NCSX CD4 with C-site Supplies

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Rev. 0

The purpose of this memo is to document how the NCSX CD4 requirements can be accomplished using only the existing C-site rectifier power supplies (the 6 Robicon supplies and the 'UCLA' supply).

1. C-site First Plasma Scenario

The proposed first plasma scenario uses a PF configuration similar to the previous D-site scenario: PF1 and PF2 in series, PF5 not energized. The modular coils (M1, M2, and M3) are all in series on a single supply. In contrast to the D-site scenario, the modular coil currents are held at fixed current during the plasma pulse. Vacuum field-line tracing shows a large volume of good flux surfaces [ref. Takahashi and Pomphrey] with all the coil currents the same and no PF currents, so this is taken as the initial configuration. A small positive TF current was introduced to slightly reduce the MC current and to slightly move the 3/7 island chain outwards.

The break-points in the coil-current waveforms for this scenario are:

Currents (A)	t = 0 sec	t = 1.55 sec	t = 1.6 sec	t = 1.67 sec
M1 + M2 + M3	0	10,000	10,000	10,000
TF	0	93	93	93
PF1 + PF2	0	0	0	5000
PF3	0	0	0	5000
PF4	0	0	0	1519
PF5	0	0	0	0
PF6	0	0	0	396
plasma	0	0	0	26,000

The precise values of the MC and TF currents can be adjusted to choose the vacuum iota, including the case where there is no TF current utilized.

2. Power supply configuration

The proposed power supply configuration first plasma and its capabilities are:

		Max current	Max voltage
M1+M2+M3	Robicon 20	20 kA	500 V
TF	Robicon 5	5 kA	300 V
PF1 + PF2	2 Robicon-5 in series	5 kA	600 V
PF3	Robicon-5	5 kA	300 V
PF4	UCLA	5 kA	500 V
PF5	--	--	--
PF6	Robicon-10	10 kA	200 V

The ability of this power supply configuration to accomplish first plasma will be discussed in the next section.

These supplies are also able to accomplish the “Coils and Power Supply Performance” criteria documented in Table 2-1 of the NCSX Project Execution Plan (PEP). It specifies that the coils be energized to the following currents:

Modular coils	12 kA	
TF	2 kA	
PF1 + PF2	12 kA	**
PF3	3 kA	
PF4	3 kA	
PF5	2 kA	**
PF6	2 kA	
Trim coils	1 kA	**

For most of the circuits, this can be accomplished by the first plasma power-supply configuration. The exceptions are:

- PF1 + PF2 will require the Robicon-20 supply to be moved from the Modular coils
- PF5 and the Trim coils are not powered in the first plasma configuration. The PEP criteria can be met by moving any of the supplies to them.

3. First plasma simulation

The required voltages were calculated using a Mathlab-based multi-circuit simulation, originally produced by Ron Hatcher. The overall block diagram is shown in Fig. 1. The power supply model simulates the D-site Transrex supplies, including a finite gain feedback loop trying to match the pre-programmed waveforms shown above. This model was previously used to validate the voltage waveforms and requirements for the D-site power supply system calculated by Wayne's spreadsheet.

For use in estimating the C-site supplies, one Transrex section has been modeled for each supply. The circuit parameters used are:

	Coil R (mOhm)	Coil self-L (mH)	External R (mOhm)	External L (mH)
M1	8.68	12.36	0.16	1.47e-3
M2	8.48	9.23	0.16	1.47e-3
M3	7.04	7.90	0.16	1.47e-3
PF1	1.18	3.03	0.54	4.4e-3
PF2	1.18	2.626	0.54	4.4e-3
PF3	1.18	2.613	1.08	8.8e-3
PF4	3.11	15.29	1.08	8.8e-3
PF5	3.97	12.87		
PF6	2.84	6.259	1.08	8.8e-3
TF	8.85	48.98	1.08	8.8e-3
Plasma		2.68e-3		

The coil resistances and self-inductances and the plasma self-inductance are from the NCSX Technical Datasheet. The resistances are at the initial cryogenic coil temperatures. The 'External R' and 'External L' assume a bus-connection of 50 feet of twisted-pair 1000 MCM cable (at room temperature). For the modular coils, a double 1000 MCM twisted-pair is assumed, as in the D-site supply design. For coils in series, it is assumed that one set of bus-work is used, so the external impudence is shared between the coils.

The simulations also include the effects of the mutual inductances coupling the coils and plasma. The mutual inductance values used are as tabulated in the NCSX Technical Datasheet.

The results of the simulations are shown in Figures 2 – 5. The current waveforms (Figs. 2 & 3) show the power supply currents achieved. The voltage waveforms (Figs. 4 & 5) show the required voltages at the power supplies.

Comments:

- The model does not accurately treat the Robicon I-V curve, as it is trying to model the Transrex supplies. However:

-- The simulation does not use the full voltage capability of the power supplies, except for the modular coils, see below.
-- For most of the circuits, the supplies are operating at much less than their full current level. E.g. the modulars only go to their half-current point. The exceptions are the supplies driving the PF1+PF2 and PF3, which provide most of the OH swing. The OH swing I put in the waveforms uses their full current range and but not the full voltage. Further voltage sag may result in a slowing of the Ip ramp-up, depending on whether it occurs before we get to full current. See (c) and (d) below.
-- Ron Hatcher at one point told me that the Robicon's do not sag as much as the Transrex supplies, but there must be some sag due to finite output impedence.

- The simulation does not model the heating of the coils and its effect on their resistance. Because the field is so low, this effect should be minimized. On the other hand, the required ramp-up time for the modulars is ~ 1.1sec (see below), so this may be worth checking.

- Currently, the simulation requests a linear ramp-up for the MC circuit. This requires less than the supply voltage at the beginning, and slightly more than the supply voltage at the end of the ramp. An analytic calculation for a constant-500V exponential ramp indicates that the optimal waveform should fill the coils to 0.5T in ~1.13 seconds using the C-site supply, significantly shortening the pulse. During the SIT phone call last week, everyone thought there was no problem if the ramp-up lasted > 1.5 seconds. So even if there is voltage droop, I don't think the supply will have difficulty at energizing the MC to 0.5T, or even somewhat higher.

- The model supplies are configured in feedback loops attempting to match programmed waveforms, with finite proportional, integral, and derivative gains. I have not had time to tune the gains for the individual circuits, so the transient performance is not optimal.

  In addition, the strong coupling between the MCs and the TF is resulting in artifacts in the TF current evolution. The TF supply takes a while to come out of blocking the back-voltage from the MC coupling. When it gets to full current, it overshoots, and then has to L/R decay back to the desired voltage. Clearly, programming the TF will require more attention.

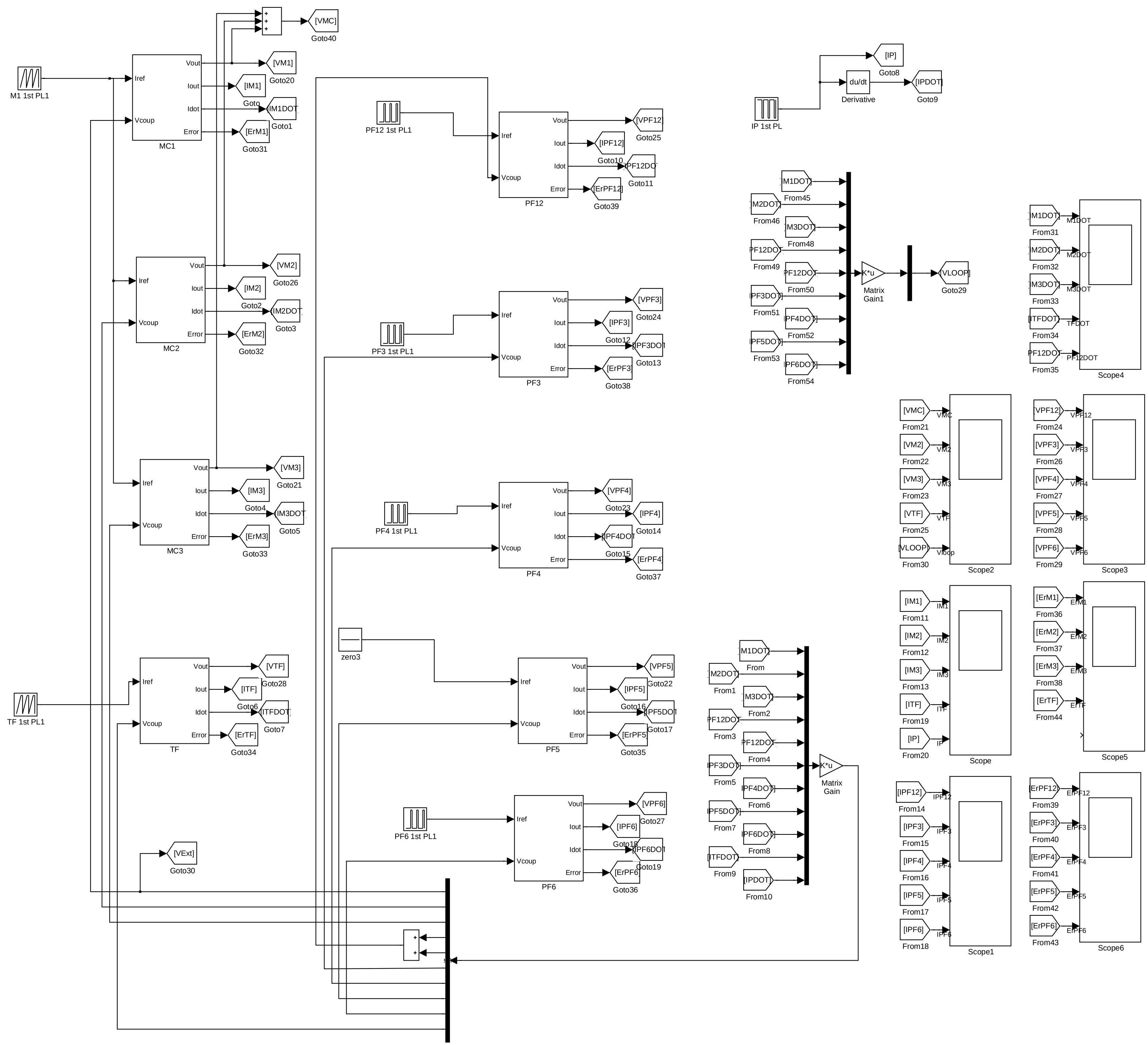
- Even if the cable lengths are longer, the results should not be significantly affected
  - For the MC circuit, the cable impedance is ~2% of the coil impedance
  - The cable impedance is comparable to that of the PF coils (especially PF1, 2, and 3), but their resistive drop is insignificant compared to their inductive voltage.

- In all cases the cable inductance is negligible. The cable impedance was calculated using Wayne's spreadsheet model that he developed to set the D-site supply requirements.

- We have not modeled the resistive flux consumption. The circuits provide 0.144 W of OH, which is more than twice the flux needed for the plasma (L*Ip) of 0.070 W. If I assume that the resistive consumption corresponds to an additional loop voltage of 1-volt, this is more than enough. But whether weshould plan on higher resistive consumption, I don' t know. This also hasn't been analyzed in detail for the D-site supply configuration, but there we have more current upgrade capability.
  (The C-site flux swing is limited by the max-current on the PF1+2 and PF3 supplies, presently 5kA).

- We have not modeled the breakdown and burnthrough. The simulation develops a loop voltage of 2.05 V, but does not use the full power supply voltage. If the full voltage is used (initially, at zero PF current), the C-site supplies should provide an initial loop voltage of ~2.3 Volts. This would be too low for a tokamak, but we will have closed flux surfaces in vacuum. W7AS had a maximum loop voltage of 1 V, and could break down with it (but not always reliably). This loop-voltage is not so different from what was configured with the D-site supplies, again without any breakdown analysis, but there we could add more sections if we ended up needing them.
  (the C-site Vloop is limited by the maximum initial voltage on the PF1+2 and PF3 supplies, presently 300V per coil).

  This low loop voltage may mean that we will have to pay attention to vessel cleanliness and gassiness in order to achieve burn-through. Possible remedies include:
  - He Glow discharge cleaning
  - Vessel baking
  - Low power ECH breakdown assist



M1 1st PL1
MC1
MC2
MC3
TF
TF 1st PL1
[VMC]
Goto40
[VM1]
Goto20
[IM1]
[IM1DOT]
Goto1
[ErM1]
Goto31
[VM2]
Goto26
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Goto2
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Goto3
[ErM2]
Goto32
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Goto30
zero3
PF12 1st PL1
PF3 1st PL1
PF4 1st PL1
PF6 1st PL1
PF12
PF3
PF4
PF5
PF6
Vout
Iout
Idot
Error
Iref
Vcoup
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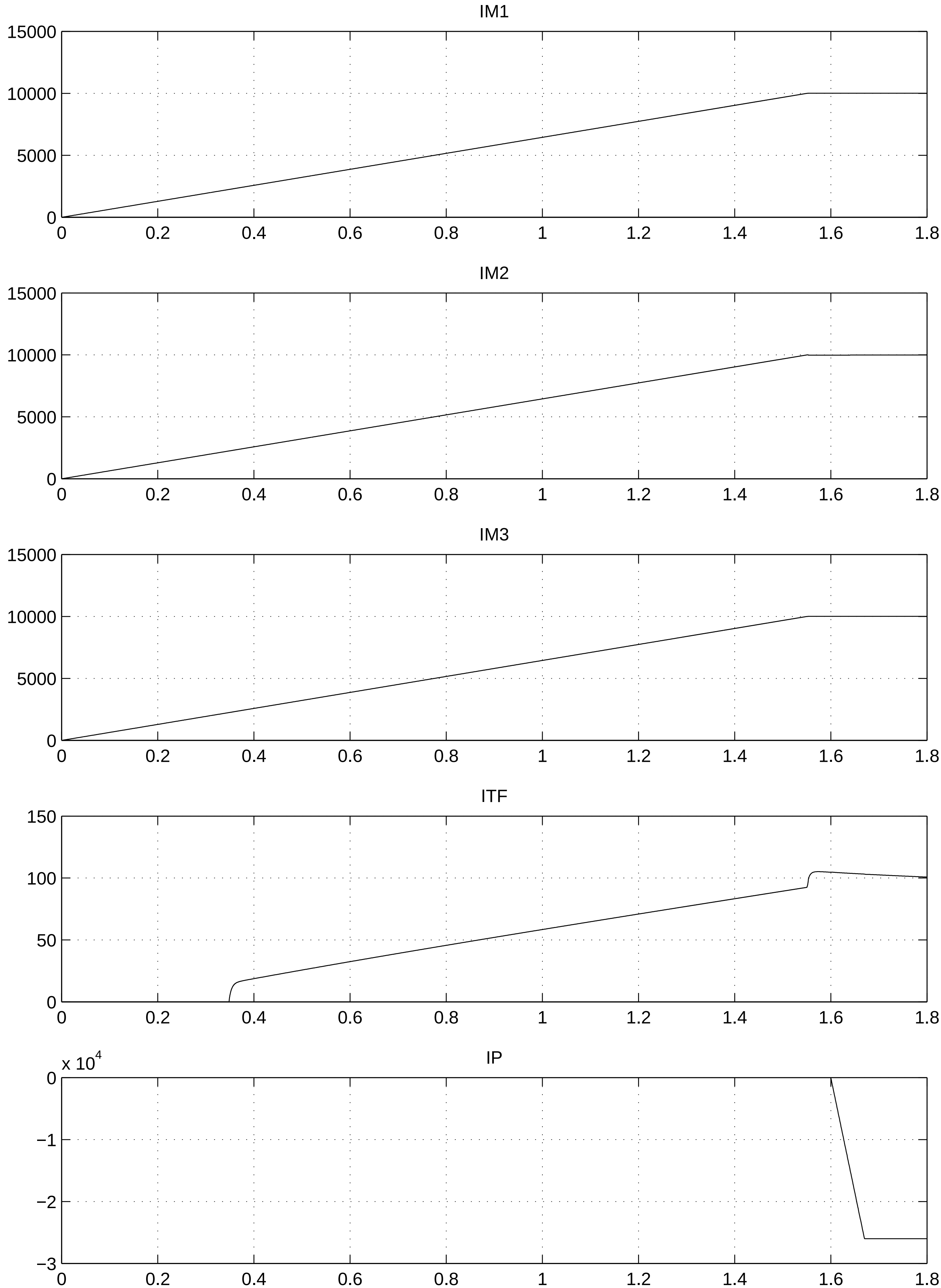
Goto19
[ErPF6]
Goto36
IP 1st PL
[IP]
Goto8
du/dt
Derivative
[IPDOT]
Goto9
K*u
Matrix Gain1
[VLOOP]
Goto29
Matrix Gain
Scope4
Scope2
Scope3
Scope
Scope5
Scope1
Scope6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IM2
IM3
ITF
IP
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0.4
0.6
0.8
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1.2
1.4
1.6
1.8
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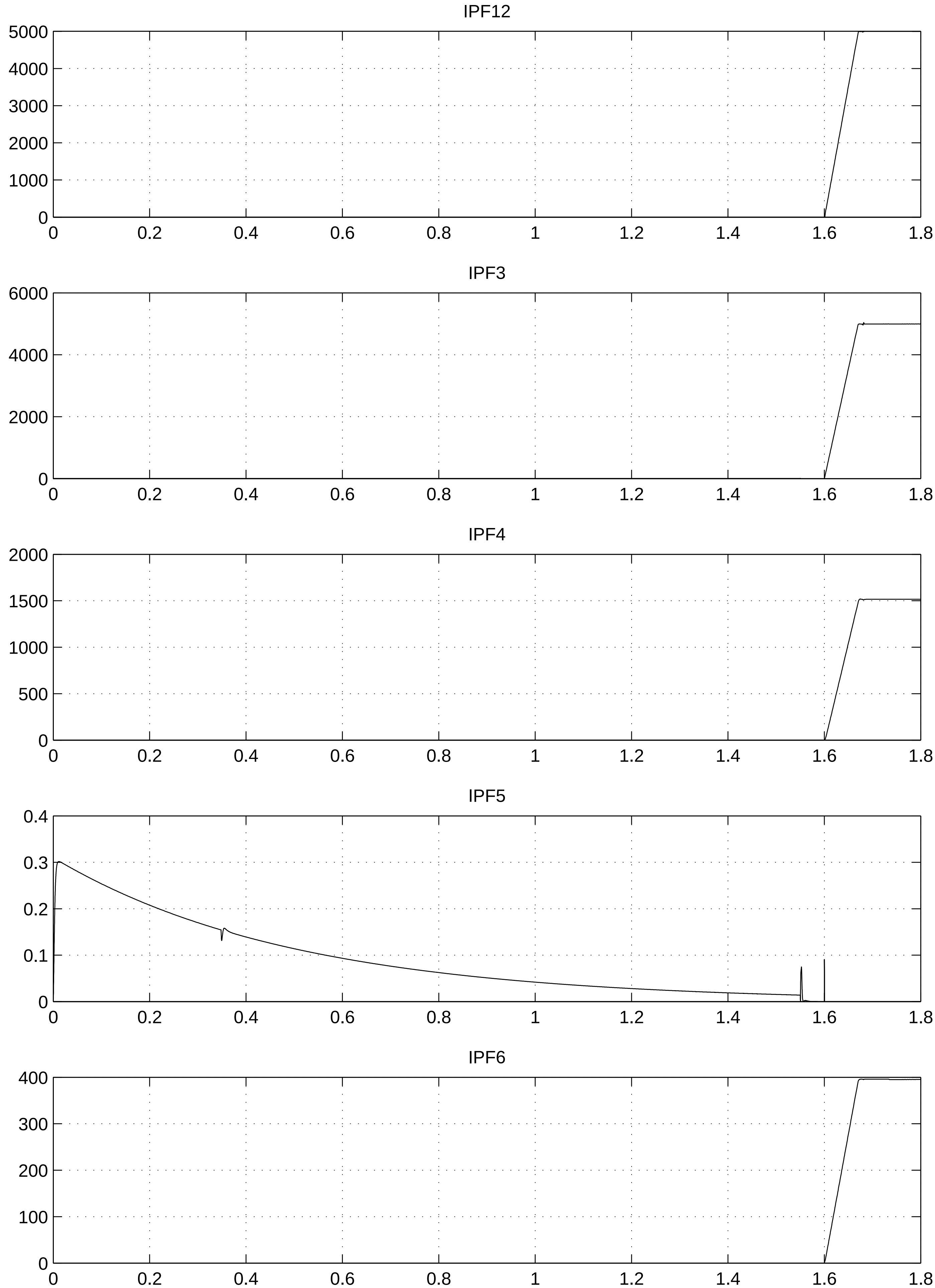
10000
5000
150
100
50
−1
−2
−3

Fig. 2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IPF3
IPF4
IPF5
IPF6
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4000
3000
2000
1000
6000
1500
500
0.4
0.3
0.2
0.1
400
300
200
100
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

Fig. 3

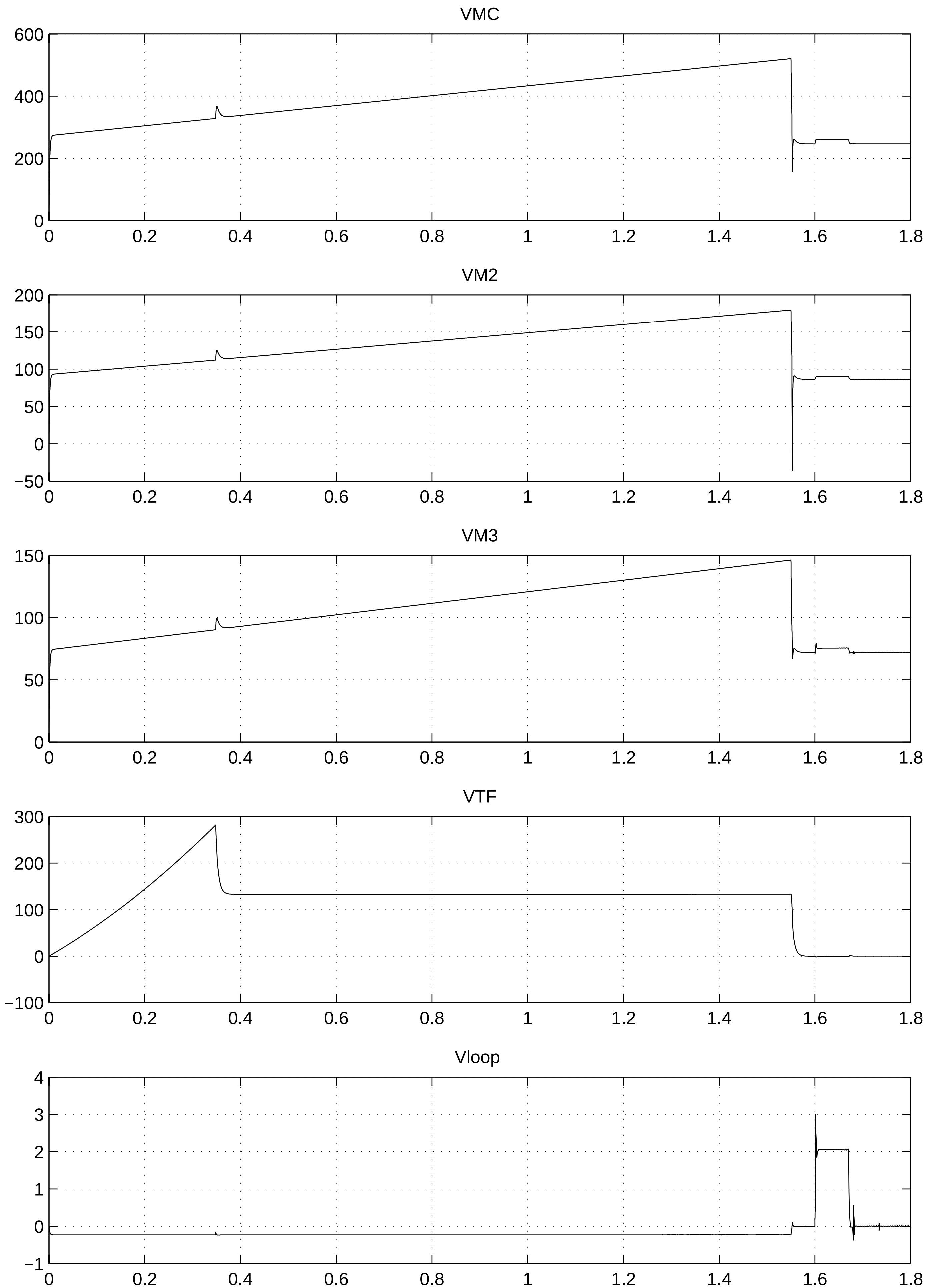
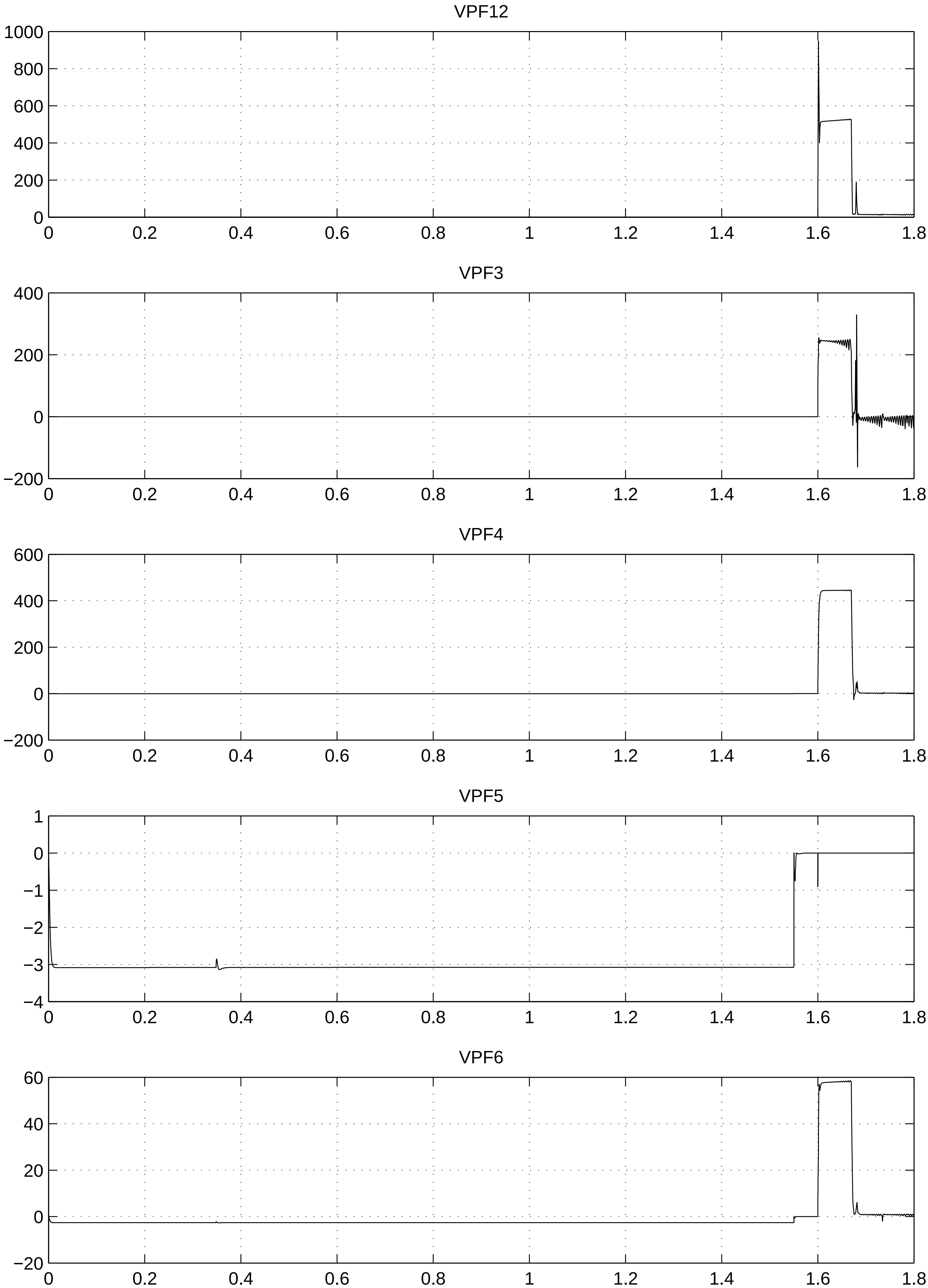

VMC
600
400
200
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
VM2
200
150
100
50
0
−50
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
VM3
150
100
50
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
VTF
300
200
100
0
−100
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
Vloop
4
3
2
1
0
−1
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8

Fig. 4



VPF12
1000
800
600
400
200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
VPF3
400
200
0
−200
VPF4
600
400
200
0
−200
VPF5
1
0
−1
−2
−3
−4
VPF6
60
40
20
0
−20

Fig. 5