t_3) \]  
\[ I_C(t) = \left(\frac{V_2}{\omega L}\right) \sin \omega(t-t_3) \]

where \( \omega^2 = \omega_{OH}^2 + \omega_{sat}^2 = (CL)^{-1} \)

and \( L \) is the inductance of \( L_{sat} \) in parallel with \( L_{OH} \).

The design of Bank 2 follows from Equation 3. In order to make \( I_{SAT} = 0 \), \( V_2 > \omega L_{sat} I_m \). If the null point is reached at \( \omega(t-t_3) = \pi/8 \), then from (3):

\[ \frac{1}{2} C_2 V_2^2 = L_{sat}(1+L_{sat}/L_{OH}) I_m^2 \]

Waveforms are shown in Figure 6. After current commutation the voltage on \( C_2 \) reverses because \( C_2 \) is flooded by the bias current, then \( V4 \) is fired. In case of \( V4 \) failure Banks 2 and 3 can be protected with spark gaps. Equation 6 gives 2250J. Consider \( W = 3kJ \), choose \( V_2 = 4kV \), then \( C = 375\mu F \), and the commutation time \( T/4 = \pi/\sqrt{LC} \approx 300\mu s \) (low current regime). If \( V_2 = 5kV \), \( C_2 = 240\mu F \) and \( T/4 \approx 250\mu s \), and the commutation time is not shortened very much; therefore the 4kV bank is preferable.

From Equation 2 one calculates the contribution of Bank 2 to the \( OH \) current, it being small, approximately 500A.
Figure 4. Equivalent circuit for commutation phase

Figure 5. Model for analysis of Figure 4.

Figure 6. Waveforms of currents through the SAT and OH inductors
3.- Start up phase.

3.1 Operation and requirements.

At time $t_4$ when $V_4$ is fired the bias current is diverted into the resistor, suffering a sudden drop which induces the electric field $E$ necessary for breaking the gas. A good analysis of the physical mechanisms responsible of this process is that of Papoular*. For present day VERSATOR II parameters, the time of effective application of the $E$ field, defined as $T/8$ (of the fast bank) is $\lesssim 1\text{ms}$, and the start voltage is $= 30\text{V}$. The following design must be able to reproduce those parameters, as well as determining the resistor, minimizing the Volt-second consumption, and determining the leftover OH current and voltage in $C_3$.

3.2 Circuit analysis and design.

The circuit operating in this phase can be reduced to that of Figure 7. For $t>t_4$, the exact expression of the OH current is:

$$I_{OH}(t) = I_m \exp\left(-\mu t/2\right) \left[ \cosh\omega t - (\mu/2\omega)\sinh\omega t \right]$$

$$- \left( V_3/\omega L_{OH} \right) \exp\left(-\mu t/2\right)\sinh\omega t$$

(7)

where $\mu=R/L_{OH}$, $R=R_{st}+R_{OH}$, $\omega_0^2 = 1/(C_3 L_{OH})$, $-\omega^2 = \omega_0^2 - \mu^2/4$

For the case of strong damping, $\omega_0 < \mu/2$, and (7) reduces to

R. Papoular.

The Genesis of Toroidal Discharges.

Nucl. Fus. 16,1,p37,(1976)
\[ I_{OH}(t) = I_m \left[ \exp(-\mu t) + \frac{(L_{OH}/R)/(RC_3) \cdot (\exp(-\mu t) - \exp(-t/RC_3))}{- V_R/R \cdot (\exp(-t/RC_3) - \exp(-\mu t))} \right] \]

As can be seen there are two decay modes: a fast one with time constant \( L_{OH}/R \), and a slow one with time constant \( RC_3 \). Equation (8) can be further reduced to

\[ I_{OH}(t) = I_m \exp(-\mu t), \text{ for } t > t_4 \]  

This is our working expression. The induced voltage is

\[ v_{st}(t) = MdI_{OH}(t)/dt = -M I_m \exp(-t/\tau_{st})/\tau_{st} \]

where \( \tau_{st} = 1/\mu = L_{OH}/R \)  

In the design we will consider a maximum voltage of 30V and a minimum voltage of 10V. The latter value should be compatible with Papoular's analysis (see below) and maybe within the operation regime of Versor II once the field error is reduced to \( \approx 2\mu \).

The volt-second consumption (VS) must be minimized in order to leave unwasted flux for a longer plasma pulse. Defining the percentile Volt-second consumption as \( VS = M( I_m - I_{OH}(t)) / M I_m \), then

\[ VS(t) = 1 - \exp(-t/\tau_{st}) \]

Setting the values of \( v_{st} \) and \( VS(t) \), from (12) and (10) one finds \( \tau_{st} \), the decay time, then from (11) the resistance, and from (12) the time \( t_f \) marking the end of the start up phase. Equation (9) gives the left-over OH current for the next phase; the energy wasted \( Q \) in the resistor can be calculated from the usual formula:
\[ Q = \int_{0}^{t_f} R_{st} I_{OH}^2 dt = R_{st} I_{m}^2 \frac{\tau_{st}}{2} \left( 1 - \exp\left(-2t/\tau_{st}\right) \right)/2 \] (13)

Finally the resistor should be specified, taking into account its increase of temperature.

\[ Q = cM\Delta T = c\rho V_{0} A_{1} \Delta T \] (14)

where \( c \) is the specific heat, \( \rho \) is the mass density, \( A \) is the cross sectional area, \( l \) is the length of the resistor, and \( \Delta T \) is the temperature increase.

Together with the usual resistance formula \( R = \rho l/A \) (15)

Consider stainless steel (\( 0.1\% \) C, 8\% Ni, 18\% Cr, 73.9\% Fe), then \( \rho = 90 \times 10^{-8} \Omega \cdot \text{m}, \rho \rho = 7,800 \text{ kg/m}^3, \) \( c = 460 \text{ J/kgC}. \) Choosing a rectangular plate of 1/16" thickness and 2" width (a rectangular geometry has more dissipation area than a cylindrical one), then from (14) and (15):

\[ \Delta T(C) = 3.85 \times 10^{-5} \frac{Q(J)}{R_{st}(\Omega)} , \quad l(m) = 89.55 \frac{R_{st}(\Omega)}{30} \]

Results are summarized in Table I. For a constant flux consumption the voltage is reduced if the resistance is reduced and the duration of the pulse increased. For a constant voltage the flux consumption is reduced by decreasing the resistance and the time duration.

For 10V loop voltage the temperature increase, 17.1 \( \text{C} \), seems rather large. It is advisable to use 1/8"x2" plate, instead. Consequently, \( \Delta T \) will be reduced by a factor of 4 and the length doubled, to a maximum of 35 m; if 15kA aren't available, then more resistance is needed. For 13kA, a resistor 40m long is necessary to induce 30V. 30 strips, each 1.5m long can be tailored from a 3.175cmx150cmx167.5cm plate, allowing for a 10\% loss of material. This material will be sufficient for making a 0.25 Ohm resistor. Shut-off operation requires 20\% extra material (See page 15b).
### TABLE I
RESULTS OF DESIGN OF THE START UP PHASE

\( I_m = 15kA \), 0.12 V-s available

<table>
<thead>
<tr>
<th>Induced voltage ( v_{st}(t_f) ) in V</th>
<th>Consumption of Volt-seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.193 40.0 28.6</td>
</tr>
<tr>
<td>0.86</td>
<td>0.164 34.3 15.2</td>
</tr>
<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>0.126</td>
<td>26.7 27.8</td>
</tr>
<tr>
<td>4.5</td>
<td>0.106 22.9 14.7</td>
</tr>
<tr>
<td>1.3</td>
<td>11.2 8.6</td>
</tr>
<tr>
<td>43.5</td>
<td>5.2 13.1 5.3</td>
</tr>
<tr>
<td>0.47</td>
<td>0.7 21.7 9.5</td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>0.058</td>
<td>13.3 25.6</td>
</tr>
<tr>
<td>9</td>
<td>0.048 11.4 13.3</td>
</tr>
<tr>
<td>2.6</td>
<td>11.2 17.1</td>
</tr>
<tr>
<td>43.5</td>
<td>10.5 13.1 10.7</td>
</tr>
<tr>
<td>5.2</td>
<td>1.4 21.7 4.3</td>
</tr>
</tbody>
</table>

**GUIDE TO TABLE I**

<table>
<thead>
<tr>
<th>( R_{st}(\Omega) )</th>
<th>( v_{st}(0) )</th>
<th>( Q(kJ) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_{st}(ms) )</td>
<td>( I_{OH}(t_f) )</td>
<td>( \Delta T(C) )</td>
</tr>
<tr>
<td>( t_f(ms) )</td>
<td>( I_{pl}(t_f) )</td>
<td>( l(m) )</td>
</tr>
</tbody>
</table>

**LIST OF SYMBOLS:**

- \( R_{st} \): Resistor for start up phase (ST)
- \( v_{st} \): Induced voltage
- \( \tau_{st} \): Decay time.
- \( t_f \): Duration of ST phase.
- \( I_{pl} \): Plasma current.
- \( Q \): Joule loss in the resistor.
- \( l \): Length of stainless steel resistor. 1/16"X2" plate.
- \( \Delta T \): Resistor's temperature increment.
See Table I, row 2 column 1 case
Voltage at $t_f$ is 20V

See Table I, Row 3, column 3 case
Both of these graphs are Start-up phase
Voltage at $t_f$ is 10V
These curves illustrate the double-swing. Note the time scale. In the ++ case less flux was wasted in plasma formation, than in the +++ case. Consequently, the $I_{OH}$ swing is larger for the +++ case, and the plasma current will also be larger. Note that the voltage does not change much, from one case to the other.
3.3 Breakdown conditions.

Papoular presents a model of breakdown in Tokamaks based on the Townsend avalanche. The competing mechanisms in the process are ionisation by electrons accelerated by the induced E field, and loss of electrons to the chamber walls due to diffusion, drift, and field errors. These mechanisms depend on \( \alpha \), the first Townsend coefficient, and on \( T_e \); which are in turn increasing functions of E/p. Since present data is limited to low values of E/p, an extrapolation is made to the range E/p \( \geq 100\text{V/cm}\cdot\text{mmHg} \). Present operation of VERSATOR II is in the range 1,200-5,000 \( \text{V/cm}\cdot\text{mmHg} \). In the future operation of VERSATOR II, E/p can be in the range 400-1000, because of the reduction of the loop voltage. (The field error is expected to diminish to 2G). Choosing E/p = 400 \( \text{V/cm}\cdot\text{mmHg} \), the loss rate equals \( \beta = 1,700 \text{ s}^{-1} \) and the ionisation rate is \( \nu = \alpha \nu = 36,000 \text{ s}^{-1} \). The avalanche will develop if \( \nu > \beta \), and breakdown will occur at a critical time \( t_{cr} \), at which a sufficient number of electrons are present within the chamber - a 10% degree of ionisation -. \( t_{cr} \) depends on the number of initial electrons prior to the external application of the E field, as well as geometrical parameters and toroidal B. Assuming a degree of preionisation of 5 electrons per million neutrals, calculation gives \( t_{cr} = 0.28\text{ms} \), which is in fact less than the escape time due to the various loss processes and \( t_f \) in Table I. According to the model the minimum E field is 0.0275\( \text{V/cm} \). For 10V of loop voltage, \( E = 0.04\text{V/cm} \). In conclusion, the design parameters in Table I are compatible with Papoular's model of breakdown conditions.
FIGURE 7. Equivalent circuit for start up phase, or continuing phases (steady state, double-swing)
4. **DOUBLE SWING PHASE.**

Once the plasma is formed the loop voltage must be reduced, because the plasma can't take so much heating. Therefore, in Figure 1, V5 is fired, and later on V6. Once the whole resistor is shorted V7 can be fired to help V3 and V4 with the Amp-sec. V3 will stop conducting when the OH voltage drops below V3 + 20V. The larger V3, the sooner the discharge will end - if V7 is not fired. Other possibility is to use a vaccum bottle, instead of V7. The bottle will stay open - non conducting - until V6 is fired.

From Figure 7, various graphs of OH current, loop voltage, and C3 voltage can be obtained. These are shown in Figures 8a-i. Ideally a 15kA swing in the OH current would produce a plasma current of 170 kA. This is clearly an overestimation, but the real plasma current can well be in the vicinity of 100kA. Time scales are shown. Pulse duration (plasma) can be 50ms or more. A 2F Bank provides longer plasma pulse and lower loop voltage.

Figures 8a-c show the circuit response when the initial voltage on C3 is diminished: the OH current falls less abruptly. Figure 8d is to be compared with 8c, the difference being a larger resistance in the circuit. Figures 8f-h form a group, having the same parameters, except that the resistance is decreased. Figure 8i is a continuation of 8f, when the resistance is shorted at 10ms; accordingly, the loop voltage is reduced.

In conclusion, the graphs are more useful to show the principle of operation, rather than to predict exact circuit dynamics, because of the problem in modelling the plasma. A 2F double-swing Bank seems preferable than a 1F Bank, because of smaller loop voltage, and longer pulse duration.
Figure 8a. ALTERN means "alternating" response
Figure 8b. Farads and Ohms, refer to Figure 7.
Amps and Volts are initial values in circuit of Figure 7.
Figure 8c.
Figure 8d.
Figure 8e.
Figure 8f. CRITIC means that the circuit is critically damped. At t=10ms it can continue to Figure 8i (R=10mOhm).
FIGURE 8g.
Figure 8h.
Figure 8i. Continuation of 8f.
Figure 8j. For calculating A-s rating of ignitrons.
5. **Shut-off phase**

In this operation the plasma is created as usual, then it is maintained for about 15-20ms, to allow for heating and thermalization; at about 20ms the primary current is gently driven to zero, without inducing large loop voltages; afterwards the loop voltage is zero, and the plasma is not driven anymore by the OHT. The OHT has been shut-off; the plasma current and heating will be maintained by RF waves.

Result of simulations are shown in Figures 9a-b. They bring out different performances obtained by charging the double-swing capacitor to 100V. Other parameters that can be varied are resistance and bias current.

After plasma formation, the loop voltage must be kept below 5V, and should be about 1V, when the primary current is zero.
This is the start-up phase, inducing 28V for plasma formation, and ending at 1ms, when V5 is fired.

This is the shut-off phase, ending at about 20ms.

Figure 9a. SHUT-OFF OPERATION.
This is the start-up phase, inducing 28V for plasma formation, and ending at 1ms when V5 is fired.

Capacitor initially charged

This phase ends at 6ms (real time) when V6 is fired

ShUT-OFF PHASE. Ends at 15ms (real time)

Figure 9b.
6. Conclusions.

6.1 Capacitor Banks.

B1 is specified on page 2.

B3 can be the 2F, 350V, 122.5kJ Bank. See page 14.

B2 is specified in Figure 1. Try a 1mF, 4kV capacitor for this task, charged to 2.5kV. If the commutation time turns out to be long and losses are important, then C2 can be lowered.

6.2 Ignitrons.

V1 and V2 are specified on page 3.

To calculate the A-s rating of V3 and V4 one can monitor the change of voltage on C3, which is then proportional to A-s.* For example, Figure 8d gives 200 A-s for C3 = 1F, and Figure 8j gives 270 A-s for a 1F Bank, and 400A-s for a 2F Bank. Therefore for V3 and V4 use 1500A-s, GL8205 tubes. V5 can be a 200A-s, GL37207A tube. For V6 it is good to take into account V7. Once V6 is fired then V7 can be closed if it is a Ross' vacuum bottle; if V7 is not a vacuum bottle but an ignitron, then it can not be fired until the reverse cycle starts. Therefore, I recommend the following combination; V6: 200A-s, GL37207A tube

with V7: a Ross' vacuum bottle

Otherwise, use two 1500A-s tubes.

V8 must be a 1500A-s tube because the crowbar time can be as long as 60ms.

* A-s = \int |i(t)| \, dt = C(v_3(t) - V_3)
Summing up:
- Three 1500A-s GL8205 ignitrons, for V3, V4, and V8.
  It is too bad there is not a tube rated between 200 and 1500A-s.
- Four 200A-s GL37207A ignitrons, for V1, V2, and V5, and V6.
  Four Ross' vacuum bottles, one of them for V7.

6.3 Resistor.

  Can be made out of stainless steel strips 5' long, with a cross section 1/8"x2". Each strip will have a resistance of 8.5mΩ. (I took 90μΩ-cm for the resistivity); as many strips can be placed on a frame as needed. Using this plate, the temperatures shown in Table I would be reduced by a factor of 4.
  40 strips would make a resistor of 0.34Ω. Neglecting cutting losses a plate 5'x7' is required.

6.4 Diodes, charging supplies, and other are not specified.
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