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Beam AccelDC Power Supply**

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## A COMPUTER MODEL OF THE MFTF-B NEUTRAL BEAM ACCEL DC POWER SUPPLY

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### Abstract

Using the SCEPTRE circuit modeling code, a computer model was developed for the MFTF Neutral Beam Power Supply System (NBPSS) Accel DC Power Supply (ADCPS). The ADCPS provides 90 kV, 88 A, to the Accel Modulator. Because of the complex behavior of the power supply, use of the computer model is necessary to adequately understand the power supply's behavior over a wide range of load conditions and faults. The model developed includes all the circuit components and parameters, and some of the stray values. The model has been well validated for transients with times on the order of milliseconds, and with one exception for steady-state operation. When using a circuit modeling code for a system with a wide range of time constants, it can become impossible to obtain good solutions for all time ranges at once. The present model concentrates on the millisecond-range transients because the compensating capacitor bank tends to isolate the power supply from the load for faster transients. Attempts to include stray circuit elements with time constants in the microsecond and shorter range have had little success because of huge increases in computing time that result. The model has been successfully extended to include the accel modulator.

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### Power Supply Description

A single line diagram and photographs of a typical ADCPS are shown in [1]. The ADCPS described here differs from that in [1] only in that the output polarity is positive on the NBPSS ADCPS. Twenty-three of these power supplies are in the final stages of construction and test at LLNL. The power supply is rated to furnish 95 kV dc at 88 A dc for pulses up to thirty seconds duration, with a pulse repetition rate of one pulse in five minutes.

### Switchgear

Primary power control is performed by a metalclad switchgear assembly, including a line switch with current-limiting fuses, a high-speed vacuum circuit breaker, and a step-start contactor. The step-start contactor switches in a resistance of 37.8 ohms per phase for the first 100ms when the power supply is energized; after this time delay, the vacuum circuit breaker closes. All these functions have been modeled.

### Step Regulator

The Step Regulator is a three-phase autotransformer with tap changing under load, providing output at 6.9-13.8 kV for 13.8 kV input. Its impedance is extremely low, so it is modeled only by changing the primary voltage sources driving the model.

### Rectifier Transformer

The Rectifier Transformer has an extended delta primary and two secondaries, one wye- and the other delta-connected. Voltage ratings are 13.1 kV-35.3 kV/35.3 kV. The rectifier bridges associated with each secondary are connected in series to provide 95 kVdc output. The transformer impedance is 20% on a rated primary current of 391 A, leading to a rated kVA of 8872. Bushing capacitances are modeled, but because of the excessive

complexity, winding distributed capacitances and inductances are not modeled.

### Power Factor Correction

The original ADCPS design incorporated power factor correction; our current design baseline deletes power factor correction to obtain a more economical and robust design for the accel modulator. (The decision to do this was based partly on results of simulations using this model.) The power factor correction network includes the series capacitors and an associated series resistor.

### Rectifier Assembly

The rectifier assembly includes the rectifier diodes and associated snubber components, a voltage divider, a current shunt, and a dc overcurrent relay. Each stack of 145 diodes is represented in this model by a single diode, with characteristics chosen to approximate the v-i characteristic behavior of the entire stack. Bushing capacitances are included in the model.

### Modeling Objectives

#### Steady-State Performance

One of the modeling objectives was to have a source of data on the steady-state performance of the ADCPS, including output v-i characteristics at various tap settings and external conditions, and ac system load characteristics including harmonic content and power factor.

#### Transient Performance

Another important objective was to understand the transient behavior of the ADCPS. The model described is intended to represent the ADCPS for conditions ranging from dc steady-state to transients with times on the order of 100 microseconds. Because of the extremely complex commutation behavior of the 12-pulse rectifier, and because the transients under study are in a time regime likely to include at least one commutation, simulation of the rectifier's behavior is necessary to accurate understanding of the power supply's performance. For shorter transients, commutations take far longer than the transient. Therefore, the circuit configuration is not changed by diode switching during the transient, and models containing only linear components can be accurate. A complicating factor in modeling short (microsecond) transients is that the distributed resistances, inductances, and capacitances of the power supply components become important. These are difficult to know, and would result in a very complex model of uncertain accuracy. In any event, an appropriate model for the transients of a few microseconds or less would be a different topology from one appropriate for the problems addressed here.

### Fault Behavior

One of the most important applications for the model is the study of fault conditions, including dc and ac short circuits, voltage surges, and shorted and open components. The model has been used to investigate such questions as whether a shorted rectifier stack could result in high enough current to detect at the ac side of the rectifier transformer and whether a given crowbar ignitron had sufficient capacity to carry the short circuit current from the ADCPS output.

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### Model Description

#### SCEPTRE Capabilities

The SCEPTRE code was chosen for this work because, of all the circuit modeling software available to the author, SCEPTRE offered the most powerful capability to design and specify nonlinear models for devices with arbitrary transfer functions. Some modeling was performed using EMTP in the past, but it proved impossible to integrate an ADCPS model with any reasonable representation of the accel modulator in EMTP. Therefore, the EMTP effort was terminated and the work done in SCEPTRE to allow an integrated model of the entire accel-voltage system to be constructed. Extensive use is made of the SCEPTRE program's model capability to simplify and clarify the circuit structure<sup>2</sup>. Figure 1 shows the overall circuit diagram and the interconnection of the various models. The overall structure is relatively simple and straightforward, and virtually all components are contained in the device models described below. The version of SCEPTRE used here is that located on the National Magnetic Fusion Energy Computer Center (MFECC) Control Data 7600 (the "A" machine).

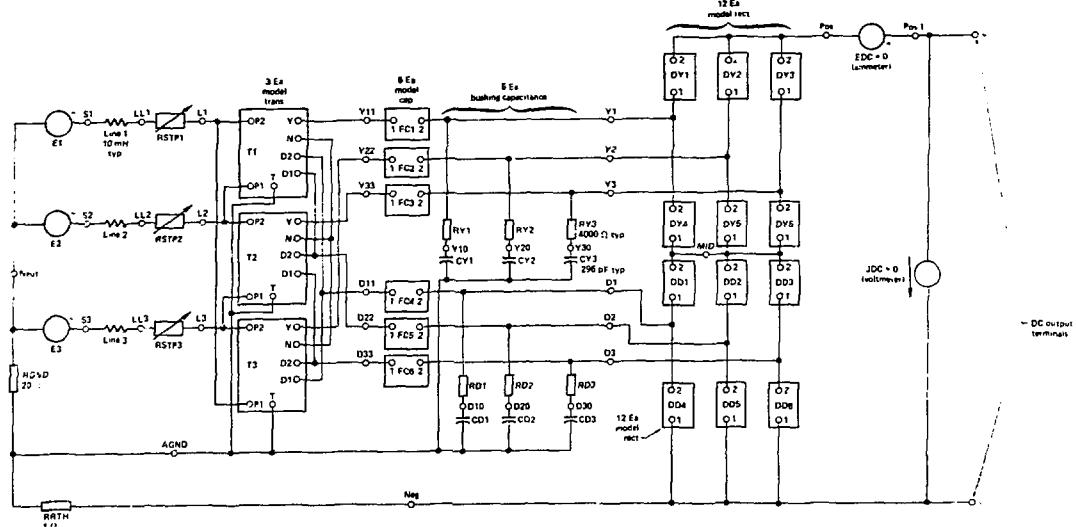


Figure 1. ADCPS SCEPTRE circuit representation

#### Subsystem Models

The Rectifier Transformer model is shown in Figure 2. It includes the leakage and magnetizing impedances of the transformer, the winding dc resistances, and the bushing capacitances. The 4000 ohm resistors R1 and R2 were added to lengthen time constants associated with the 296 pF bushing capacitances CD and CY, because numerical instabilities resulted without some damping at this point in the circuit. The 1.2 microsecond time constant that results from this resistance is well below the time regime of interest, but is very effective in reducing computation time. Values for the self and mutual inductances were chosen from test data taken from the first rectifier transformer during short-circuit testing. No attempt is made to model the distributed inductances and capacitances of the transformer because of the time considerations described above. Also, in the interest of avoiding complexity, the transformer is modeled as if the primary were a simple delta connection instead of the extended delta actually used.

#### The Power Factor Correction Capacitors

The power factor correction capacitors are modeled as shown in Figure 3. This is a straightforward lumped model of the nominal component values, including the internal bleeder resistor.

The Rectifier Stacks are modeled as shown in Figure 4. Here, the entire stack of diodes, each in parallel with a resistor and capacitor used as a snubber network, is modeled as a single diode with a very small exponent and a relatively large leakage current. The model thus approximates the exponential characteristic of the large number of diodes in series that makes up the rectifier stack. It was necessary to include a series resistor in the model to damp the short time constants associated with the junction capacitance CJ; this is RB at 0.25 ohm. The location of rectifier assembly bushings in the circuit made it impossible to include them in the rectifier model; they are represented by CY1, CY2, CY3, CD1, CD2, CD3, and the associated resistors in the main model shown in Figure 1.

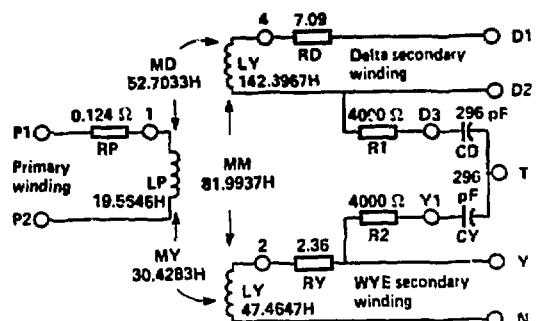


Figure 2. The rectifier transformer model

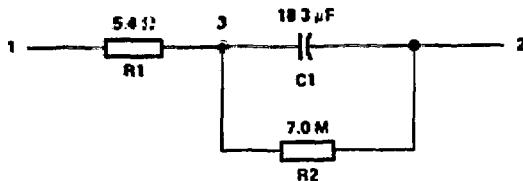


Figure 3. The power factor correction capacitor model

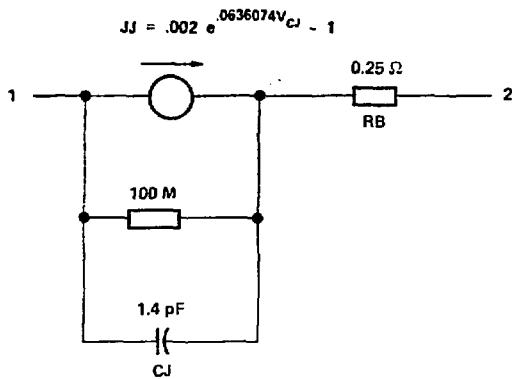


Figure 4. The rectifier stack model, representing a complete diode stack

#### Switching Devices

In this model, all switching is represented by variable resistors whose value is specified as a table. In most cases, the open condition is represented by a resistance of 100M, and the closed condition is represented by a resistance of 0.1 ohm. Switches can therefore be opened and closed at arbitrary times in the run. Representing a circuit breaker in the process of opening requires three runs. In the first run, the exact time of current zero can be found for the first phase to clear. The table controlling the resistor that models that pole is then changed to "open" the switch at the current zero, and another run is made. From the second run, the time of current zero for the remaining two poles is determined, and the tables controlling the resistors that model those poles are then changed to "open" the switches at their current zero. A final run is then made to give the results. An example of this is shown in the ECRH crowbar study, Figure 5(a).

#### Loads

The ADCPS load is switched and controlled by a series modulator-regulator tube, which regulates the load voltage. This looks to the ADCPS like a current sink. SCEPTR-E allows arbitrarily complex functions to be defined to control the value of any component, including a current sink, so load current waveforms can be simulated and their effect on ADCPS performance studied. The modulator includes a shunt compensation capacitor and a crowbar, simulated as shown in Figure 6(a). Figure 6(b) shows how testing into a resistive dummy load was simulated, using a resistor which switches from an open circuit to the load resistance value of 1000 ohms.

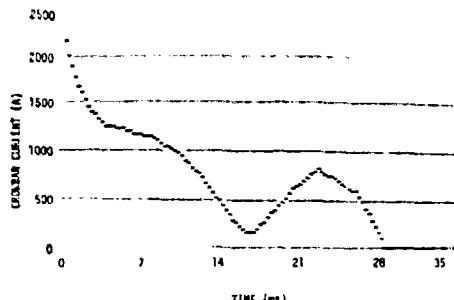


Figure 5(a). Simulated ECRH crowbar current. Note that this represents a system with a 54 microfarad filter capacitor.

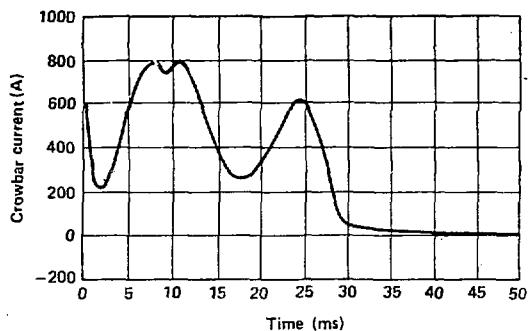


Figure 5(b). Measured NBPS crowbar current. At the time of this measurement, a 5 microfarad filter capacitor was used. Note the relatively short discharge time of the initial spike compared with Figure 5(a).

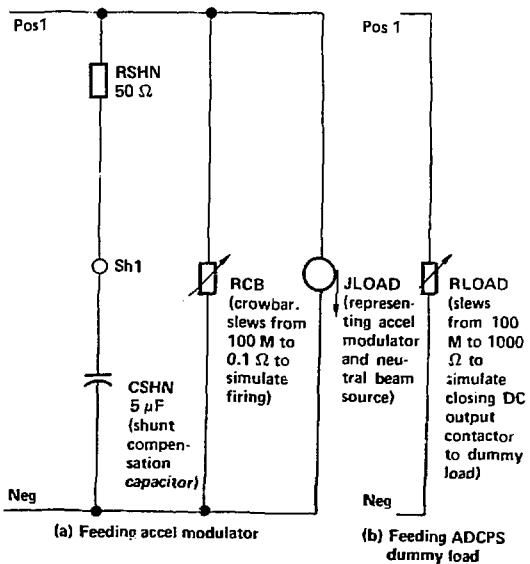


Figure 6. Two typical load models used to simulate specific situations.

### Some Problems Encountered

#### Evasiveing SCEPTR E Bugs

SCEPTR E has a problem in that the user must limit all values to avoid overflow errors that terminate the run. This requirement includes intermediate values which may be produced in any formula or table calculation, not just when the system has converged, but at all iterations. The code for the diode model is shown below.

```
model rect(1-2)
elements
  jj,1-3=equation d(pv)
  rj,1-3=100.e6
  cj,1-3=1.4e-12
  rb,3-2=25
defined parameters
  pv=table (1|p1)
  p1=equation x(.0636074,vcj)
functions
  equation d(v)=(.002*(exp(v)-1))
  equation x(a,b)=(a*b)
  table 1
    -1.e300,-100.
    -100.,100.
    100.,100.
    1.e300,100.
```

Figure 7 shows a block diagram of the resulting mathematics. The reason all this is necessary is that, with the exponential term in the diode equation, any unconverged system state usually results in an overflow condition because SCEPTR E "tries" forward voltages larger than the computer can represent. The limitation imposed by the table keeps this within values that prevent overflow. Note that the values in the table apply to the MFEC C6000; use of other processors might require changes in the values in the table because of different word size and number representation. The constraint is that the processor be able to represent  $\exp(av)-1$ .

#### Time Constants

A number of components were added to the model to lengthen time constants that otherwise would have been too short for SCEPTR E to obtain good solutions. The 4000 ohm resistors in series with all of the bushing capacitances are an example; they result in a time constant of 1.2 microseconds as discussed above. If such too-short time constants are present, SCEPTR E either fails to find any solution or prints a "SMALLER MINIMUM TIME STEP REQUIRED" error message. When we encountered such a message, we had more success by changing the circuit topology to add some damping in an appropriate place than by reducing the minimum time step in the "RUN CONTROLS" section of SCEPTR E input. In every case it was possible to do this without introducing time constants so long that they jeopardized the accuracy of the simulation over the time range of interest.

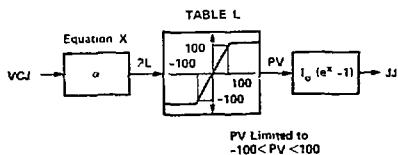


Figure 7. Functional block diagram of MODEL RECT

#### Verification

Two tests provide verification of the model. These tests involve operation of real ADCPS under accel modulator load crowbar conditions.

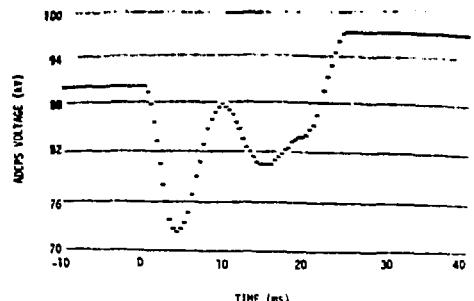


Figure 8(a). Simulated power supply voltage sag for a 20 ms load pulse, with CSHN at 5 microfarads

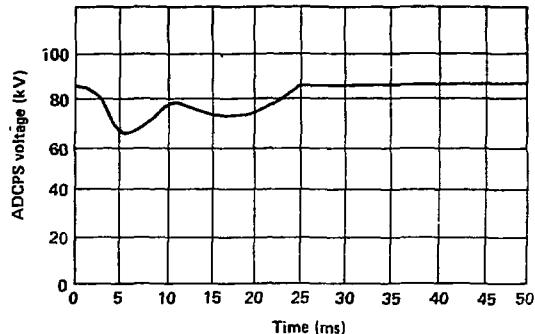


Figure 8(b). Measured sag for the case studied in Figure 8(a)

Figures 5 and 8 show comparisons of the simulated and actual waveforms obtained. The close agreement inspires considerable confidence that the model can be trusted.

#### Conclusion

A serviceable model of a complex dc power supply was produced, with reasonable limitations. The model was verified against the behavior of actual power supplies, when they became available to test. Several design decisions have already been made using the model's results as input. One of the most important is the decision not to proceed with power factor correction in the ADCPS, because the model result was that a shunt compensation capacitor of 80 microfarads or more would have been required. This surprising result came about because the power factor capacitor voltages contain a dc offset, introduced when the ADCPS output is switched on, analogous to the well-known dc offset current in a switched inductor in an ac circuit. The dc offset introduces a 60Hz damped ripple component into the ADCPS output voltage, requiring the large compensation capacitor. The present compensation capacitor of 24 microfarads is adequate to control the ADCPS output voltage transient when current is switched on, without power factor correction. The model confirmed field measurements that the power factor was within contractual limitations.

An interesting way in which the model has been used is as a basis for much simpler models, of very limited scope, to approximate the ADCPS behavior over a small time frame. Designs can then be worked out using the simplified model and confirmed on the detailed model described here. For example, empirically derived values of R, L, and C for the model shown in Figure 8 have been used in the new compensation capacitor design.

Another way in which the model had proved useful is during maintenance and repair. When a fault or an unexpected transient occurs, the model can be run with voltages, currents, and other parameters measured. This is a useful tool in understanding the power supply's behavior.

### Appendix A

The following is a listing of the SCEPTRE code for the basic ADCPS model. The power factor correction capacitors are short-circuited in this model, but are included as comments to facilitate re-insertion when needed.

#### model description

model trans(p1-p2-y-n-d1-d2-t)

##### elements

rp,p1-1=.124  
lp,l-p2=9.5646  
ry,y-2=2.36  
ly,2-n=47.6647  
rl,y-1=4000.  
cy,y-1-t=2.96e-10  
rd,d1-4=7.09  
ld,d4-d2=142.3967  
r2,d2-d3=4000.  
cd,d3-t=2.96e-10  
my,lp-ly=30.4283  
md,lp-ld=52.7033  
mm,ly-ld=81.9937

model rect(1-2)

##### elements

jj,j-3=equation d(pv)  
rj,l-3=100.e6  
cj,l-3=1.4e-12  
rb,3-2=.25

##### defined parameters

pv=table k(p1)  
pl=equation x(.0636074,vc,j)

##### functions

equation d(v)=(.002\*(exp(v)-1))  
equation x(a,b)=(a\*b)

##### table

-1.e300,-100.  
-100.,100.  
100.,100.  
1.e300,100.

model cap(1-2)

##### elements

rl,l-3=5.4  
cl,3-2=18.3e-6  
r2,3-2=7.e6

#### circuit description

##### elements

e1,neut-s1=equation src(time,pv\$,phase1)  
e2,neut-s2=equation src(time,pv\$,phase2)  
e3,neut-s3=equation src(time,pv\$,phase3)  
rgnd,neut-agnd=20.

rrth,agnd-neg=1.

line1,s1-l1=pline

line2,s2-l2=pline

line3,s3-l3=pline

rstp1,l1-l1=table step(time)

rstp2,l2-l2=table step(time)

rstp3,l3-l3=table step(time)

t1,l2-l1-y1-yn-d2-d1-agnd=model trans

t2,l1-l3-y2-yn-d1-d3-agnd=model trans

t3,l3-l2-y3-yn-d3-d2-agnd=model trans

f1,y1-l1=model cap

f2,y22-y2=model cap

f3,y33-y3=model cap

f4,d1-l1=model cap

f5,d22-d2=model cap

f6,d33-d3=model cap

dy1,y1-pos=model rect

dy2,y2-pos=model rect

dy3,y3-pos=model rect

dy4,m1-y1=model rect  
dy5,m1-d-y2=model rect  
dy6,m1d-y3=model rect  
dd1,d1-mid=model rect  
dd2,d2-mid=model rect  
dd3,d3-mid=model rect  
dd4,neg-d1=model rect  
dd5,neg-d2=model rect  
dd6,neg-d3=model rect  
rc1,d1-d10=4000.  
cd1,d10-agnd=2.96e-10  
rc2,d2-d20=4000.  
cd2,d20-agnd=2.96e-10  
rc3,d3-d30=4000.  
cd3,d30-agnd=2.96e-10  
rc4,y1-y10=4000.  
cy1,y10-agnd=2.96e-10  
rc5,y2-y20=4000.  
cy2,y20-agnd=2.96e-10  
rc6,y3-y30=4000.  
cy3,y30-agnd=2.96e-10  
edc,pos-pos1=9.  
jdc,pos1-neg=0.  
jload, pos1-neg=table load(time)  
defined parameters  
pvs=3633.83  
phasel=0.  
phase2=2.09439  
phase3=4.18879  
pline=i.e-2  
plg=equation sub(e1,vline1)  
outputs  
vjdc(vadcps),iedc(iadcps),plot  
functions  
equation src(t,v,p)=(v\*(sin((376.991\*t)+p)))  
equation sub(a,b)=(a-b)  
equation load(p1,p2,t)=(p1\*sin(376.991\*t)+p2)  
table step  
0.,37.8  
0.1,37.8  
0.100001,1.e-3  
0.21,1.e-3  
table load  
0.,0.  
0.21,0.  
run controls  
stop time=.21  
maximum print points=10000  
maximum integration passes=1000000  
end input

#### References

1. S. R. Bishop, R. A. Goodman, J. H. Wilson, "Startup Experience with the MFTF-B ECRH 100 kV dc Power Supply", in Proceedings of the Tenth Symposium on Fusion Engineering, 1983.
2. J. C. Bowers and S. R. Sedor, SCEPTRE: a Computer Program for Circuit and Systems Analysis, Englewood Cliffs, N.J., Prentice Hall, 1971.

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