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COMPUTER-AIDED MODELING AND ANALYSIS OF POWER PROCESSING SYSTEMS (CAMAPPS) - PHASE I

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User's Handbook

(NASA-CR-177123) COMPUTER-AIDED MODELING AND ANALYSIS OF POWER PROCESSING SYSTEMS (CAMAPPS). PHASE 1: USERS HANDBOOK (Virginia Polytechnic Inst. and State Univ.) 82 p HC A05/MF A01 CSCL 09B H1/61

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CONTENTS

I. Introduction

This manual contains descriptions of EASY5 macro component models developed for the spacecraft power system simulation sponsored by NASA GSFC. A brief explanation about how to use the macro components with the EASY5 Standard Components to build a specific system is given through an example in Section III.

The macro components are ordered according to the following functional group.

1. Converter power stage models
2. Compensator models
3. Current-feedback models
4. PWM models
5. Load models
6. Solar array models
7. Shunt regulator models

The format of the component model descriptions is similar to the format of the EASY5 Standard Components descriptions in the EASY5 User's Guide. The circuit model of each macro component model is included along with some key equations and the model program is also attached for each model. The port inputs and outputs used for interconnection among models are shown on the right and left side of the box with arrows.

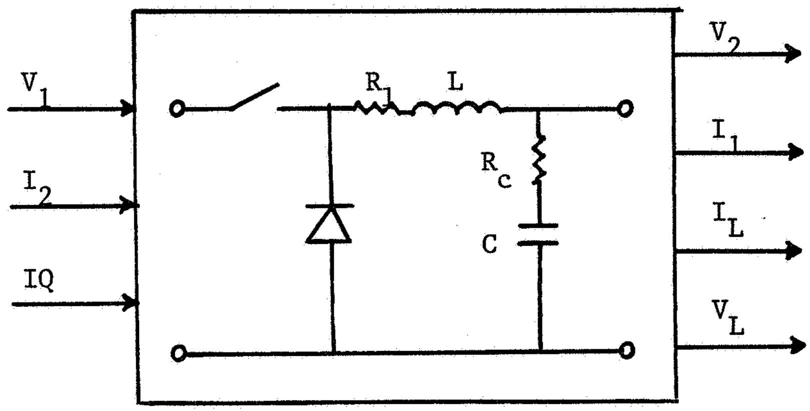
II. Macro component descriptions

This section describes a set of EASY5 macro components developed in this study. Major equations, a circuit model and a program listing are provided for each macro component. The macro components are listed in the following table.

TABLE OF MACRO COMPONENTS

BC

BUCK CONVERTER POWER STAGE



INPUT

V1	variable	input voltage	Volts
I2	variable	input current from load	Amps
IQ	variable	switching function (if switch is on, IQ=1) (if switch is off, IQ=0)	
C	parameter	capacitance	Farads
L	parameter	inductance	Henries
RC	parameter	capacitor effective resistance	Ohms
RL	parameter	inductor effective resistance	Ohms

OUTPUT

V2	variable	output voltage	Volts
I1	variable	output current to source	Amps
IL	state variable	inductor current	Amps
VC	state variable	capacitor voltage	Volts
IS	variable	switch current	Amps
VL	variable	inductor voltage	Volts

EQUATIONS

For IQ = 1 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} -(RL+RC)/L & -1/L \\ 1/C & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 1/L & RC/L \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

$$\begin{bmatrix} V2 \\ I1 \end{bmatrix} = \begin{bmatrix} RC & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

For IQ = 0, IL > 0 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} -(RL+RC)/L & -1/L \\ 1/C & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC/L \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

$$\begin{bmatrix} V2 \\ I1 \end{bmatrix} = \begin{bmatrix} RC & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

For IQ = 0, IL = 0 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

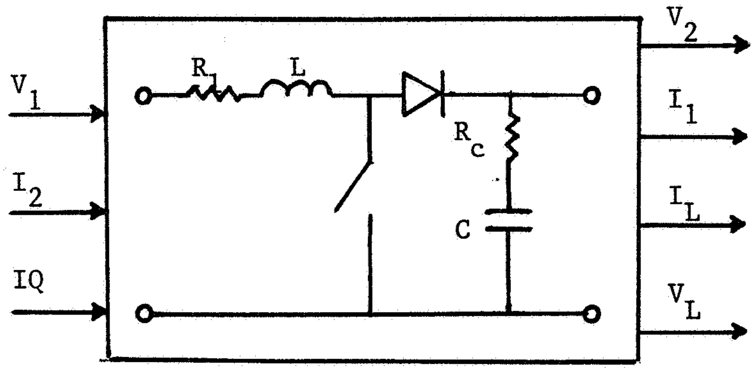
$$\begin{bmatrix} V2 \\ I1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

```
*********************************
**  LARGE SIGNAL MODEL OF BUCK(W/O LOAD)
*   POWER STAGE ONLY
****************************************
** REVISED 12/3/85
MACRO FILE NAME=MACROS
DEFINE MACRO=BC
MACRO INPUTS=
     C      L      RL     RC
     IQ      V1     I2
*  IQ ; SWITCHING FUNCTION
*       IQ=1 (SWITCH; ON)
*       IQ=0 (SWITCH; OFF)
*  V1 ; INPUT VOLTAGE
*  I2 ; INPUT CURRENT(FROM LOAD)
MACRO OUTPUTS=
     IS     IL
     ILL    VL
     VC     V2     I1
*  IL ; INDUCTOR CURRENT(STATE)
*  VC ; CAPACITOR VOLTAGE(STATE)
*  IS ; SWITCH CURRENT
*  ILL; INDUCTOR CURRENT(DUMMY)
*  VL ; TRANSFORMER VOLTAGE
*  V2 ; OUTPUT VOLTAGE
*  I1 ; OUTPUT CURRENT(TO SOURCE)
MACRO CODE
MACRO STOP SORT
****
      IF(DABS(IQ BC--).LT.1.E-10)THEN
         IF(IL BC--.LE.0.)THEN
         ILLBC--=0.
MACRO DERIVATIVE,IL BC--=0.
         GOTO +++77
         ELSE
**** TOFF *****
      A11=-(RL BC--+RC BC--)/L  BC--
      A12=-1/L  BC--
      A21=1/C  BC--
      A22=0.
      B11=0
      B12=RC BC--/L  BC--
      B21=0.
      B22=-1/C  BC--
      C11=RC BC--
      C12=1
      C21=0
      C22=0
      D11=0
      D12=-RC BC--
      D21=0
      D22=0
*
      IS BC--=0
         END IF
      ELSE
*** TON ***
      A11=-(RL BC--+RC BC--)/L  BC--
      A12=-1/L  BC--
      A21=1/C  BC--
```

```
        A22=0
        B11=1/L   BC--
        B12=RC BC--/L   BC--
        B21=0
        B22=-1/C   BC--
        C11=RC BC--
        C12=1
        C21=1
        C22=0
        D11=0
        D12=-RC BC--
        D21=0
        D22=0
        IS BC--=IL BC--
        END IF
** OUTPUT EQ.
*
*--- -
*| V2 |     | C11 C12 | | IL |     | D11 D12 | | V1 |
*|    |  =  |         | |    |  +  |         | |    |
*| I1 |     | C21 C22 | | VC |     | D21 D22 | | I2 |
*___ _|     |         | |    |     |         | |    |
*
        V2 BC--=C11 *IL BC--+C12*VC BC--
      &    +  D11*V1 BC-- +D12*I2 BC--
        I1 BC--=C21*IL BC--
        VL BC--=(A11*IL BC--+A12*VC BC--+B11*V1 BC--+
      &     B12*I2 BC--)*L  BC--
** STATE EQ.
*
* | dIL/dt |   | A11 A12 | | IL |   |B11 B12 | | V1 |
* |        | = |         | |    | + |        | |    |
* | dVC/dt |   | A21 A22 | | VC |   |B21 B22 | | I2 |
* |        |   |         | |    |   |        | |    |
*
MACRO DERIVATIVE, IL BC--=VL BC--/L  BC--
+++77 CONTINUE
MACRO DERIVATIVE, VC BC--=A21*IL BC--+A22*VC BC--+
      &                B21*V1 BC--+B22*I2 BC--
*
          ILLBC--=IL BC--
          IF(ILLBC--.LE.0.)ILLBC--=0.
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION= 22, BC
END OF MODEL
```

BT

BOOST CONVERTER POWER STAGE



INPUT

V1	variable	input voltage	Volts
I2	variable	input current from load	Amps
IQ	variable	switching function (if switch is on, IQ=1) (if switch is off, IQ=0)	
C	parameter	capacitance	Farads
L	parameter	inductance	Henries
RC	parameter	capacitor effective resistance	Ohms
RL	parameter	inductor effective resistance	Ohms

OUTPUT

V2	variable	output voltage	Volts
I1	variable	output current to source	Amps
IL	state variable	inductor current	Amps
VC	state variable	capacitor voltage	Volts
IS	variable	switch current	Amps
VL	variable	inductor voltage	Volts

EQUATIONS

For IQ = 1 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} RL/L & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 1/L & 0 \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

$$\begin{bmatrix} V2 \\ I1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

For IQ = 0, IL > 0 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} -(RL+RC)/L & -1/L \\ 1/C & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 1/L & RC/L \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

$$\begin{bmatrix} V2 \\ I1 \end{bmatrix} = \begin{bmatrix} RC & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

For IQ = 0, IL = 0 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 1/C & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

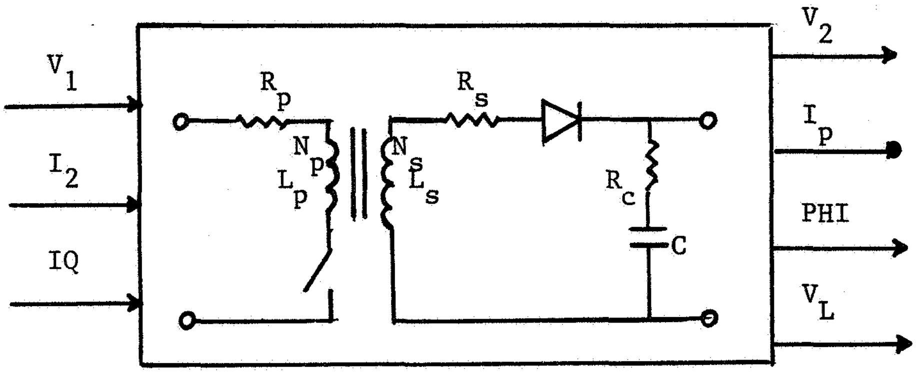
$$\begin{bmatrix} V2 \\ I1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

```
*************************************
**  LARGE SIGNAL MODEL OF BOOST(W/O LOAD)
*     POWER STAGE ONLY
* REVISED 11/19/85
*********************************************
MACRO FILE NAME=MACROS
DEFINE MACRO=BT
MACRO INPUTS=
     C       L       RL      RC
     V1      I2
MACRO OUTPUTS=
     IS      IL
     ILL
     VC      V2      11
MACRO CODE
MACRO STOP SORT
****
      IF(DABS(IQ BT--).LT.1.E-5)THEN
         IF(IL BT--.LE.0.)THEN
         ILLBT--=0.
MACRO DERIVATIVE,IL BT--=0.
         GOTO +++77
         ELSE
**** TOFF *****
      A11=-(RL BT--+RC BT--)/L  BT--
      A12=-1/L  BT--
      A21=1/C  BT--
      A22=0.
      B11=1/L  BT--
      B12=RC BT--/L  BT--
      B21=0.
      B22=-1/C  BT--
      C11=RC BT--
      C12=1
      C21=1
      C22=0
      D11=0
      D12=-RC BT--
      D21=0
      D22=0
*
      IS BT--=0
         END IF
      ELSE
*** TON ***
      A11=-(RL BT--)/L  BT--
      A12=0
      A21=0
      A22=0
      B11=1/L  BT--
      B12=0
      B21=0
      B22=-1/C  BT--
      C11=0
      C12=1
      C21=1
      C22=0
      D11=0
      D12=-RC BT--
      D21=0
```

```
        D22=0
        IS BT--=IL BT--
        END IF
        Q  BT--=IQ
** OUTPUT EQ.
*
*--- -
*| V2 |   | C11 C12 | | IL |   | D11 D12 | | V1 |
*|    | = |         | |    | + |         | |    |
*| I1 |   | C21 C22 | | VC |   | D21 D22 | | I2 |
*___ _|   |         | |    |   |         | |    |
*
        V2 BT--=C11 *IL BT--+C12*VC BT--
      &    +  D11*V1 BT-- +D12*I2 BT--
        I1 BT--=C21*IL BT--
        VL=(A11*IL BT--+A12*VC BT--+B11*V1 BT--+
      &     B12*I2 BT--)*L   BT--
** STATE EQ.
*
* | dIL/dt |   | A11 A12 | | IL |   |B11 B12 | | V1 |
* |        | = |         | |    | + |        | |    |
* | dVC/dt |   | A21 A22 | | VC |   |B21 B22 | | I2 |
* |        |   |         | |    |   |        | |    |
*
MACRO DERIVATIVE,IL BT--=VL/L   BT--
+++77 CONTINUE
MACRO DERIVATIVE,VC BT--=A21*IL BT--+A22*VC BT--+
      &                B21*V1 BT--+B22*I2 BT--
*
         ILLBT--=IL BT--
         IF(ILLBT--.LE.0.)ILLBT--=0.
*
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION= 22, BT
END OF MODEL
```

FB

BUCK/BOOST(FLYBACK) CONVERTER POWER STAGE



INPUT

V1	variable	input voltage	Volts
I2	variable	input current from load	Amps
IQ	variable	switching function (if switch is on, IQ=1) (if switch is off, IQ=0)	
C	parameter	capacitance	Farads
LP	parameter	primary inductance	Henries
LS	parameter	secondary inductance	Henries
RC	parameter	capacitor effective resistance	Ohms
RP	parameter	inductor effective resistance (primary)	Ohms
NP	parameter	no. of turn of primary	
NS	parameter	no. of turn of secondary	

OUTPUT

V2	variable	output voltage	Volts
IP	variable	output current to source	Amps
PHI	state variable	flux	
VC	state variable	capacitor voltage	Volts
IS	variable	secondary current	Amps
VL	variable	inductor voltage	Volts

EQUATIONS

For IQ = 1 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} -RP/NP & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 1/NP & 0 \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

$$\begin{bmatrix} V2 \\ IP \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ NP/LP & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

For IQ = 0, PHI > 0 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} -(RS+RC)/LS & -1/NS \\ NS/C/LS & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 1/L & RC/NS \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

$$\begin{bmatrix} V2 \\ IP \end{bmatrix} = \begin{bmatrix} NS*RC/LS & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

For IQ = 0, PHI = 0 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

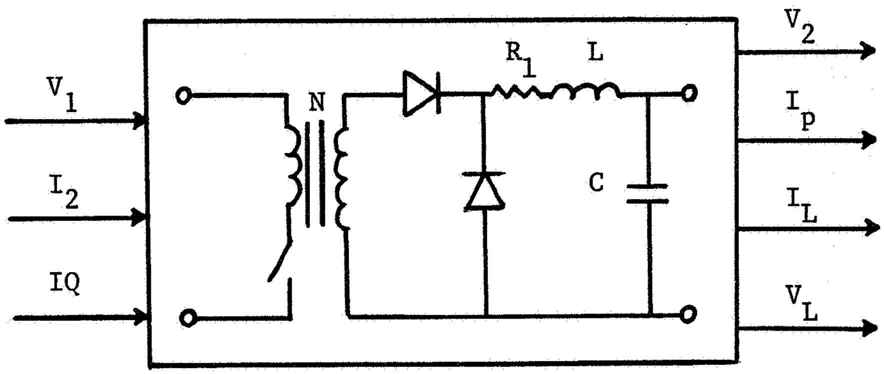
$$\begin{bmatrix} V2 \\ IP \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

```
********************************* ***************
**  LARGE SIGNAL MODEL OF FLYBACK(W/O LOAD)
*  POWER STAGE ONLY
*********************************************
** REVISED 12/7/85
MACRO FILE NAME=MACROS
DEFINE MACRO=FB
MACRO INPUTS=
     C        LP      LS      NS      NP
     RP       RS      RC
     QQ       V1      I2
*   V1 ;  INPUT VOLTAGE
*   I2 ;  INPUT CURRENT(FROM LOAD)
*   LP ;  PRIMARY INDUCTANCE
*   LS ;  SECONDARY INDUCTANCE
*   NP ;  # OF TURN (PRIMARY)
*   NS ;  # OF TURN (SECONDARY)
*   QQ ;  SWITCHING FUNCTION
*         QQ=1 (SW:ON)
*         QQ=0 (SW:OFF)
MACRO OUTPUTS=
     PHI      I1      IP      IS
     VL       VC      V2
*   PHI;  FLUX(STATE)
*   VC ;  CPACITOR VOLTAGE(STATE)
*   IP ;  PRIMARY CURRENT
*   IS ;  SECONDARY CURRENT
MACRO CODE
MACRO STOP SORT
****
      IF(DABS(QQ FB--).LT.1.E-5)THEN
         IF(PHIFB--.LE.0.)THEN
MACRO DERIVATIVE,PHIFB--=0.
         GOTO +++77
         ELSE
**** TOFF *****
      A11=-(RS FB---RC FB--)/LS FB--
      A12=-1/NS FB--
      A21=NS FB--/(C  FB--*LS FB--)
      A22=0.
      B11=0
      B12=RC FB--/NS FB--
      B21=0.
      B22=-1/C  FB--
      C11=NS FB--*RC FB--/LS FB--
      C12=1
      C21=0
      C22=0
      D11=0
      D12=-RC FB--
      D21=0
      D22=0
*
      SE=1
         END IF
      ELSE
*** TON ***
      A11=-RP FB--/LP FB--
      A12=0
      A21=0
```

```
       A22=0
       B11=1/NP FB--
       B12=0
       B21=0
       B22=-1/C  FB--
       C11=0
       C12=1
       C21=NP FB--/LP FB--
       C22=0
       D11=0
       D12=-RC FB--
       D21=0
       D22=0
       SE=0
       END IF
** OUTPUT EQ.
*
*--  -
*| V2 |   | C11 C12 | | PHI|   | D11 D12 | | V1 |
*|    | = |         | |    | + |         | |    |
*| I1 |   | C21 C22 | | VC |   | D21 D22 | | I2 |
*__  _|   |         | |    |   |         | |    |
*
       V2 FB--=C11 *PHIFB--+C12*VC FB--
      &    +  D11*V1 FB-- +D12*I2 FB--
       I1 FB--=C21*PHIFB--
       VL FB--=A11*PHIFB--+A12*VC FB--+B11*V1 FB--+
      &      B12*I2 FB--
       IP FB--=I1 FB--
       IS FB--=SE*NS FB--*PHIFB--/LS FB--
** STATE EQ.
*
* | dPHI/dt |   | A11  A12 | | PHI|   |B11 B12 | | V1 |
* |         | = |          | |    | + |        | |    |
* | dVC/dt  |   | A21  A22 | | VC |   |B21 B22 | | I2 |
* |         |   |          | |    |   |        | |    |
*
MACRO DERIVATIVE,PHIFB--=VL FB--
+++77 CONTINUE
MACRO DERIVATIVE,VC FB--=A21*PHIFB--+A22*VC FB--+
      &                  B21*V1 FB--+B22*I2 FB--
*
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION= 22, FB
END OF MODEL
```

FW

FORWARD CONVERTER POWER STAGE



INPUT

V1	variable	input voltage	Volts
I2	variable	input current from load	Amps
IQ	variable	switching function (if switch is on, IQ=1) (if switch is off, IQ=0)	
C	parameter	capacitance	Farads
L	parameter	inductance	Henries
RC	parameter	capacitor effective resistance	Ohms
RL	parameter	inductor effective resistance	Ohms
N	parameter	turns ratio(N=NS/NP)	

OUTPUT

V2	variable	output voltage	Volts
IP	variable	output current to source	Amps
IL	state variable	inductor current	Amps
VC	state variable	capacitor voltage	Volts
IS	variable	switch current	Amps
VL	variable	inductor voltage	Volts

EQUATIONS

For IQ = 1 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} -(RL+RC)/L & -1/L \\ 1/C & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} N/L & RC/L \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

$$\begin{bmatrix} V2 \\ IP \end{bmatrix} = \begin{bmatrix} RC & 1 \\ 1/N & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

For IQ = 0, IL > 0 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} -(RL+RC)/L & -1/L \\ 1/C & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

$$\begin{bmatrix} V2 \\ IP \end{bmatrix} = \begin{bmatrix} RC & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

For IQ = 0, IL = 0 :

$$\begin{bmatrix} \dot{IL} \\ \dot{VC} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -1/C \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

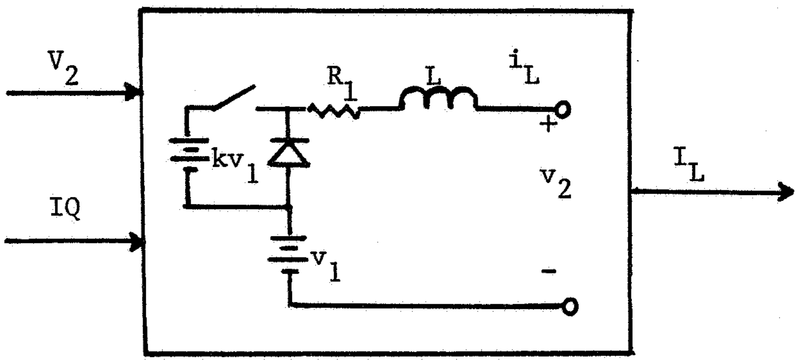
$$\begin{bmatrix} V2 \\ IP \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} IL \\ VC \end{bmatrix} + \begin{bmatrix} 0 & -RC \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V1 \\ I2 \end{bmatrix}$$

```
*****************************************
**  LARGE SIGNAL MODEL OF FORWARD CONVERTER
*   POWER STAGE ONLY
*****************************************
** REVISED 12/20/85
MACRO FILE NAME=MACROS
DEFINE MACRO=FW
MACRO INPUTS=
     C      L      RL     RC
     IQ      V1     I2
     NS     NP
*   IQ ;  SWITCHING FUNCTION
*         IQ=1  (SWITCH; ON)
*         IQ=0  (SWITCH; OFF)
*   V1 ;  INPUT VOLTAGE
*   I2 ;  INPUT CURRENT(FROM LOAD)
MACRO OUTPUTS=
     IS     IL
     ILL    VL
     VC     V2     IP
*   IL ;  INDUCTOR CURRENT(STATE)
*   VC ;  CAPACITOR VOLTAGE(STATE)
*   IS ;  SWITCH CURRENT
*   ILL;  INDUCTOR CURRENT(DUMMY)
*   VL ;  TRANSFORMER VOLTAGE
*   V2 ;  OUTPUT VOLTAGE
*   IP ;  PRIMARY CURRENT(TO SOURCE)
MACRO CODE
MACRO STOP SORT
****
      XN=NS FW--/NP FW--
      IF(DABS(IQ FW--).LT.1.E-10)THEN
         IF(IL FW--.LE.0.)THEN
         ILLFW--=0.
MACRO DERIVATIVE,IL FW--=0.
         GOTO ++77
         ELSE
**** TOFF *****
      A11=-(RL FW--+RC FW--)/L  FW--
      A12=-1/L  FW--
      A21=1/C  FW--
      A22=0.
      B11=0
      B12=RC FW--/L  FW--
      B21=0.
      B22=-1/C  FW--
      C11=RC FW--
      C12=1
      C21=0
      C22=0
      D11=0
      D12=-RC FW--
      D21=0
      D22=0
*
      IS FW--=0
         END IF
      ELSE
*** TON ***
      A11=-(RL FW--+RC FW--)/L  FW--
```

```
        A12=-1/L   FW--
        A21=1/C  FW--
        A22=0
        B11=XNL   FW--
        B12=RC FW--/L   FW--
        B21=0
        B22=-1/C  FW--
        C11=RC FW--
        C12=1
        C21=1/XN
        C22=0
        D11=0
        D12=-RC FW--
        D21=0
        D22=0
        IS FW--=IL FW--
        END IF
** OUTPUT EQ.
*
*--  -
*| V2 |   | C11 C12 | | IL |   | D11 D12 | | V1 |
*|    | = |         | |    | + |         | |    |
*| IP |   | C21 C22 | | VC |   | D21 D22 | | I2 |
*__  _|   |         | |    |   |         | |    |
*
        V2 FW--=C11 *IL FW--+C12*VC FW--
      &    + D11*V1 FW-- +D12*I2 FW--
        IP FW--=C21*IL FW--
        VL FW--=(A11*IL FW--+A12*VC FW--+B11*V1 FW--+
      &     B12*I2 FW--)*L  FW--
** STATE EQ.
*
* | dIL/dt |   | A11  A12 | | IL |   |B11 B12 | | V1 |
* |        | = |          | |    | + |        | |    |
* | dVC/dt |   | A21  A22 | | VC |   |B21 B22 | | I2 |
* |        |   |          | |    |   |        | |    |
*
MACRO DERIVATIVE,IL FW--=VL FW--/L  FW--
+++77 CONTINUE
MACRO DERIVATIVE,VC FW--=A21*IL FW--+A22*VC FW--+
      &                  B21*V1 FW--+B22*I2 FW--
*
         ILLFW--=IL FW--
         IF(ILLFW--.LE.0.)ILLFW--=0.
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION= 22, FW
END OF MODEL
```

BATTERY DISCHARGER POWER STAGE

BP



INPUT

V1	variable	input voltage	Volts
V2	variable	bus voltage	Volts
IQ	variable	switching function (if switch is on, IQ=1) (if switch is off, IQ=0)	
L	parameter	inductance	Henries
RL	parameter	inductor effective resistance	Ohms

OUTPUT

IL	state variable	inductor current	Amps

EQUATIONS

For IQ = 1 :

$$\dot{IL} = ((1 + GAM) * V1 - IL * RL - V2) / L$$

For IQ = 0, IL > 0 :

$$\dot{IL} = (V1 - IL * RL - V2) / L$$

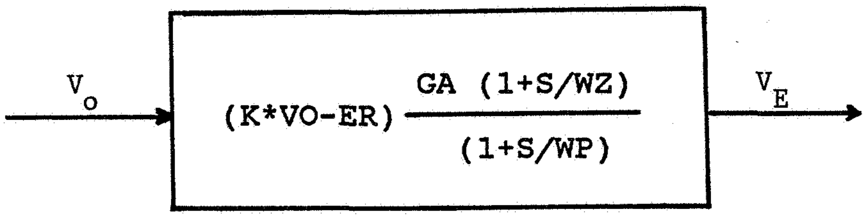
For IQ = 0, IL = 0 :

$$\dot{IL} = 0$$

```
**********************************
* LARGE SIGNAL MODEL OF BATTERY DISCHARGER
* POWER STAGE ONLY
* REVISED 3/4/86
MACRO FILE NAME=MACROS
DEFINE MACRO=BP
MACRO INPUTS=
     L          RL
     V1         V2         V2L
     IQ           GAM          EPS
*   IQ ;  SWITCHING FUNCTION
*         IQ=1  (SWITCH; ON)
*         IQ=0  (SWITCH; OFF)
*   V1 ;  INPUT VTG FROM BATTERY
*   V2 ;  BUS VTG
*
MACRO OUTPUTS= IL       ILL      Q
*   IL ;  INDUCTOR CURRENT(STATE VARIABLE)
MACRO CODE
MACRO STOP SORT
      Q   BP--=IQ BP--
      IF(V2 BP--.GT.V2LBP--)Q   BP--=0
      IF(Q  BP--.LT.EPSBP--)THEN
         IF(IL  BP--.LE.0.)THEN
         ILLBP--=0.
MACRO DERIVATIVE,IL  BP--=0.
         GOTO +++77
         ELSE
         CC=1.
         END IF
      ELSE
      CC=1.+GAMBP--
      END IF
MACRO DERIVATIVE,IL  BP--=(CC*V1 BP---IL BP--*RL BP---
     &      V2 BP--)/L  BP--
+++77 CONTINUE
       ILLBP--=IL  BP--
       IF(ILLBP--.LE.0.)ILLBP--=0.
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION= 22, BP
END OF MODEL
```

DG

LEAD/LAG COMPENSATOR



INPUT

VO	variable	input bus voltage	Volts
K	parameter	voltage dividing factor	
ER	parameter	op.amp.reference voltage	Volts
WZ	parameter	frequency of zero	rad/sec
WP	parameter	frequency of pole	rad/sec

OUTPUT

VE	variable	ac component of control vtg.	Volts
X1	state variable	intermediate state variable	

EQUATIONS

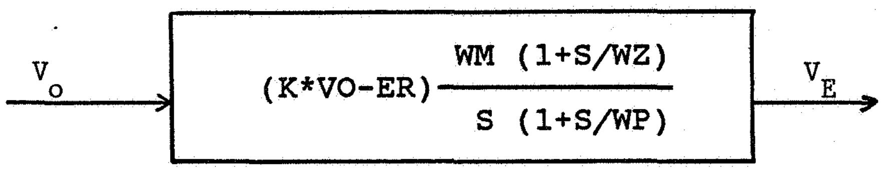
$$VE = [\ X1 + (K * VO - ER) * GA / WZ\ ] * WP$$

$$\dot{X1} = GA * (\ K * VO - ER\ )$$

```
********************************
*** COMPENSATOR(LEAD,LAG)
******************************
MACRO FILE NAME=MACROS
DEFINE MACRO=DG
MACRO INPUTS=
     GA     WZ     WP
     K      ER     VO
*
*   VO ;POWER STAGE OUTPUT VOLTAGE
*   WZ ;ZERO FREQUENCY(2*PI*F)
*   WP ;POLE FREQUENCY(2*PI*F)
*    K ;OUTPUT VOLTAGE DIVIDING RATIO
*        (IF VTG IVIDER NOT USED,K=1)
*   ER ;REFERENCE VOLTAGE
*
MACRO OUTPUTS=X1     VE
*   X1 ;DUMMY STATE
*   VE ;OUTPUT VOLTAGE(TO PWM)
MACRO CODE
MACRO STOP SORT
*
      TC1=1/WZ DG--
      TC2=1/WP DG--
      ERR=K  DG--*VO DG-- - ER DG--
      VE DG--=(X1 DG--+ERR*TC1*GA DG--)/TC2
MACRO DERIVATIVE,X1 DG--=GA DG--*ERR - VE DG--
*
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION=22,DG
END OF MODEL
```

MP

TWO-POLE ONE-ZERO COMPENSATOR



INPUT

VO	variable	input bus voltage	Volts
K	parameter	voltage dividing factor	
ER	parameter	op.amp.reference voltage	Volts
WZ	parameter	frequency of zero	rad/sec
WP	parameter	frequency of pole	rad/sec

OUTPUT

VE	state variable	ac component of control vtg.	Volts
X1	state variable	intermediate state variable	

EQUATIONS

ERR= K * VO - ER

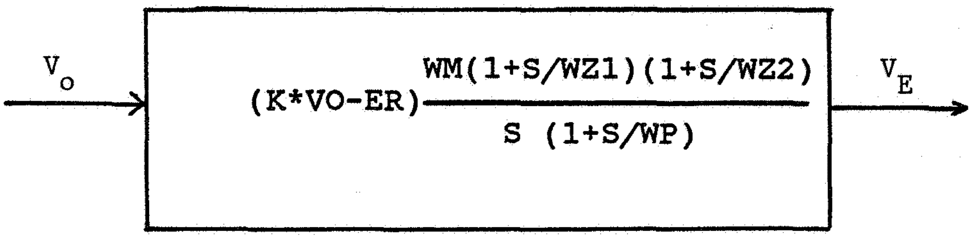
$\dot{X1}$ = ERR - (X1 + ERR / WZ) * WP

$\dot{VE}$ = WM * (X1 + ERR / WZ) * WP

```
********************************
*** COMPENSATOR(1 ZERO,2 POLE)
******************************
MACRO FILE NAME=MACROS
DEFINE MACRO=MP
MACRO INPUTS=
     WM     WZ     WP
     K      ER     VO
*
*  VO ;POWER STAGE OUTPUT VOLTAGE
*  WZ ;ZERO FREQUENCY(2*PI*F)
*  WP ;POLE FREQUENCY(2*PI*F)
*   K ;OUTPUT VOLTAGE DIVIDING RATIO
*       (IF VTG IVIDER NOT USED,K=1)
*  ER ;REFERENCE VOLTAGE
*
MACRO OUTPUTS=X1      VE
*  X1 ;DUMMY STATE
*  VE ;OUTPUT VOLTAGE(TO PWM)
MACRO CODE
MACRO STOP SORT
*
      TC1=1/WZ MP--
      TC2=1/WP MP--
      ERR=K  MP---*VO MP-- - ER MP--
MACRO DERIVATIVE,X1 MP---=ERR - (X1 MP--+ERR*TC1)/TC2
MACRO DERIVATIVE,VE MP---=~~0A~~ MP--*(X1 MP--+ERR*TC1)/TC2
*                             wM
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION=22,MP
END OF MODEL
```

TWO-POLE TWO-ZERO COMPENSATOR

PZ



INPUT

VO	variable	input bus voltage	Volts
K	parameter	voltage dividing factor	
ER	parameter	op.amp. reference voltage	Volts
WZ1,WZ2	parameters	frequency of zero	rad/sec
WP	parameter	frequency of pole	rad/sec

OUTPUT

VE	variable	ac component of control vtg.	Volts
X1,X2	state variables	intermediate state variable	

EQUATIONS

Z2 = WM * WP / WZ1 /WZ2

ERR= K * VO - ER

VE = X2 + Z2 * ERR

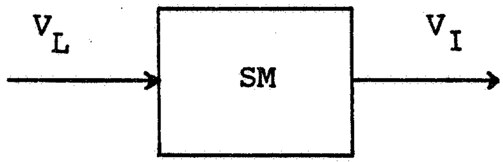
$\dot{X}1$ = ERR * WM * WP

$\dot{X}2$ = X1 +Z2 * (WZ1 + WZ2) * ERR - WP * VE

```
******************************
*** COPZENSATOR(2 ZERO,2 POLE)
******************************
MACRO FILE NAME=MACROS
DEFINE MACRO=PZ
MACRO INPUTS=
      WM      WZ1      WZ2      WP
      K       ER      VO
*
*  VO ;POWER STAGF OUTPUT VOLTAGE
*  WZ1,WZ2 ;ZERU FREQUENCIES(2*PI*F)
*  WP ;POLE FREGUENCY(2*PI*F)
*   K ;OUTPUT VOLTAGE DIVIDING RATIO
*      (IF VTG IVIDER NOT USED,K=1)
*  ER ;REFERENCE VOLTAGE
*
MACRO OUTPUTS=X1      X2       VE
*  X1,X2 ;DUMMY STATE
*  VE ;OUTPUT VOLTAGE(TO PWM)
MACRO CODE
MACRO STOP SORT
*
      Z2=WM PZ--*WP PZ--/WZ1PZ--/WZ2PZ--
      ERR=K  PZ--*VO PZ-- - ER PZ--
      VE PZ--=X2 PZ--+Z2*ERR
MACRO DERIVATIVE,X1 PZ --=ERR *WM PZ--*WP PZ--
MACRO DERIVATIVE,X2 PZ--=X1 PZ--+Z2*(WZ1PZ--+WZ2PZ--)*ERR
     &         -WP PZ--*VE PZ--
*
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION=22,PZ
END OF MODEL
```

SM

S.C.M CURRENT LOOP



INPUT

VL	variable	input bus voltage	Volts
NV	parameter	transformer turns ratio	
C	parameter	current-loop capacitance	Farads
R	parameter	current-loop resistance	Ohms

OUTPUT

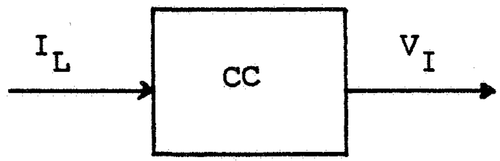
VI	state variable	current-loop output voltage	Volts

EQUATIONS

$$\dot{VI} = NV * VL / (C * R)$$

```
******************************************
*** CURRENT LOOP (S C M) MODULE
*****************************************
*
MACRO FILE NAME=MACROS
DEFINE MACRO=SM
MACRO INPUTS=
    VL     NV     C     R
*
*  VL ; TRNASFORMER VOLTAGE(FROM POWER STAGE)
*  NV ; TRANSFORMER TURNS RATIO
*
MACRO OUTPUTS=VI
*
*  VI ; CURRENT LOOP OUTPUT VOLTAGE
*         (TO PWM BLOCK)
*
MACRO CODE
MACRO STOP SORT
*
*STATE EQUATION
MACRO DERIVATIVE,VI SM--=NV SM--*VL SM--/
     &                     (C  SM--*R  SM--)
*
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION=22,SM
END OF MODEL
```

CURRENT INJECTION CONTROL



INPUT

IL	variable	inductor current (if flyback, flux)	Amps
NI	parameter	current transformer turns ratio	
NP	parameter	if flyback, primary # of turns otherwise NP=1	
LP	parameter	if flyback, primary inductance otherwise LP=1	Henries
RW	parameter	current loop resistance	Ohms

OUTPUT

VI	variable	current loop output voltage	Volts

EQUATIONS

For FLYBACK CONVERTER :

VI = NP / LP * IL * RW / NI

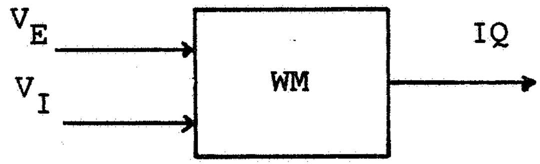
For OTHER CONVERTERS :

VI = IL * RW / NI

```
************************************
*** CURRENT LOOP (C I C) MODULE
************************************
MACRO FILE NAME=MACROS
DEFINE MACRO=CC
MACRO INPUTS=
     IL     NI     RW
     NP     LP
*
*   IL ; INDUCTOR CURRENT(FROM POWER STAGE)
*        (FLUX IF BUCK/BOOST)
*   NI ; CURRENT TRANSFORMER TURNS RATIO
*   NP ; IF FLYBACK : POWER STAGE PRIMARY # OF TURNS
*        OTHERWISE NP=1
*   LP ; IF FLYBACK ; POWER TRANSFORMER PRIMARY INDUCTANCE
*        OTHERWISE LP=1
*
MACRO OUTPUTS=VI
*
*   VI ; CIC OUTPUT CONTROL VOLTAGE
*
MACRO CODE
MACRO STOP SORT
*
      VI CC--=NP CC-- /LP CC--*
     &        IL CC--*RW CC--/NI CC--
*
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION=22,CC
END OF MODEL
```

WM

PWM(CONSTANT FREQUENCY CONTROL)



INPUT

VE	variable	voltage-loop error voltage	Volts
VI	variable	current-loop error voltage	Volts
TI	parameter	switching period	Seconds
VP	parameter	amplitude of external ramp	Volts
VQ	parameter	thershold voltage	Volts
ER	parameter	reference voltage of op.amp.	Volts

OUTPUT

VR	variable	reference voltage	Volts
VC	variable	total control voltage	Volts
IQ	variable	switching function	

EQUATIONS

VR = VP * (TN - N) + VQ

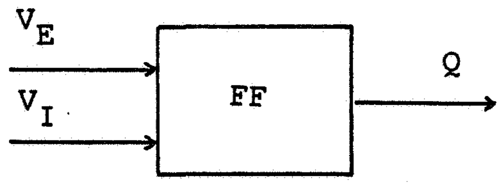
VC = - VE - VI

IF VR $\geq$ VC , IQ = 0

```
*********************************
**   P.W.M (CONSTANT FREQUENCY)***
***********************************
MACRO FILE NAME=MACROS
DEFINE MACRO=WM
MACRO INPUTS=
     TI      VP     VQ     ER
     CIC      SCM
     VE       VI     EPS
     VCX      VCN     ILX
     DMN      DMX
*
*    VE ;  AMPLIFIED ERROR VTG(FROM COMPENSATOR)
*    VI ;  INPUT VOLTAGE FROM CURRENT FEEDBACK MODULE
*    CIC;  IF CIC, CIC=1
*          OTHERWISE CIC=0
*    SCM;  IF SCM, SCM=1
*          OTHERWISE SCM=0
*    TI ;  SWICHING INTERVAL
*    VP ;  AMPLITUDE OF EXTERNAL RAMP
*          ( IF EXT.RAMP NOT USED,VP=0)
*    VQ ;  THRESHOLD VOLTAGE
*    ER ;  REFERNCE VOLTAGE OF OP.AMP
*
MACRO OUTPUTS=
     VR     VC     IQ     TN
     VS
*
*    VR ;  EXTERNAL RAMP VOLTAGE
*    VC ;  TOTAL CONTROL VOLTAGE
*    IQ ;  SWITCHING FUNCTION
*          (IF SWITCH=ON,  IQ=1)
*          (IF SWITCH=OFF, IQ=0)
*
MACRO CODE
MACRO STOP SORT
****
***  RAMP GENERATION
*
      TN WM--=(TIME+TI WM--)/TI WM--
      NP=N
      N=IDINT(TN WM--)
      VR WM--=VP WM--*(TN WM-- -N)+VQ WM--
****
      VC WM--=         -VE WM---CICWM--*VS WM---
     &          SCMWM  *VI WM--
* OP-AMP SATURATION
      IF(VC WM--.GT.VCXWM--)VC WM--=VCXWM--
      IF(VC WM--.LT.VCNWM--)VC WM--=VCNWM--
* COMPARATOR
      IF(IQ WM--.GT.EPS)THEN
       VS WM--=VI WM--
         IF(VR WM--.GT.VC WM--)THEN
         IQ WM--=0
         END IF
      ELSE
       VS WM--=0.
      END IF
      IF(NP.NE.N)IQ WM--=1
*PROTECTION
      D=TN WM---N
      IF(D.LT.DMNWM--)IQ WM--=1
      IF(D.GT.DMXWM--)IQ WM--=0
      IF(IL WM--.GT.ILXWM--)IQ WM--=0
*
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION= 22, WM
END OF MODEL
```

FF

PWM(CONSTANT OFF-TIME CONTROL)



INPUT

VE	variable	voltage-loop error voltage	Volts
VI	variable	current-loop error voltage	Volts
TOF	parameter	constant off-time interval	Seconds
SLP	parameter	slope of external ramp	Volts/sec
VTH	parameter	threshold voltage	Volts
ER	parameter	reference voltage of op.amp.	Volts

OUTPUT

Q	variable	switching function	
VR	variable	reference voltage	Volts
VC	variable	total control voltage	Volts

EQUATIONS

VC = - VE - VI

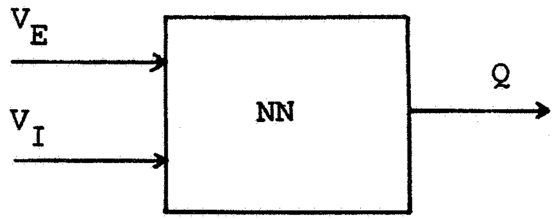
VR = V(RAMP) + VTH

IF VR $\geq$ VC, Q = 0

```
*****************************************
* P W M (CONSTANT OFF TIME CONTROL )
*****************************************
MACRO FILE NAME=MACROS
DEFINE MACRO=FF
MACRO INPUTS=
        VE       VI       IL
       TOF      EPS       VTH      SLP      ILM
        ER      CIC       SCM
*
*   VE ;AMPLIFIED ERROR VTG(FROM COMPENSATOR)
*   VI ;INPUT VTG FROM CURRENT FEEDBACK MODULE
*      CIC; IF CIC, CIC=1
*           OTHERWISE CIC=0
*      SCM; IF SCM, SCM=1
*           OTHERWISE SCM=0
*      TOF ; CONSTANT OFF TIME INTERVAL
*      SLP ; SLOP OF EXTERNAL RAMP
*            ( IF EXT.RAMP NOT USED,SLP=0)
*      VTH; THRESHOLD VOLTAGE
*      ER ; REFERNCE VOLTAGE OF OP.AMP
*
MACRO OUTPUTS=
        VR       VC       Q
*
*      VR ; EXTERNAL RAMP VOLTAGE PLUS THRESHOLD VTG
*      VC ; TOTAL CONTROL VOLTAGE
*      Q ; SWITCHING FUNCTION
*            (IF SWITCH=ON,  Q=1)
*            (IF SWITCH=OFF,Q=0)
*      TC ; OFF TIME INSTANT
*      TR ; ON  TIME INSTANT
MACRO CODE
MACRO STOP SORT
****
*
        VC FF--=          -VE FF---CICFF--*VI FF---
      &          SCMFF--*VI FF--
******
        IF(TIME.GT.EPS)GOTO +++11
        T=TIME
        Q  FF--=1
        GOTO +++22
+++11   CONTINUE
*
        IF(Q   FF--.LT.EPSFF--)THEN
*
            IF((TIME-TC).GE.TOFFF--)THEN
             TR=TIME
             Q   FF--=1
            END IF
        ELSE
        VR FF--=SLPFF--*(TIME-TR)+VTHFF--
              IF(VR FF--.GE.VC FF--)THEN
              Q   FF--=0
              TC=TIME
              END IF
        END IF
+++22   CONTINUE
        IF(IL FF--.GE.ILMFF--)Q   FF--=0
        MACRO RESUME SORT
        END OF MACRO
        MODEL DESCRIPTION
        LOCATION= 22, FF
        END OF MODEL
        *
```

PWM(CONSTANT ON-TIME CONTROL)

NN



INPUT

VE	variable	voltage loop error voltage	Volts
VI	variable	current loop error voltage	Volts
TOF	parameter	constant off-time interval	Seconds
SLP	parameter	slope of external ramp	Volts/sec
VTH	parameter	threshold voltage	Volts
ER	parameter	refernce voltage of op.amp.	Volts

OUTPUT

Q	variable	switching function	
VR	variable	reference voltage	Volts
VC	variable	total control voltage	Volts

EQUATIONS

VC = - VE - VI

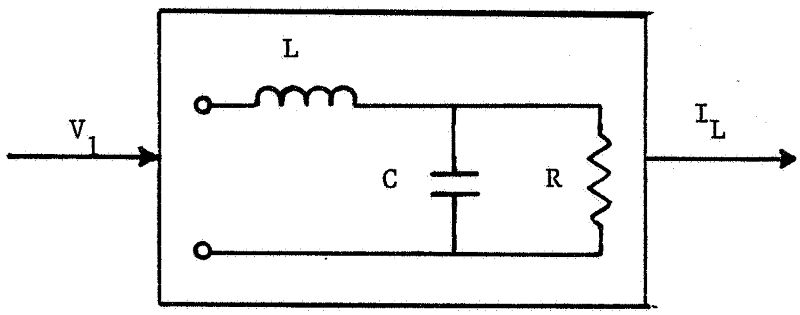
VR = V(RAMP) + VTH

IF VR $\leq$ VC, Q = 1

```
****************************************
* P W M (CONSTANT ON TIME CONTROL)
****************************************
MACRO FILE NAME=MACROS
DEFINE MACRO=NN
MACRO INPUTS=
      VE      VI        IL
     TON      EPS       VTH       SLP       ILM
      ER      CIC       SCM
*
*   VE ;AMPLIFIED ERROR VTG(FROM COMPENSATOR)
*   VI ;INPUT VTG FROM CURRENT FEEDBACK MODULE
*     CIC;  IF CIC,  CIC=1
*           OTHERWISE CIC=0
*     SCM;  IF SCM,  SCM=1
*           OTHERWISE SCM=0
*     TON ;  CONSTANT ON TIME INTERVAL
*     SLP ;  SLOP OF EXTERNAL RAMP
*            ( IF EXT.RAMP NOT USED,SLP=0)
*     VTH;  THRESHOLD VOLTAGE
*     ER ;  REFERNCE VOLTAGE OF OP.AMP
*
MACRO OUTPUTS=
      VR      VC       Q
*
*     VR ;  EXTERNAL RAMP VOLTAGE PLUS THRESHOLD VTG
*     VC ;  TOTAL CONTROL VOLTAGE
*     Q ;  SWITCHING FUNCTION
*            (IF SWITCH=ON,  Q=1)
*            (IF SWITCH=ONN,Q=0)
*     TC ;  ON TIME INSTANT
*     TR ;  OFF TIME INSTANT
MACRO CODE
MACRO STOP SORT
****
*
****
      VC NN--=          -VE NN---CICNN--*VI NN---
     &          SCMNN--*VI NN--
******
      IF(TIME.GT.EPS)GOTO +++11
      T=TIME
      Q   NN--=1
      GOTO +++22
+++11 CONTINUE
*
      IF(Q   NN--.GT.EPSNN--)THEN
*
          IF((TIME-TC).GE.TONNN--)THEN
           TR=TIME
           Q   NN--=0
          END IF
      ELSE
      VR NN--=SLPNN--*(TIME-TR)+VTHNN--
           IF(VR NN--.LE.VC NN--)THEN
           Q   NN--=1
           TC=TIME
           END IF
      END IF
+++22 CONTINUE
      IF(IL NN--.GE.ILMNN--)Q   NN--=0
*
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION= 22, NN
END OF MODEL
*
```

LO

R-L-C LOAD



INPUT

V1	variable	input bus voltage	Volts
RA	parameter	resistance	Ohms
RB	parameter	resistance	Ohms
L	parameter	inductance	Henries
C	parameter	capacitance	Farads
TC	parameter	time for step change	seconds

OUTPUT

IL	state variable	inductor current	Amps
VC	state variable	capacitor voltage	Volts
R	variable	resistance	Ohms

EQUATIONS

For $TIME < TC$: $R = RA$

For $TIME \geq TC$: $R = RB$

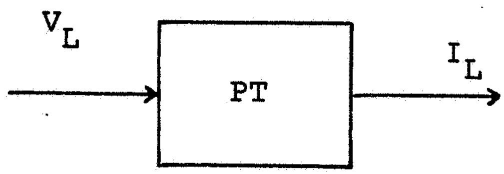
$$\dot{IL} = (V1 - VC) / L$$

$$\dot{VC} = (IL - VC / R) / C$$

```
********************************
******** LOAD MODEL **********
******************************
MACRO FILE NAME=MACROS
DEFINE MACRO=LO
MACRO INPUTS= V1      RA     RB
              L      C     TC
*
*  V1 ; INPUT VOLTAGE(FROM POWER STAGE)
*  RA ; RESISTOR VALUE BEFORE STEP CHANGE
*  RB ; RESISTOR VALUE AFTER  STEP CHANGE
*  TC ; TIME FOR STEP CHANGE
*
MACRO OUTPUTS= IL      VC     R
MACRO CODE
MACRO STOP SORT
*
      R  LO--=RA LO--
      IF(TIME.GT.TC LO--)R  LO--=RB LO--
*STATE EQUATION
MACRO DERIVATIVE,IL LO--=(V1 LO-- - VC LO--)/L  LO--
MACRO DERIVATIVE,VC LO--=(IL LO-- - VC LO--/R  LO--)/C  LO--
*
MACRO RESUME SORT
END OF MACRO
MODEL DESCRIPTION
LOCATION=25, LO
END OF MODEL
```

PT

CONSTANT POWER LOAD



INPUT

VL	variable	input bus voltage	Volts
PW1,PW2 PWO	parameters	constant power values	Watts
PC	parameter	if PC=1, const. power if PC=0, time varying power if PC=2, time varying power	
VR	parameter	minimum voltage to maintain const.power	Volts
SW	parameter	slope of time varying power	Watts/sec

OUTPUT

IL	variable	load current	Amps
PW	variable	load power	Watts

EQUATIONS

For PC = 1 :

$$PW = PW1 \quad (\text{ IF TIME} < TC)$$
$$PW = PW2 \quad (\text{ IF TIME} \geq TC)$$

For PC = 2 :

$$PW = PW1 - (SW * TIME)$$
$$PW = PW2 \quad (\text{ IF } PW \leq PW2)$$

For PC = 0 :

$$PW = SW * TIME + PWO$$

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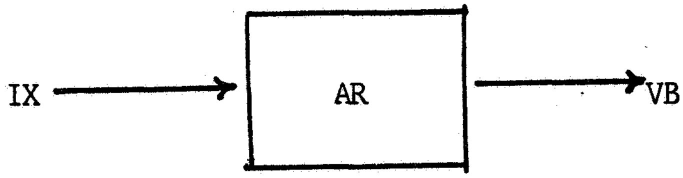
```
MACRO FILE NAME = MACROS
**********************************************************
DEFINE MACRO = PT
* LOAD MODEL
* INPUT IS BUS VOLTAGE (VL) AND POWER (PW) OUTPUT IS I(LOAD)
*
**** FOR STEP POWER CHANGE ; PC PT = 1.
**** FOR RAMP CHANGE OF POWER ; PC PT =0. OR 2.
* PC PT = 0 : PW = SW * TIME + PWO
* PC PT = 2 : PW = PW1 - (SW * TIME)

MACRO INPUTS = VL      PO     PW1      PW2      PC
               VR      TC      SW
MACRO OUTPUTS = IL     PW      SL
MACRO CODE
MACRO STOP SORT

      IF ( PC PT-- .EQ. 1. ) GO TO +++23
      IF ( PC PT-- .EQ. 2. ) GO TO +++43
      PW PT-- = SW PT--*TIME + PWOPT--
      IL PT-- = PW PT-- / VL PT--
      GOTO +++33

* STEP CHANGE OF POWER AT TIME = TC PT
+++23 CONTINUE
      PW PT--=PW1PT--
      IF(TIME.GE.TC PT--)PW PT--=PW2PT--
      IL PT-- =  PW PT-- / VL PT--
+++33 SL PT-- =  PW PT-- /VR PT--/VR PT--
      IF (VL PT-- .LT. VR PT--) IL PT-- = SL PT--*VL PT--
      IF(IL PT-- .LT. 0. ) IL PT-- = 0.
      GO TO +++53

* RAMP CHANGE OF POWER FROM PW1PT TO PW2PT WITH THE SLOPE
* OF SW PT [W] PER SECOND
+++43 PW PT-- = PW1PT-- - ( SW PT-- * TIME )
      IF ( PW PT-- .LT. PW2PT-- ) PW PT-- = PW2PT--
      IL PT-- = PW PT-- / VL PT--
      SL PT-- = PW PT-- / VR PT-- / VR PT--
      IF ( IL PT-- .LT. 0. ) IL PT-- = 0.

* DUMMY STATEMENT
+++53 PW PT-- = PW PT--
MACRO RESUME SORT
END OF MACRO
*******************************************************
MODEL DESCRIPTION
LOCATION=42, PT
END OF MODEL
PRINT
```

SOLAR ARRAY [AR]

AR



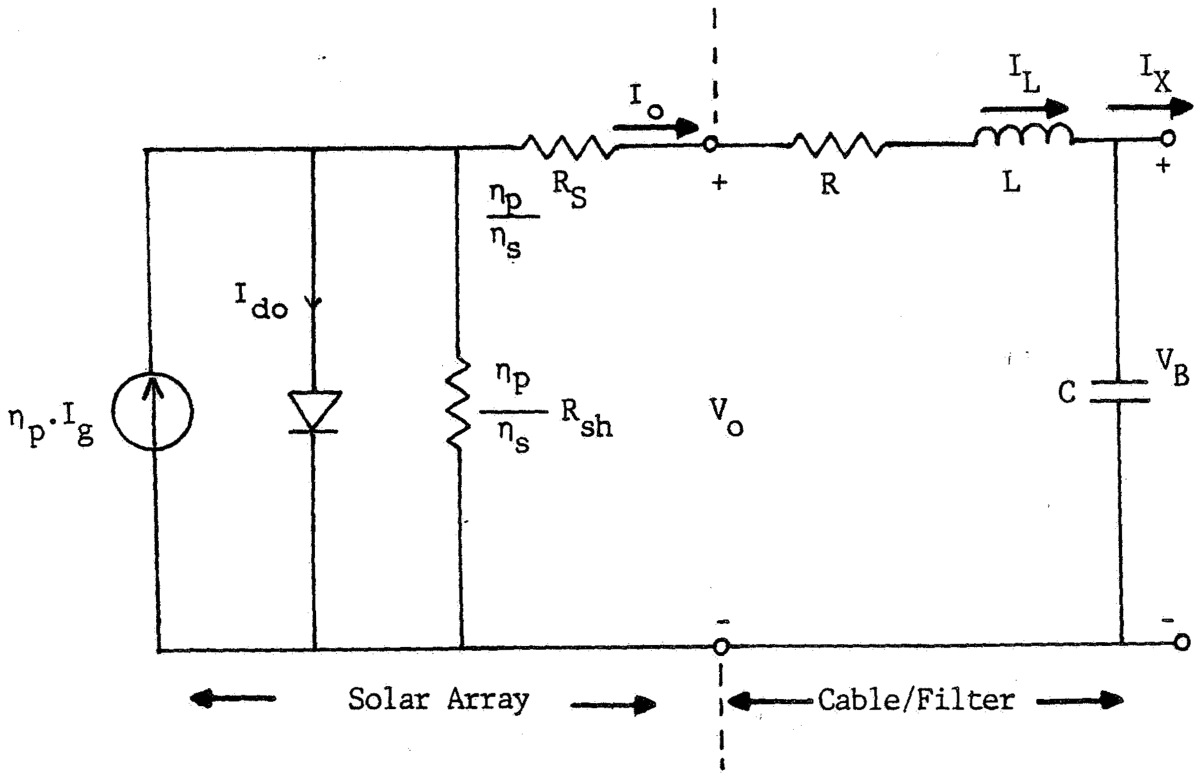
INPUT

Physical Quantity Name		Description	units
IX	variable	Bus current	amps
LL	parameter	Illumination level	
R	parameter	Filter resistance	ohms
L	parameter	Filter inductance	henries
C	parameter	Filter capacitance	farads
TA	parameter	Ambient temperature	°K
NP	parameter	No. of parallel arrays	
NS	parameter	No. of serial cell	
FC, FV	parameter	Temperature coeffieients	

OUTPUT

VB*	variable	Bus voltage	volts
VO	variable	Solar array output voltage	volts
I1*	variable	Filter inductor current	volts

* state variable



Equations:

$$I_o = n_p \left[I_g - I_{do} \left| \text{EXP } K_o \cdot \left(\frac{V_o}{n_s} + I_o \cdot \frac{R_s}{n_p} \right) \right| - \left(\frac{V_o}{n_s} + I_o \cdot \frac{R_s}{n_p} \right) \cdot \frac{1}{R_{sh}} \right]$$

$$L \frac{dI_L}{dt} = V_o - R \cdot I_L - V_B$$

$$C \frac{dV_B}{dt} = I_L - I_X$$

Circuit Model of Solar Array and Cable/Filter [AR]

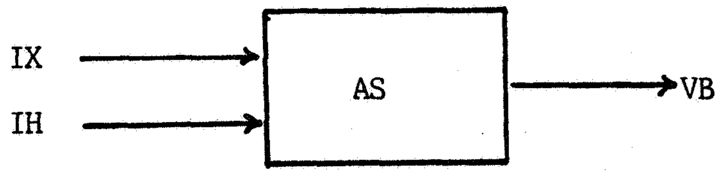
```
MACRO FILE NAME = MACROS
DEFINE MACRO = AR
********************************
**   SOLAR ARRAY MODEL   ******
********************************

*========> VB

*========< IX

***

MACRO INPUTS = IX      LL       LLS
   R       L      C      TA
   FC      FV     NP     NS
* IX = INPUT CURRENT
* LL = ILLUMINATION LEVEL
* LLS = SLOPE OF ILLUMINATION CHANGE
* R,L,C, : CABLE IMPEDANCE
* TA = AMBIENT TEMPERATURE
* FC,FV : TEMPERATURE COEFFICIENTS
* NP = NO. OF PARALLEL ARRAYS
* NS = NO. OF SERIAL CELLS
* R,L,C, : CABLE IMPEDANCE

MACRO OUTPUTS = VO     IL      VB

* VO = SOLAR ARRAY OUTPUT VOLTAGE
* VB = BUS VOLTAGE

MACRO CODE
MACRO STOP SORT

*** SOLAR CELL PARAMETERS ****
*
* RS = INTERNAL SERIES RESISTANCE
* RSH= INTERNAL SHUNT  RESISTANCE
* XIO= REVERSE SATURATION CURRENT
* TN = NOMINAL TEMPERATURE
* Q  = ELECTRON CHARGE
* XK = BOLTZMANN CONSTANT
* XIG= LIGHT-GENERATED CURRENT
* VOC= OPEN  CIRCUIT VOLTAGE
*
      RS = .42
      RSH = 250.
      XIG = .14115
      XIO = 4.1869E-11
      A = .967
      TN = 301.
      Q = 1.602E-19
      XK = 1.381E-23
      VOC = .5512
*     XKO = Q / ( XK * A * TN )
      XKO=39.8
*
* ILLUMINATION CHANGE WITH A LINEAR SLOPE OF LLS
      FILL = LL AR-- + LLSAR-- * TIME

* EFFECT OF ILLUMINATION CHANGE
```

[AR.MOD] continued

```
       XIG = XIG * FILL
*
       C1 = ( 1.  + RS / RSH )
       C2 = NP AR-- / ( NS AR-- * RSH )
       C3 = -NP AR-- * XIG
       A1 = XKD / NS AR--
       A2 = XKD * RS / NP AR--
       IF ( TIME .NE. O. ) GOTO +++10
*
* INITIAL GUESS FOR SOLAR ARRAY OUTPUT VOLTAGE
       VO AR-- = VB AR--

****************************************************
***    NEWTON ITERATION    **************************
****************************************************

+++10  CONTINUE
       VOP = VO AR--

       FV = C1 * IL AR-- + C2 * VO AR-- + C3 + NP AR--
      &       * XIO * DEXP ( A1 * VO AR-- + A2 * IL AR-- )
       DFV = C2 + A1 * NP AR-- * XIO * DEXP ( A1 * VO AR--
      &       + A2 * IL AR--)
       VO AR-- = VO AR-- - FV / DFV
       ZZ = ( VO AR-- - VOP ) / VO AR--
       IF ( DABS ( ZZ ) .LE. 1.E-4 ) GOTO +++20
       GO TO +++10

********************************************************
*  TEMPERATURE CORRECTION FOR S.A. I-V CURVE           *
*  DEL(I) = FC * DEL(T)                                *
*  DEL(V) = ( FV + FC * RS ) * DEL(T)                  *
********************************************************

+++20  DELI = FC AR-- * ( TA AR-- - TN )
       DELV = ( FV AR-- + FC AR-- * RS ) * ( TA AR-- - TN )
       ILT = IL AR-- + DELI
       VO AR-- = VO AR-- + DELV
*
       VL = VO AR-- - ILT * R  AR-- - VB AR--
MACRO DERIVATIVES, IL AR-- = VL / L  AR--
MACRO DERIVATIVES, VB AR-- = ( IL AR-- - IX AR-- ) / C  AR--
MACRO RESUME SORT
END OF MACRO
**********************************************************
MODEL DESCRIPTION
LOCATION = 22, AR
END OF MODEL
PRINT
```

[AR.MOD]

AS



INPUT

Physical Quantity Name		Description	units
IX	variable	Load current	amps
IH	variable	Shunt current	amps
DL	parameter	Delay time between switchings	seconds
R	parameter	Filter resistance	ohms
L	parameter	Filter inductance	henries
C	parameter	Filter capacitance	farads
R1	parameter	Filter resistance	ohms
C1	parameter	Filter capacitance	farads
NP	parameter	No. of parallel arrays	
NS	parameter	No. of serial cells	
NNP	parameter	No. of parallel arrays switched at a time	

OUTPUT

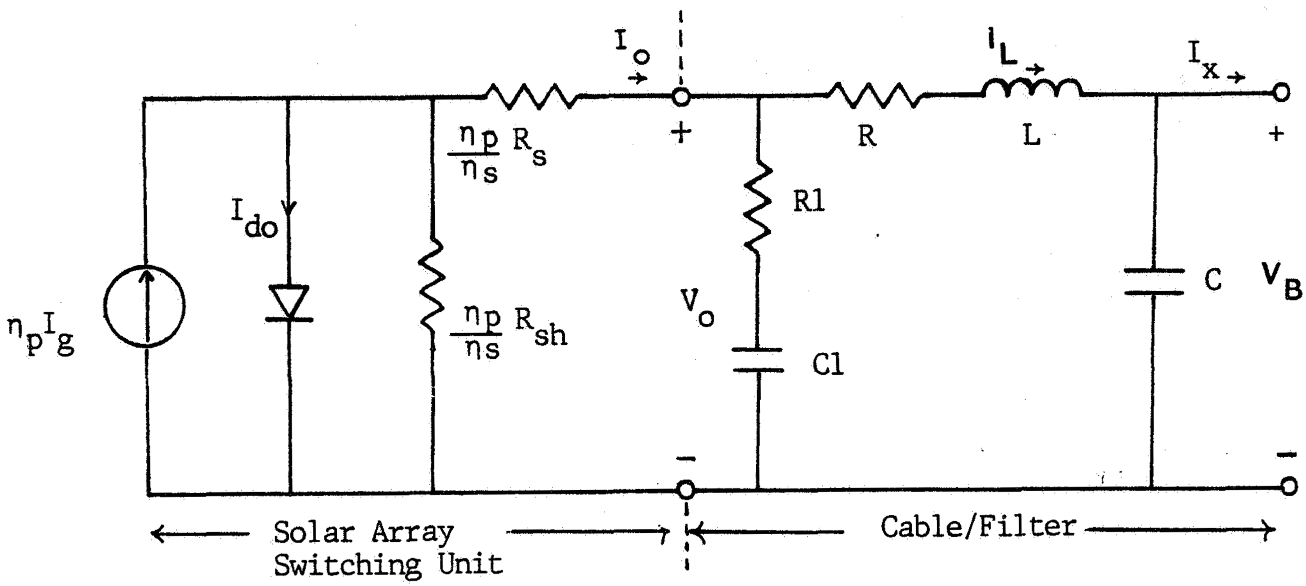
VB*	variable	Bus voltage	volts
VO	variable	Solar array output voltage	volts
VC1*	variable	Filter capacitor voltage	volts
IS	variable	Solar array output current	amps
IL*	variable	Filter inductor current	amps
NPP	variable	No. of parallel arrays on bus	

* state variable

OUTPUT

Physical Quantity Name		Description	units
VB*	variable	Bus voltage	volts
VO1	varialbe	Output voltage to upper array	volts
VO2	variable	Output voltage of lower array	volts
IL1*	variable	Upper array output current	amps
I2	variable	Lower array output current	amps

* state variable



Equations:

$$I_o = \eta_p \left[I_g - I_{do} \left| \mathrm{EXP}\; K_o \cdot \left(\frac{V_o}{\eta_s} + I_o \cdot \frac{R_s}{\eta_p} \right) \right| - \left(\frac{V_o}{\eta_s} + I \cdot \frac{R_s}{\eta_p} \right) \cdot \frac{1}{R_{sh}} \right]$$

$$V_L = V_o - R\, I_L - V_B$$

$$C1 \frac{dV_{C1}}{dt} = I_o - I_L$$

$$L \frac{dI_L}{dt} = V_L$$

$$C \frac{dV_B}{dt} = I_L - I_X$$

Circuit Model of SASU and Cable/Filter [AS]

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```
MACRO FILE NAME = MACROS

DEFINE MACRO = AS

*****************************************
**   SOLAR ARRAY SWITCHING UNIT MODEL   ***
*****************************************

*=======> VB

*========< IX


***


MACRO INPUTS = IX         IH         DL
      R       L       C        R1         C1
     NP      NS      NNP
* IX = LOAD CURRENT
* IH = SHUNT CURRENT
* DL = DELAY TIME BETWEEN SWITCHINGS
* R,L,C,  : CABLE IMPEDANCE
* R1,C1,  : FILTER
* NP = NO. OF PARALLEL ARRAYS
* NS = NO. OF SERIES CELL NO.
* NNP = NO. OF PARALLEL ARRAYS SWITCHED AT A TIME


MACRO OUTPUTS = VO      IL       VB      NPP
                VC1      IO
* VO = SOLAR ARRAY OUT VOLTAGE
* VB = BUS VOLTAGE
* NPP = NO. OF PARALLEL ARRAYS
* IO = SOLAR ARRAY OUTPUT CURRENT

MACRO CODE
MACRO STOP SORT


*** SOLAR CELL PARAMETERS ****
*
* RS = INTERNAL SERIES RESISTANCE
* RSH= INTERNAL SHUNT  RESISTANCE
* XIO= REVERSE SATURATION CURRENT
* TE = TEMPERATURE
* Q  = ELECTRON CHARGE
* XK = BOLTZMANN CONSTANT
* XIG= SHORT CIRCUIT CURRENT
* VOC= OPEN  CIRCUIT VOLTAGE
      RS=.42
      RSH=250.
      XIG=.14115
      XIO=4.1869E-11
      A=.969
```

```
      TE=301.
      Q=1.602E-19
      XK=1.381E-23
      VOC=.5512
*     XKO=Q/(XK*A*TE)
      XKO=37.8
*****************************************************************
* SOLAR ARRAY SWITCHING LOGIC                                   *
*****************************************************************
      IF (TIME.GT.0.) GOTO +++10
        NPPAS-- = NP AS--
        FTIME = 0.
+++10 CONTINUE

      IF ( IH AS-- .GE.  5.  .AND. NPPAS-- .GT.   64 ) GOTO +++20
      IF ( IH AS-- .LT.  2.  .AND. NPPAS-- .LT.  324 ) GOTO +++30
      GOTO +++40

+++20   IF ( TIME .LT. FTIME+DL AS-- ) GOTO +++40
        NPPAS-- = NPPAS-- - NNPAS--
        FTIME = TIME
        GOTO +++40
+++30   IF ( TIME .LT. FTIME+DL AS-- ) GOTO +++40
        NPPAS-- = NPPAS-- + NNPAS--
        FTIME = TIME
        GOTO +++40
+++40 CONTINUE

*   ILLUMINATION CHANGE

      LL AS-- = 1.
*
      XIG = XIG * LL AS--
      C1 = ( 1.  + RS/RSH )
      C2= NPPAS-- / ( NS AS-- * RSH )
      C3= -NPPAS-- * XIG
      A1= XKO / NS AS--
      A2= XKO * RS / NPPAS--
      IF ( TIME .NE. 0. ) GOTO +++50
*
* INITIAL GUESS
      VO AS--=VB AS--
************************************
***   NEWTON ITERATION   ***************
************************************

+++50 CONTINUE
      VOP=VO AS--
* I - V EQUATION
* CAPACITOR ADDED
      IF ( TIME.NE.0. ) GOTO +++60
        IO AS-- = 30.5

+++60 FV = C1 * IO AS-- + C2 * VO AS-- + C3 + NPPAS-- * XIO *
     &      DEXP ( A1 * VO AS-- + A2 * IO AS-- )
      DFV = C2 + A1 * NPPAS-- * XIO *
     &      DEXP ( A1 * VO AS-- + A2 * IO AS-- )
      VO AS-- = VO AS-- - FV / DFV
      ZZ = ( VO AS-- - VOP ) / VO AS--
```

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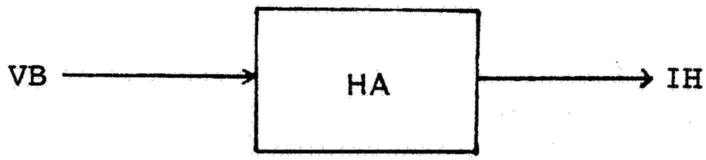
```
      IF ( DABS ( ZZ ) .LE. 1.E-4 ) GOTO +++70
      GO TO +++50
***********************************
+++70    VL = VO AS-- - IL AS--*R  AS-- - VB AS--
MACRO DERIVATIVES, VC1AS-- = (IO AS-- - IL AS--)/C1 AS--
MACRO DERIVATIVES, IL AS--= VL / L  AS--
MACRO DERIVATIVES, VB AS--= (IL AS-- - IX AS--)/C  AS--
      IO AS-- = (VO AS-- - VC1AS--) / R1 AS-- + IL AS--
      IF (VO AS-- .LE. 0.) VO AS-- = 0.
      IF (IO AS-- .LE. 0.) IO AS-- = 0.
  MACRO RESUME SORT
END OF MACRO
*********************************************************
MODEL DESCRIPTION
LOCATION = 22, AS
END OF MODEL
PRINT
```

HA

FULL SHUNT REGULATOR (TYPE 1) [HA]



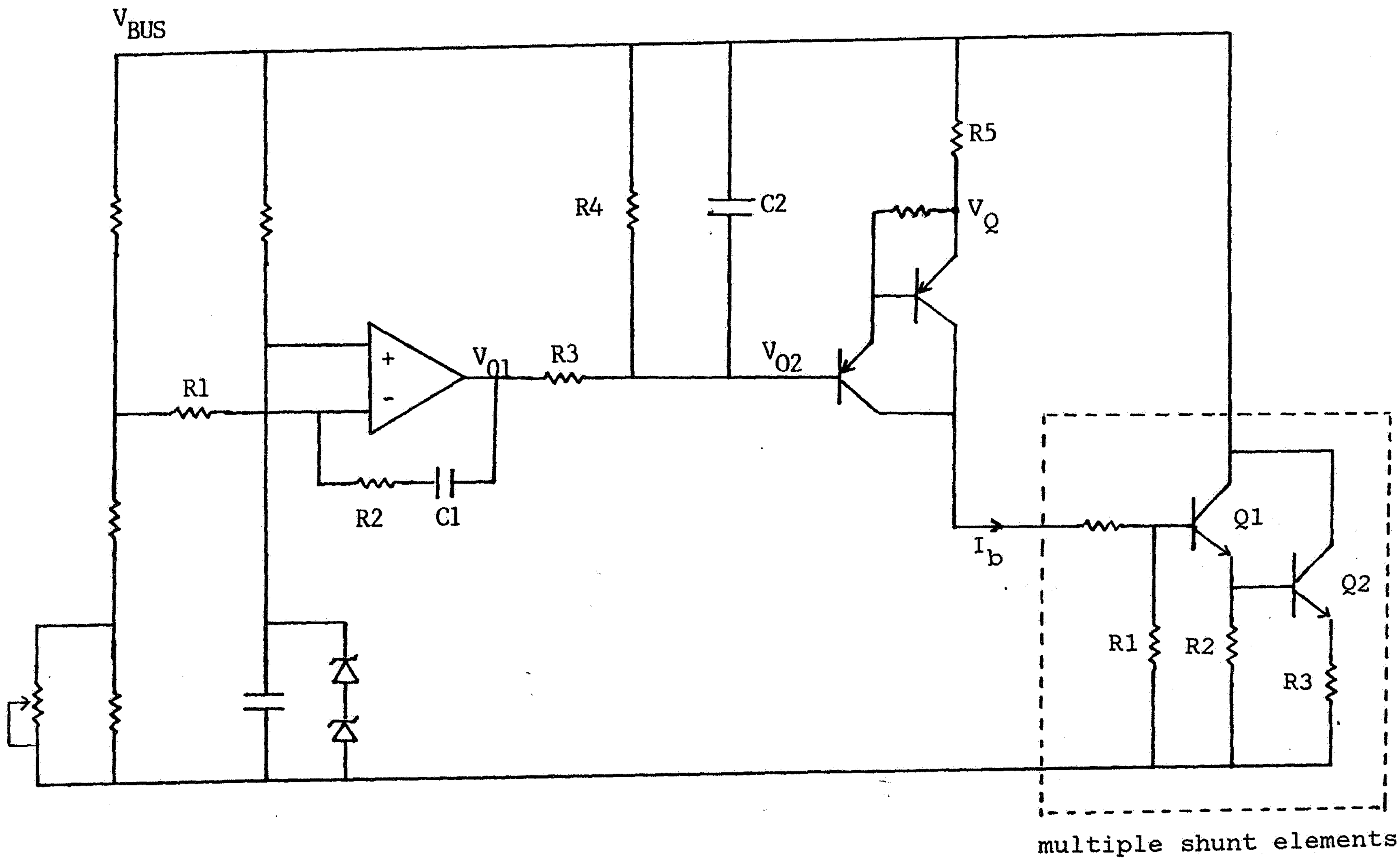
INPUT

Physical Quantity Name		Description	Units
VB	variable	input bus voltage	Volts
VR	parameter	reference voltage	Volts
K1	parameter	bus voltage divider ratio	Volts
A1,Z0,P0	parameters	As block parameters (See figure)	
L1	parameter	OP-Amp saturation voltage	Volts
Z1,P1	parameters	G1 block parameters (See figure)	
A2,Z2,P2	parameters	G2 block parameters (See figure)	
VF	parameter	junction voltage drop of darlington circuit	Volts
K2	parameter	gain of control voltage to base current	
K3	parameter	No. of shunt elements	
L3	parameter	Ic vs V(be) characteristic	Volts
C1,C2	parameters	shunt transistor circuit coefficients	
IMA	parameter	maximum shunt current	Amps

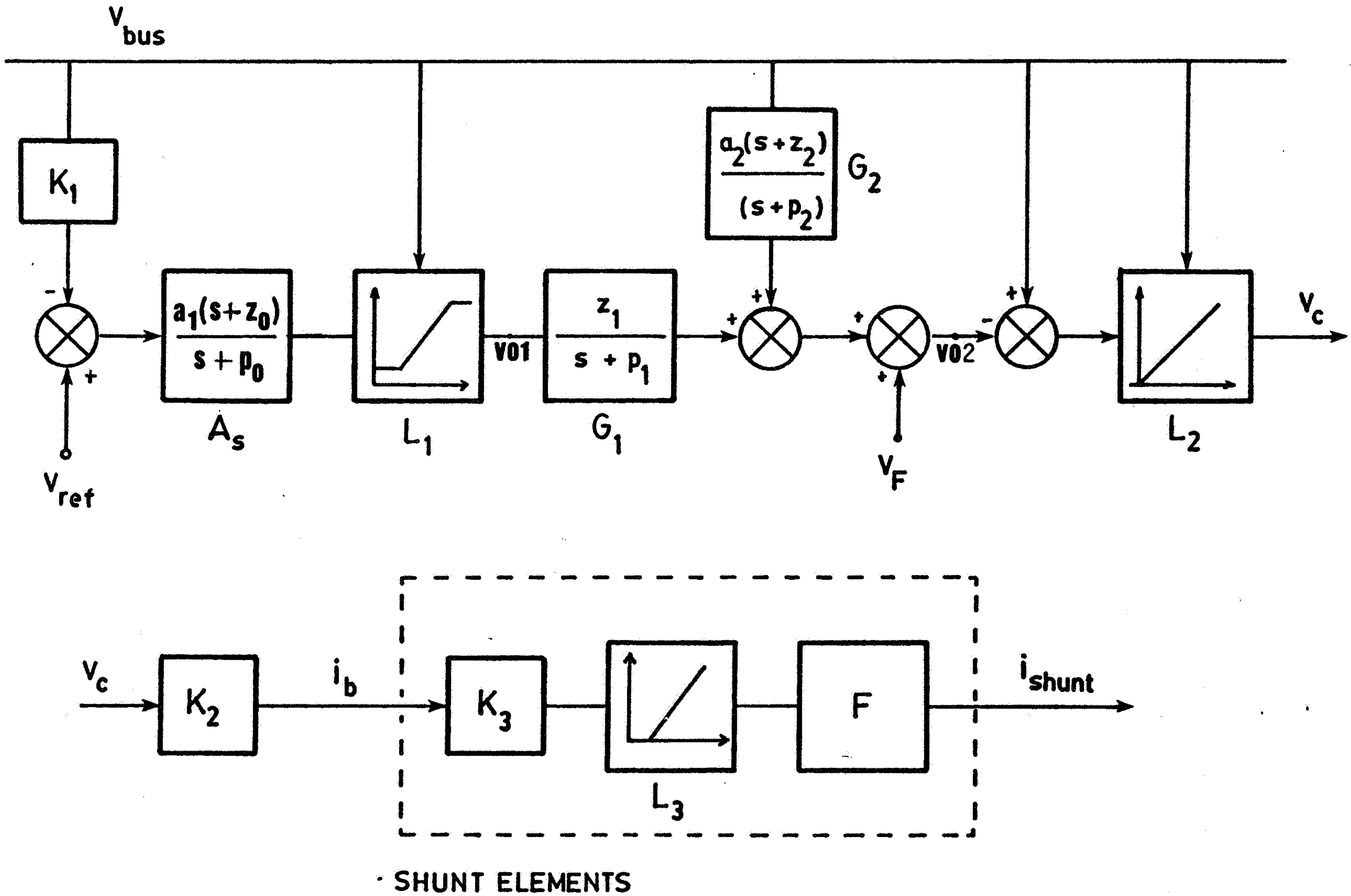
OUTPUT

Vo1	variable	output voltage of error amplifier	Volts
X1,X2,S2	variables *	dummy state variables	
IH	variable	shunt current	Amps

* state variable



Shunt Regulator Circuit Diagram (Type 1)



Type-1 Shunt Regulator Circuit Block Diagram

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```
MACRO FILE NAME = MACROS
*****************************************************
* SHUNT REGULATOR MODEL (TYPE 1) WITH               *
* TRANSFER FUNCTION                                 *
*****************************************************
DEFINE MACRO = HA
MACRO INPUTS = VB      VR      K1
      A1      ZO      PO      L1
      Z1      P1      A2      Z2      P2
      VF      K2      K3      L3      C1      C2
      IMA

* VB = BUS VOLTAGE
* VR = REFERENCE VOLTAGE
* K1 = BUS VOLTAGE DIVIDER RATIO
* IMA = SHUNT MAXIMUM CURRENT

MACRO OUTPUTS = VO1       X1
      IH     S2     X2
* VO1 = OUTPUT VOLTAGE OF ERROR AMPLIFIER
* X1, S2,X2 = DUMMY STATE VARIABLES
* IH = SHUNT CURRENT

*************************************
MACRO CODE
MACRO STOP SORT
*---------------------------------------------------------
*
* THIS SECTION SIMULATES THE SHUNT ERROR AMPLIFIER
* REFERENCE VOLTAGE IS VR HA--
*
* << AS BLOCK >>
* ERROR AMPLIFIER MODEL

      GAI = A1 HA--
      S1 = K1 HA-- * VB HA--   - VR HA--
      S2 = GAI * S1 + X1 HA--
MACRO DERIVATIVE, X1 HA-- = GAI * S1 * ZO HA-- - S2 * PO HA--
      DD = S2 + VR HA--

* << L1 BLOCK >>
* OP AMP OUTPUT VOLTAGE IS LIMITED TO A VALUE BETWEEN L1 AND
* (VB - L1)
      BB = VB HA-- - L1 HA--
      CC = L1 HA--
      IF(DD .LT. CC ) DD = CC
      IF(DD .GT. BB ) DD = BB
      VO1HA-- = DD

* << G1 BLOCK >>
* MODEL OF NETWORK AT THE OUTPUT OF ERROR AMPLIFIER

MACRO DERIVATIVE, S2 HA-- = Z1 HA-- * VO1HA-- - P1 HA-- * S2 HA--
      VV1 =  S2 HA--

* << G2 BLOCK >>
      GAI = A2 HA--
      S3 = VB HA--
      S4 = GAI * S3 + X2 HA--
MACRO DERIVATIVE, X2 HA-- = GAI * S3 * Z2 HA-- - S4 * P2 HA--
```

```
      VV2 =   S4
*
*
      VOC = VV1 + VV2
*
* MODEL OF TRANSISTOR DRIVER CIRCUIT
      VQ = VB HA-- - (VOC + VF HA--)
* << L2 BLOCK >>
      IF (VQ.LT.0.) VQ = 0.
* MODEL OF SHUNT ELEMENTS
* << K2, K3 BLOCKS >>
      FIB = VQ * K2 HA-- * K3 HA--
* << L3 BLOCK >>
      IF ( FIB .LT. L3 HA--) FIB = 0.
* << F BLOCK >>
      IH HA-- = C1 HA-- * FIB + C2 HA--
* LIMITING THE SHUNT CURRENT
      IF ( IH HA-- .LE. 0.0 ) IH HA-- = 0.0
      IF ( IH HA-- .GT. IMAHA-- ) IH HA-- = IMAHA--
*      IH HA--  ===> ISHUNT
MACRO RESUME SORT
END OF MACRO
***********************************************************
MODEL DESCRIPTION
LOCATION = 22,HA
END OF MODEL
```

FULL SHUNT REGULATOR (TYPE 1) [HB]

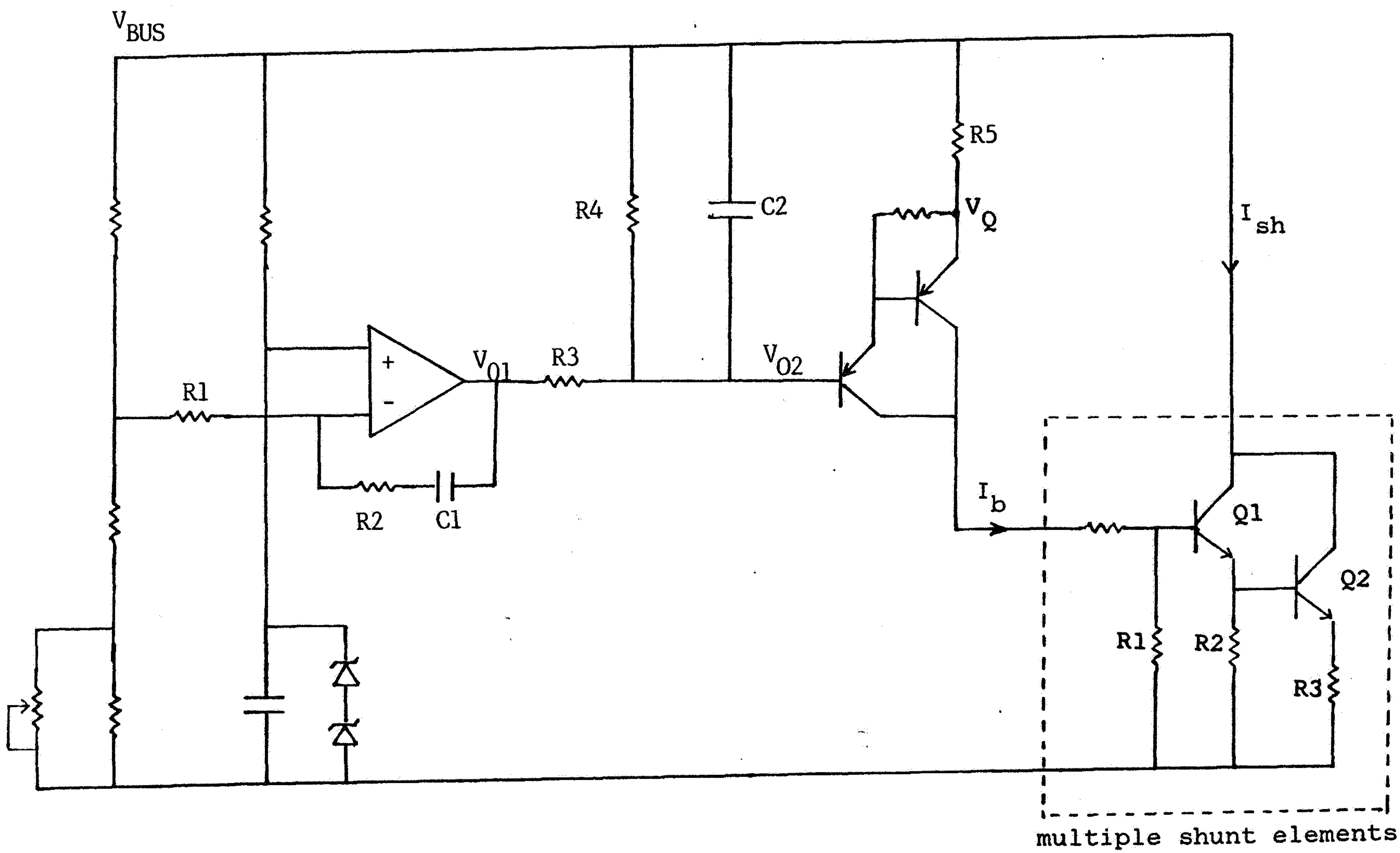
INPUT

Physical Quantity Name		Description	Units
VB	variable	input bus voltage	Volts
RR1	parameter	resistance R1	Ohms
RR2	parameter	OP-Amp feedback resistance	Ohms
CC1	parameter	OP-Amp feedback capacitance	Farads
RR3	parameter	OP-Amp output circuit elements	Ohms
RR4	parameter	(See figure)	Ohms
CC2	parameter		Farads
C1,C2	parameters	shunt transistor circuit coefficients	

OUTPUT

Vo1	variable	output voltage of error amplifier	Volts
Vc1	variable *	See figure	Volts
Vo2	variable	See figure	Volts
Vc2	variable *	OP-Amp output circuit capacitor voltage	Volts
IH	variable	shunt current	Amps

* state variable

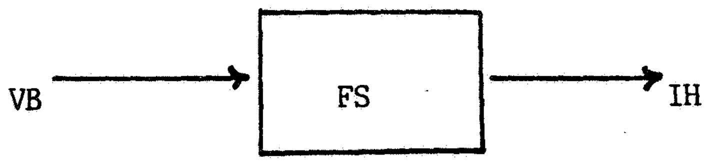


Shunt Regulator Circuit Diagram (Type 1)

```
MACRO FILE NAME = MACROS
**********************************************************
* SHUNT REGULATOR MODEL ( TYPE 1 ) WITH                  *
* STATE EQUATIONS                                        *
**********************************************************

DEFINE MACRO = HB

MACRO INPUTS = VB
      RR1     RR2     CC1
      RR3     RR4     CC2
      C1       C2

* VB = BUS VOLTAGE
* RR1 = SOURCE RESISTANCE
* RR2 = OP AMP FEEDBACK RESISTANCE
* CC1 = OP AMP FEEDBACK CAPACITANCE
* RR3,RR4,CC2 : OP AMP OUTPUT CIRCUIT
* C1, C2 : SHUNT TRANSISTOR CIRCUIT COEFFICIENTS

MACRO OUTPUTS = VO1      VC1
      VO2     VC2     IH

* VO1 = OUTPUT VOLTAGE OF ERROR AMPLIFIER
* VC1 = OP AMP FEEDBACK CAPACITOR VOLTAGE
* VO2 = OUTPUT VOLTAGE OF OP AMP OUTPUT CIRCUIT
* VC2 = OP AMP OUTPUT CIRCUIT CAPACITOR VOLTAGE
* IH = SHUNT CURRENT

**************************************
MACRO CODE
MACRO STOP SORT

*----------------------------------------------------------
*
* REFERENCE VOLTAGE IS 12.8 VOLTS
* SHUNT REF VTG IS 28.14
* SENSE VOLTAGE IS (VB SH/2.1984375)
*
* THIS SECTION SIMULATES THE SHUNT ERROR AMPLIFIER

      AA = RR2HB-- / RR1HB--
      BB = 1.  + AA
      DD = -AA * (VB HB--/2.1984375) + BB * 12.8 + VC1HB--
*
* OP AMP VOLTAGE IS LIMITED TO WITHIN 1.5 VOLTS OF
* SUPPLY VOLTAGES (VB SH AND GROUND)
*
      BB = VB HB-- - 1.5
      CC = 1.5
      IF(DD .LT. CC ) DD = CC
      IF(DD .GT. BB ) DD = BB
      VO1HB-- = DD
*
      EE = VO1HB-- - 12.8 - VC1HB--
MACRO DERIVATIVE,VC1HB-- = EE / (CC1HB-- * RR2HB--)

* MODEL OF CIRCUIT AT THE OUTPUT OF CONTROL AMPLIFIER
*
      AA = VB HB-- - VC2HB--
```

```
      VO2HB-- = AA
      BB = CC2HB-- * RR3HB--
      FIC2 = AA * ( RR3HB-- + RR4HB-- ) / ( BB * RR4HB--)
     &        -  VO1HB-- / BB - VB HB-- /(CC2HB--*RR4HB--)
MACRO DERIVATIVE, VC2HB-- = FIC2
*
* MODEL OF SHUNT TRANSISTOR DRIVER CIRCUIT
*
      VOC = VO2HB--
      VQ = VB HB-- - (VOC + 1.4)
      IF ( VQ .LT. 0. ) VQ = 0.
      FIB = VQ / ( 66.5 * 12.  )
      IF ( FIB .LT. 1.4E-3 ) FIB = 0.
*
* MODEL OF SHUNT ELEMENTS
*
      IH HB-- = C1 HB-- * FIB + C2 HB--
      IF (IH HB--.LE.0.0) IH HB-- = 0.0
      IF (IH HB--.GT. 40.) IH HB-- = 40.
*      IH HB --  ===> ISHUNT

MACRO RESUME SORT
END OF MACRO
***********************************************************
MODEL DESCRIPTION
LOCATION = 22,HB
END OF MODEL
```

FS

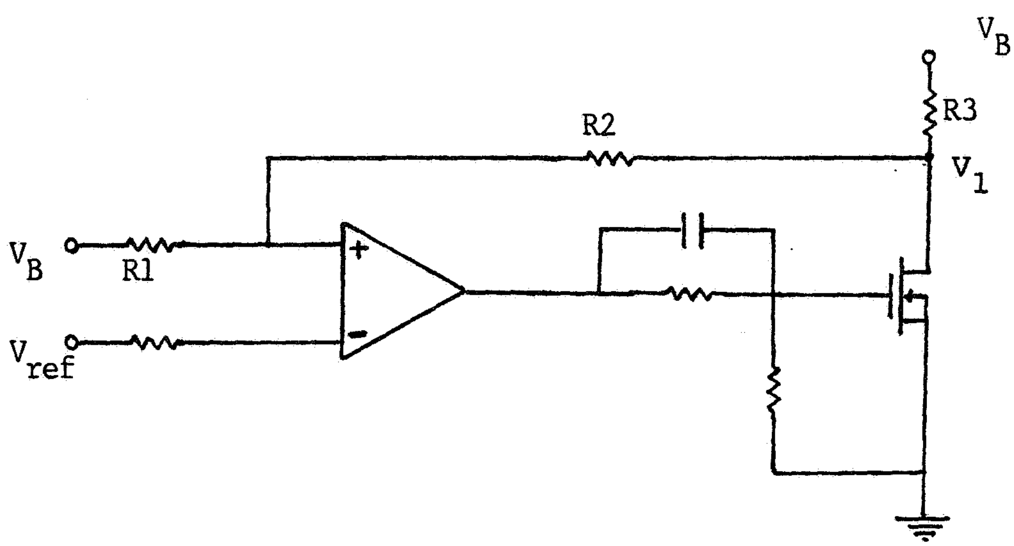


INPUT

Physical Quantity Name		Description	units
VB	variable	Bus voltage	volts
VR	parameter	Reference voltage	volts
R1	parameter	Refer to Figure	ohms
R2	parameter		ohms
R3	parameter		ohms
GM	parameter	Forward transconductance of FET	

OUTPUT

IH		Shunt current	amps

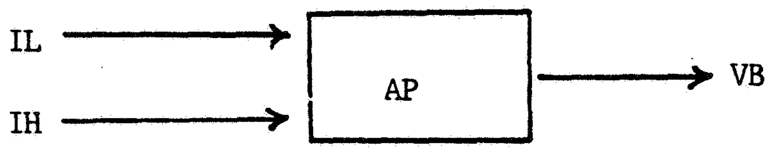


Shunt regulator circuit diagram (Type 2)

```
MACRO FILE NAME = MACROS
************************************************************
* FULL SHUNT REGULATOR MODEL (TYPE 2)                      *
************************************************************

DEFINE MACRO = FS

MACRO INPUTS = VB      VR      VSA      R1      R2      R3
               GM      VTH     ILM
MACRO OUTPUTS = IH      VGS
*************************************
MACRO CODE
MACRO STOP SORT
*-------------------------------------------------------------
* VB = BUS VOLTAGE
* VR = SHUNT REFERENCE VTG
* VSA = OPERATIONAL AMPLIFIER SATURATION VOLTAGE
* GM = TRANSCONDUCTANCE OF MOSFET
* VTH = THRESHOLD VOLTAGE, V(GST), OF POWER MOSFET
* ILM = HIGH LIMIT OF SHUNT CURRENT
* IH = SHUNT CURRENT
* VGS = GATE-SOURSE VOLTAGE OF MOSFET
*-------------------------------------------------------------

       VD = VB FS-- - VR FS--
       GAIN = ( R1 FS-- + R2 FS-- ) / ( R1 FS-- * R3 FS-- )
       VGSFS-- = GAIN * VD / GM FS-- + VTHFS--

* LIMITING THE OP-AMP OUTPUT VOLTAGE
       IF ( VB FS-- .LE. VR FS-- ) VGSFS-- = 0.
       IF ( VGSFS-- .GT. VSAFS-- ) VGSFS-- = VSAFS--

* MOSFET TRANSFER CHARACTERISTIC
       IF ( VGSFS-- .LT. VTHFS-- ) IH FS-- = 0.
       IH FS-- = GM FS-- * ( VGSFS-- - VTHFS-- )

* LIMITING THE SHUNT CURRENT
       IF ( IH FS-- .GT. ILMFS-- ) IH FS-- = ILMFS--
       IF ( IH FS-- .LE.  0. ) IH FS-- =  0.
*
MACRO RESUME SORT
END OF MACRO
***************************************************************
MODEL DESCRIPTION
LOCATION = 22,FS
END OF MODEL
```

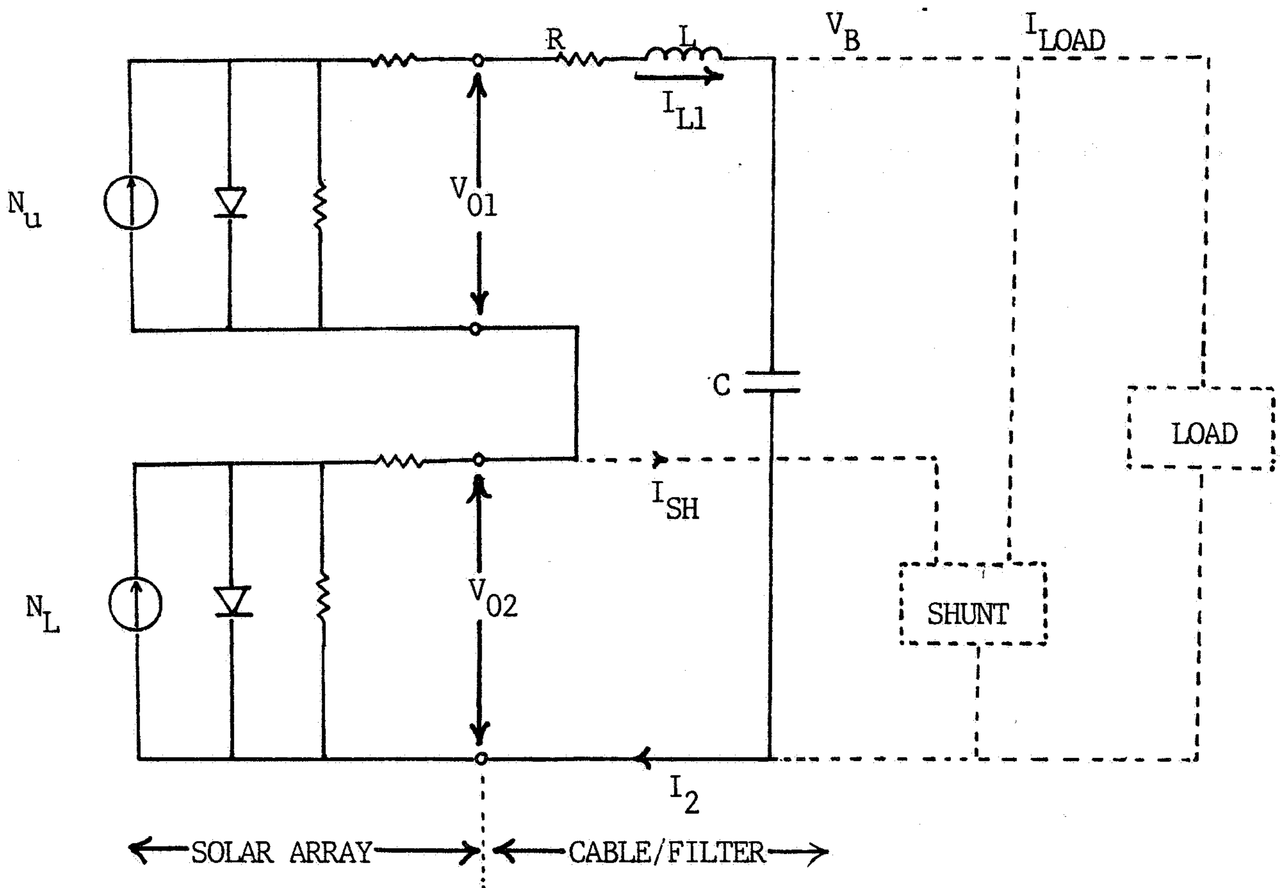
SOLAR ARRAY/PARTIAL SHUNT [AP]

AP



INPUT

Physical Quantity Name		Description	units
IL	variable	Load current	amps
IH	variable	Shunt current	amps
ILM	variable	Max. solor array output current	amps
V1H	variable	Max. output voltage of upper array	volts
V1L	variable	Low limit of output voltage of upper array	volts
V2H	variable	Max. output boltabe of lower array	volts
V2L	variable	Low limit of output voltage of lower array	volts
R	parameter	Filter resistance	ohms
L	parameter	Filter inductacne	henries
C	parameter	Filter capacitance	farads
NP	parameter	No. of parallel solar arrays	
NS1	parameter	No. of upper serial cells	
NS2	parameter	No, of lower serial cells	



STATE EQUATIONS

$$I_2 = I_{L1} + I_{SH}$$

$$V_L = V_{01} + V_{02} - R \cdot I_{L1} - V_B$$

$$L \frac{dI_L}{dt} = V_L$$

$$C \frac{dV_C}{dt} = I_{L1} - I_{LOAD}$$

Circuit Model of Solar Array/Partial Shunt [AP]

ORIGINAL PAGE IS
OF POOR QUALITY

```
MACRO FILE NAME = MACROS
DEFINE MACRO = AP
*********************************************
**   SOLAR ARRAY MODEL FOR PARTIAL SHUNT ******
*********************************************

*========> VR

*========< IX

***

MACRO INPUTS = IL     IH     LL     ILM
   R      L      C      NP
   NS1    NS2    V1H    V1L    V2H    V2L
* IL = LOAD CURRENT
* IH = SHUNT CURRENT
* LL = ILLUMINATION LEVEL
* ILM = MAXIMUM CURRENT OF SOLAR ARRAYS
* R,L,C,  : CABLE IMPEDANCE
* NP = NO. OF PAPALLEL ARRAYS
* NS1 = NO. OF UPPER SERIAL CELLS
* NS2 = NO. OF LOWER SERIAL CELLS
* V1H = MAXIMUM OUTPUT VOLTAGE OF UPPER SOLAR ARRAY
* V1L = LOW LIMIT OF OUTPUT VOLTAGE OF UPPER SOLAR ARRAY
* V2H = MAXIMUM OUTPUT VOLTAGE OF LOWER SOLAR ARRAY
* V2L = LOW LIMIT OF OUTPUT VOLTAGE OF LOWER SOLAR ARRAY

MACRO OUTPUTS = VO1     VO2     IL1     I2
                VR

* VO1 = OUTPUT VOLTAGE OF UPPER SOLAR ARRAY
* VO2 = OUTPUT VOLTAGE OF LOWER SOLAR ARRAY
* IL1 = UPPER SOLAR ARRAY OUTPUT CURRENT
* I2  = LOWER SOLAR ARRAY OUTPUT CURRENT
* VB = BUS VOLTAGE

MACRO CODE
MACRO STOP SORT

*** SOLAR CELL PAPAMETERS ****
*
* RS = INTERNAL SERIES RESISTANCE
* RSH= INTERNAL SHUNT  RESISTANCE
* XIO= REVERSE SATURATION CURRENT
* TN = NOMINAL TEMPERATURE
* Q  = ELECTRON CHARGE
* XK = BOLTZMANN CONSTANT
* XIG= LIGHT-GENERATED CURRENT
* VOC= OPEN  CIRCUIT VOLTAGE
*
      RS = .42
      RSH = 250.
      XIG = .14115
      XIO = 4.1869E-11
      A = .769
      TN = 301.
      Q = 1.602E-19
      XK = 1.381E-23
      VOC = .5512
```

```
*      XKO = Q / ( XK * A * TN )
       XKO=37.8
*
* EFFECT OF ILLUMINATION CHANGE
       XIG = XIO * LL AP--
*
       C1 = ( 1. + RS / RSH )
       C21 = NP AP-- / ( NS1AP-- * RSH )
       C22 = NP AP-- / ( NS2AP-- * RSH )
       C3 = -NP AP-- * XIG
       A11 = XKO / NS1AP--
       A12 = XKO / NS2AP--
       A2 = XKO * RS / NP AP--
       IF ( TIME .NE. O. ) GOTO +++5
*
* INITIAL GUESS FOR SOLAR ARRAY OUTPUT VOLTAGE
       VO1AP-- = ( NS1AP-- / ( NS1AP-- + NS2AP-- ) ) *  VB AP--
       VO2AP-- = VB AP-- - VO1AP--

*********************************************
**     LIMITING OF SOLAR ARRAY OUTPUT CURRENT BY   *
**     MAXIMUM SOLAR ARRAY CURRENT                 *
**     ILX = LIMITED SOLAR ARRAY OUTPUT CURRENT    *
*********************************************
+++5   CONTINUE
       FILX = IL1AP--
       IF ( FILX .GT. ILMAP-- )  FILX = ILMAP--
       IF ( FILX .LT. O.  )  FILX =  O.

*********************************************
***    NEWTON ITERATION FOR UPPER ARRAYS   **********
*********************************************

+++10  CONTINUE
       VO1P = VO1AP--
       FV = C1 * FILX + C21 * VO1AP-- + C3 + NP AP--
     &      * XIO * DEXP ( A11 * VO1AP-- + A2 * FILX )
       DFV = C21 + A11 * NP AP-- * XIO * DEXP ( A11 * VO1AP--
     &      + A2 * FILX )
       VO1AP-- = VO1AP-- - FV / DFV
       ZZ1 = ( VO1AP-- - VO1P ) / VO1AP--
       IF ( DABS ( ZZ1 ) .LE. 1.E-4 ) GOTO +++20
       GO TO +++10

* LIMIT THE UPPER SOLAR ARRAY OUTPUT VOLTAGE
+++20  IF ( VO1AP-- .GT. V1HAP-- ) VO1AP-- = V1HAP--
       IF ( VO1AP-- .LT. V1LAP-- ) VO1AP-- = V1LAP--

       I2 AP-- = IL1AP-- + IH AP--
       IF ( I2 AP-- .GT. ILMAP-- ) I2 AP-- = ILMAP--
       IF ( I2 AP-- .LT. O.   ) I2 AP-- = O.


*********************************************
***    NEWTON ITERATION FOR LOWER ARRAYS   **********
*********************************************

+++30  CONTINUE
       VO2P = VO2AP--
```

```
      FV = C1 * I2 AP-- + C22 * VO2AP-- + C3 + NP AP--
     &       * XIO * DEXP ( A12 * VO2AP-- + A2 * I2 AP-- )
      DFV = C22 + A12 * NP AP-- * XIO * DEXP ( A12 * VO2AP--
     &     + A2 * I2 AP--)
      VO2AP-- = VO2AP-- - FV / DFV
      ZZ2 = ( VO2AP-- - VO2P ) / VO2AP--
      IF ( DABS ( ZZ2 ) .LE. 1.E-4 ) GOTO +++40
      GO TO +++30

*  LIMIT THE LOWER SOLAR ARRAY OUTPUT VOLTAGE
+++40 IF ( VO2AP-- .GT. V2HAP-- ) VO2AP-- = V2HAP--
      IF ( VO2AP-- .LT. V2LAP-- ) VO2AP-- = V2LAP--
      VL = VO1AP-- + VO2AP-- - IL1AP-- * R   AP-- - VB AP--

MACRO DERIVATIVES, VB AP-- = ( IL1AP-- - IL AP-- ) / C  AP--
MACRO DERIVATIVES, IL1AP-- = VL  / L  AP--
MACRO RESUME SORT
END OF MACRO
*****************************************************************
MODEL DESCRIPTION
LOCATION = 22, AP
END OF MODEL
PRINT
```

III. Example of Sysytem-Level Modeling and Simulation

1. Introduction

In this section, one example of a spacecraft power system is modeled and simulated to show users how to apply the macro component models. In addition, the general procedures of system-level modeling and simulation are briefly explained for the novice.

The EASY5 commands used in this example are the commands used in an interactive mode.

2. System Model Generation and Simulation

Step 1. Draw a Block Diagram of the System

An engineering block diagram of the system to be modeled may be drawn to identify the components and their interconnections of the system. The block diagram of a solar array switching system with a buck converter is shown Fig.1.

Step 2. Write Model Description Statements

Once required component models and their interconnections are identified, appropriate macro components and/or standard components are collected from the macro component model library and the EASY5 standard component library.

As shown in Fig.2, the EASY5 system model[NASA2.MOD] can be described with simple mnemonic statements.

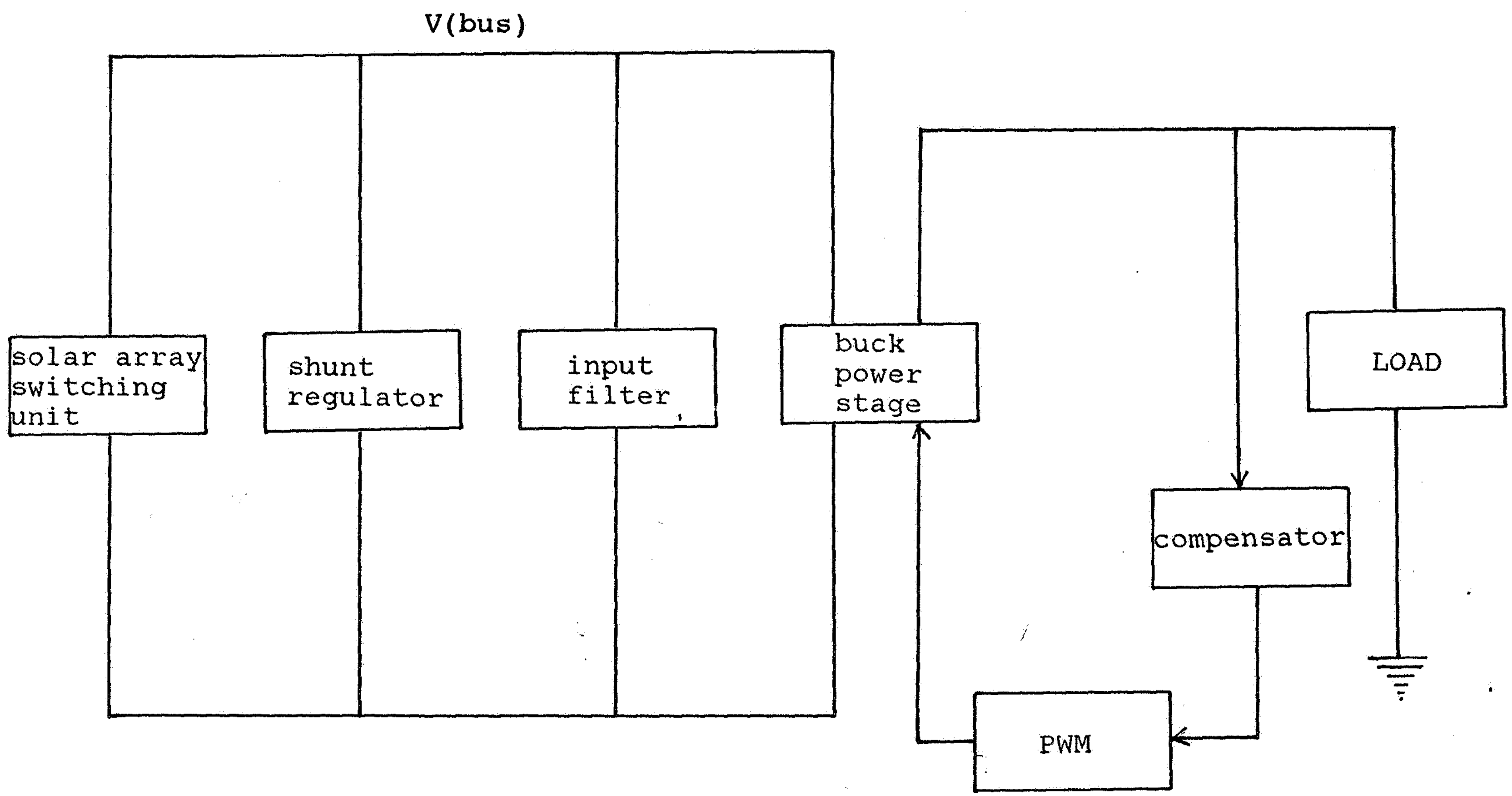


Fig.1 Engineering block diagram of solar array switching system

The LOCATION command phrase indicates the start of a new component in the system model. This command must be followed by a numeric value phrase that specifies the location of the component on the model schematic. In the example of Fig.2, the location number of the solar array switching unit [AS] is 1 and the shunt regulator [FS] is 23, etc. The location number phrase is followed by the name of the component at that location. A LOCATION statement must be given only once for each statement. This means that once a LOCATION statement is started for a component, the complete description of that component must be given. The location of each component model should be arranged so that the interconnections among the components can be clearly visualized in the EASY5 Model Generation program generated schematic diagram.

Each component model is described with an 'INPUTS' phrase. The input component name must be supplemented by the name of the particular output quantity that is to provide the input. As an example, consider the load component [LO] in Fig.2. Since the output voltage (V2) of the buck-converter power stage [BC] is to be the input voltage (V1) to the load component, the following statement indicates to the program that the output of [BC], V2, is to be used as the input to the load component, [LO]:

```
LOCATION=10, LO, INPUTS=BC(V2=V1)
```

```
MACRO FILE NAME = MACROS

******************************************************
*  SOLAR ARRAY SWITCHING UNIT SYSTEM WITH A BUCK     *
*  CONVERTER LOAD                                    *
******************************************************
*  REVISED ON 3/12/85

LIST MACRO COMPONENTS = AS,FS,FI,BC,LO,ZP,WM
MODEL DESCRIPTION
LOCATION= 1,AS,  INPUTS=FS(IH=IH), MC(S,2=IX)
LOCATION=23,FS,  INPUTS=AS(VB=VB)
LOCATION= 4,FI,  INPUTS=AS(VB=V1), BC(I1=I2)
LOCATION= 6,BC,  INPUTS=FI(V2=V1), LO(IL=I2), WM(IQ=IQ)
LOCATION=10,LO,  INPUTS=BC(V2=V1)
LOCATION=29,ZP,  INPUTS=BC(V2=VO)
LOCATION=37,WM,  INPUTS=ZP(VE=VE)
LOCATION=41,MC,  INPUTS=FS(IH=S,1),FI(I1=S,3)
END OF MODEL
PRINT
```

Fig.2 System Model Generation [NASA2.MOD]

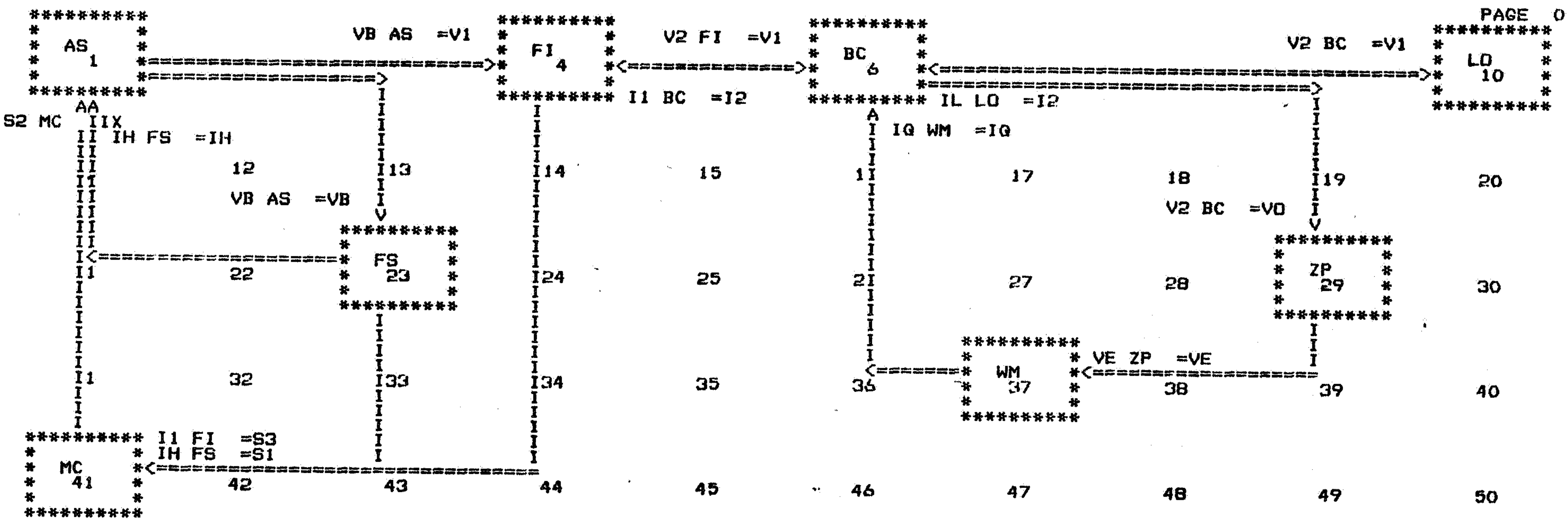


Fig.3 Schematic diagram of [NASA2.MOD]

The input and output connections between the component models are made by using the port variables shown with the right and left side arrow of the box in the input-output list of each component model.

In model connection an 'implicit loop' should always be avoided. The 'implicit loop' is formed whenever the blocks are connected with all non-state variables and the connection comprises a loop. If a system consists of an implicit loop, the Model Generation program will not generate a model, instead, it will give the error message showing where in the system an implicit loop occurs.

Step 3. Run the EASY5 Model Generation Program

Whenever a new macro component model is developed, the macro model should be compiled and linked by the EASY5 model generation program using the command as follows:

```
EASY5 AS AS.MOD
```

Once the macro component model is compiled and linked, the executable file for the model is stored in the user's permanent file 'MACROS.DAT' for subsequent use. After all the component models are compiled and linked, the system model [NASA2.MOD] should be also compiled and linked by the EASY5 Model Generation program. With the file 'NASA2.MOD', the EASY5 Model Generation program will make all the connections between the component blocks according to the Model Description data. The command for the EASY5 Model Generation program is as follows:

```
EASY5 NASA2 NASA2.MOD
```

With the above command, the EASY5 program creates a new file, 'NASA2.MGL', which contains a FORTRAN listing of component model programs (Fig.4), a schematic diagram (Fig.3) and input data requirements list (Fig.5).

Step 4. Write and Run Analysis Program

In order to conduct a specific analysis, parameter values, initial conditions and any other necessary data in the input data requirements list must be supplied. Integration controls, output data formats and variable names for plot are specified as needed. The analysis program of the system is given in Fig.6.

The command for running the analysis program is

```
EASY5 NASA2 * NASA2.ANC
```

With this command, the EASY5 creates new files such as NASA2.APL, NASA2.PPT and NASA2.RPD.

Step 5. Analyze the results

```
               LIST OF MACROS      MACRO COMPONENTS

                    COMPONENT NO.   5    NAME = AS

         INPUTS               OUTPUTS
NAME   PORT   DIM        NAME   PORT   DIM
 IX                       VO
 IH                       NPP
 DL                       IO
 R                        VC1          STATE
 L                        IL           STATE
 C                        VB           STATE
 R1
 CJ
 NP
 NS
 NNP

                    MACRO CODE
MACRO  STOP SORT
       RS=.42
       RSH=250.
       XIG=.14115
       XIO=4.1869E-11
       A=.967
       TE=301.
       Q=1.602E-19
       XK=1.381E-23
       VOC=.5512
       XKO=39.8
       IF (TIME.GT.0.) GOTO +++10
         NPPAS-- = NP AS--
         FTIME = 0.
+++10  CONTINUE
       IF ( IH AS-- .GE. 5. .AND. NPPAS-- .GT.  64 ) GOTO +++20
       IF ( IH AS-- .LT. 2. .AND. NPPAS-- .LT. 324 ) GOTO +++30
       GOTO +++40
+++20    IF ( TIME .LT. FTIME+DL AS-- ) GOTO +++40
         NPPAS-- = NPPAS-- - NNPAS--
         FTIME = TIME
         GOTO +++40
+++30    IF ( TIME .LT. FTIME+DL AS-- ) GOTO +++40
         NPPAS-- = NPPAS-- + NNPAS--
         WRITE (6,*) IH AS--
         FTIME = TIME
         GOTO +++40
+++40  CONTINUE
       LL AS-- = 1.
       XIG = XIG * LL AS--
       C1 = ( 1. + RS/RSH )
       C2= NPPAS-- / ( NS AS-- * RSH )
       C3= -NPPAS-- * XIG
       A1= XKO / NS AS--
       A2= XKO * RS / NPPAS--
       IF ( TIME .NE. 0. ) GOTO +++50
       VO AS--= VB AS--
+++50  CONTINUE
       VOP=VO AS--
```

Fig.4 Part of FORTRAN listing of [AS]

INPUT DATA REQUIREMENTS LIST

PARAMETERS REQUIRED

COMPONENT	PARAMETER NAME (AND DIMENSION DATA FOR VECTOR AND MATRIX PARAMETERS)					
AS	NP AS L AS	DL AS C AS	NNPAS R1 AS	NS AS	R AS	C1 AS
FS	VR FS VSAFS	R1 FS ILMFS	R2 FS	R3 FS	GM FS	VTHFS
FI	R FI	L FI	C FI			
BC	RL BC	RC BC	L BC	C BC		
LO	RA LO	TC LO	RB LO	L LO	C LO	
ZP	WM ZP	WP ZP	WZ1ZP	WZ2ZP	K ZP	ER ZP
WM	TI WM VI WM	VP WM	VQ WM	ER WM	CICWM	SCMWM
MC	S4 MC	C1 MC	C2 MC	C3 MC	C4 MC	

STATES (INITIAL CONDITIONS AND ERROR CONTROLS REQUIRED)

COMPONENT	STATE NAME (AND DIMENSION DATA FOR VECTOR AND MATRIX STATES)		
AS	VC1AS	IL AS	VB AS
FI	I1 FI	V2 FI	
BC	I1 BC	VC BC	
LO	IL LO	VC LO	
ZP	X1 ZP	X2 ZP	VE ZP

Fig.5 Input data requirements list

```
TITLE=NASA(LARGE SIGNAL)
*****************************************************
*TITLE = SOLAR ARRAY SWITCHING SYSTEM WITH          *
*        SHUNT REGULATOR AND A BUCK CONVERTER LOAD *
*****************************************************
PARAMETER VALUES
R  AS = .001,  C  AS = 5E-5,    L  AS = 1E-6
C1 AS = 1.E-3;   R1 AS = 1.0
NP AS = 324,   NS AS = 58,   NNPAS =20, DL AS = .001
*************************
INITIAL CONDITIONS
VB AS = 28.155, IL AS = 29.477, VC1AS = 28.184
********
PARAMETER VALUES
VR FS = 28.14,  VSAFS = 15.
R1 FS = 12400, R2 FS = 2.2E6, R3 FS = 1.78419
GM FS = 4,      VTHFS = 3,     ILMFS = 45
********
C1 MC=1,C2 MC=1,C3 MC=1,C4 MC=0
*
INITIAL CONDITIONS
I1 FI = 27.985, V2 FI = 28.
PARAMETER VALUES
R  FI=0.05,  L  FI=3E-6,   C  FI=1000E-6

**BC (POWER STAGE)
INITIAL CONDITIONS
IL BC=9.47,VC BC=20
PARAMETER VALUES
L  BC=1E-4,C  BC=4E-4
RL BC=5E-2,RC BC=1E-1

**VTG LOOP COMPENSATER
K  ZP=.3, ER ZP=6
WM ZP=4E3
WZ1ZP=5E4,WZ2ZP=1.25E2
WP ZP=1E6

** PWM
TI WM=20E-6,VP WM=6,VQ WM=.5
ER WM=6,CICWM=0,SCMWM=0

** LOAD
RA LO=0.65,RB LO=.6,TC LO=100E-3
L  LO=1E-6,C  LO=1E-6
INITIAL CONDITIONS
X1 ZP=34400,X2 ZP=.73,VE ZP=.3
IL LO=10,VC LO=20

PRINTER PLOTS
ONLINE PLOTS
INT MODE=4
TMAX=3E-3, TINC=2E-7
PRATE= 100, OUTRATE=100
SIMULATE

XIC-X
PARAMETER VALUES
RA LO = 0.65, RB LO = .76, TC LO = 2E-3
DISPLAY1
V2 BC
INT MODE=4
DISPLAY5
VB AS
DISPLAY2 (OVERPLOT)
IH FS,IO AS,I1 FI
DISPLAY3,NPPAS
TMAX=6E-3,TINC=2E-7
PRATE=50,OUTRATE=100
SIMULATE
```

Fig.6 User's Parameter Values and Analysis Commands [NASA2.ANC]

The printed data of various variables and parameter values at a specified time interval are found in NASA2.APL(Fig.7). The plotting data for a line printer is in NASA2.PPT(Fig.8), and NASA2.RPD contains a plotting data for a graphics terminal. The simulation result shown in Fig.9 was drawn from the data in NASA2.RPD.

```
                        /*/*/*/   SIMULATION ANALYSIS   /*/*/*/

PRATE  =  100   OUTRATE  =  100   PRINT CONTROL =   3   INT MODE =   4   TINC =  0.20000E-06   TMAX =  0.30000E-02
PRATE2 =  100   OUTRATE2 =  100   PRINT2 =   3   PRINT2 FROM 0.10000E+37 TO 0.10000E+37   TINC2 =  0.20000E-06
                                   NASA(LARGE SIGNAL)

 CASE NO.   1                                                          12-MAR-86   21:16:19

    TIME = 0.0000E+00    ----------------------------------------------------    CASE NO.     1

                                         STATES

 1 VC1AS   =  28.184       2 IL AS   =  29.479       3 VB AS   =  28.155       4 I1 FI   =  27.985       5 V2 FI   =  28.000
 6 IL BC   =  9.4700       7 VC BC   =  20.000       8 IL LO   =  10.000       9 VC LO   =  20.000      10 X1 ZP   =  34400.
11 X2 ZP   = 0.73000      12 VE ZP   = 0.30000

                                         RATES

 1 VC1AS   =  1021.0       2 IL AS   = -.17525E+06   3 VB AS   = -20120.       4 I1 FI   = -.41475E+06   5 V2 FI   =  18515.
 6 IL BC   =  75795.       7 VC BC   = -1325.0       8 IL LO   = -53000.       9 VC LO   = -.20769E+08  10 X1 ZP   = -.63600E+08
11 X2 ZP   = -.77567E+06  12 VE ZP   = -.97460E+08

                                         VARIABLES

 1 VGSFS   =  3.3750       2 IH FS   =  1.5000       3 S2 MC   =  30.485       4 NPPAS   =  324.00       5 VD AS   =  28.009
 6 IS AS   =  29.304       7 X  WM   =  1.0000       8 VR WM   = 0.50000       9 IQ WM   =  1.0000      10 VC WM   =  5.7000
11 VS WM   = 0.99999      12 ILLBC   =  9.4700      13 IS BC   =  9.4700      14 V2 BC   =  19.947      15 I1 BC   =  9.4700
16 VL BC   =  7.5795      17 P  FI   =  783.58      18 IC FI   =  18.515      19 R  LO   = 0.65000

                                         PARAMETERS

 1 NP AS   =  324.00       2 DL AS   = 0.10000E-02   3 NNPAS   =  20.000       4 NS AS   =  58.000       5 R  AS   = 0.10000E-02
 6 C1 AS   = 0.10000E-02   7 L  AS   = 0.10000E-05   8 C  AS   = 0.50000E-04   9 R1 AS   =  1.0000      10 VR FS   =  28.140
```

Fig.7 Part of [NASA2.APL]

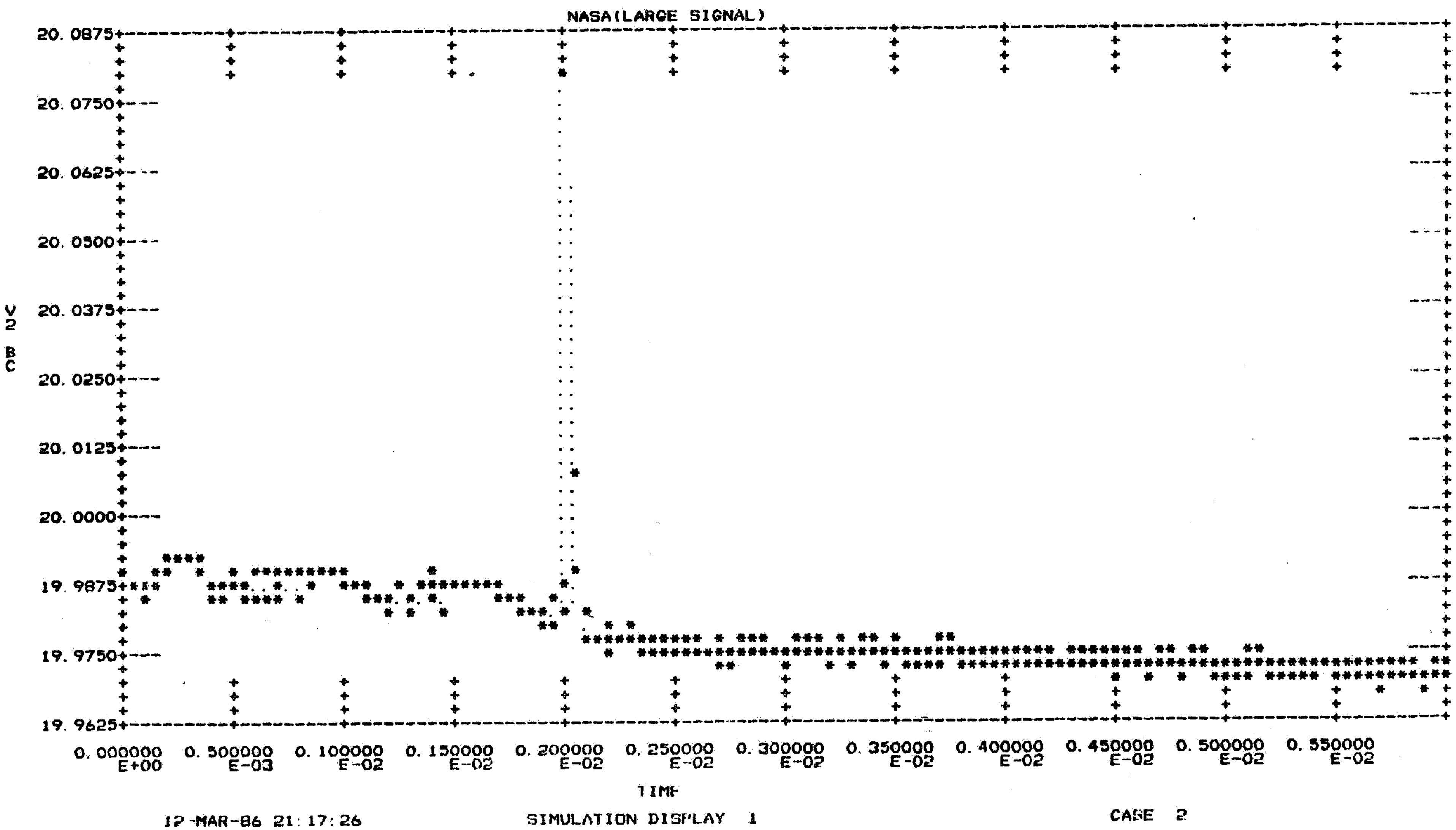


Fig.8 Part of [NASA2.PPT]

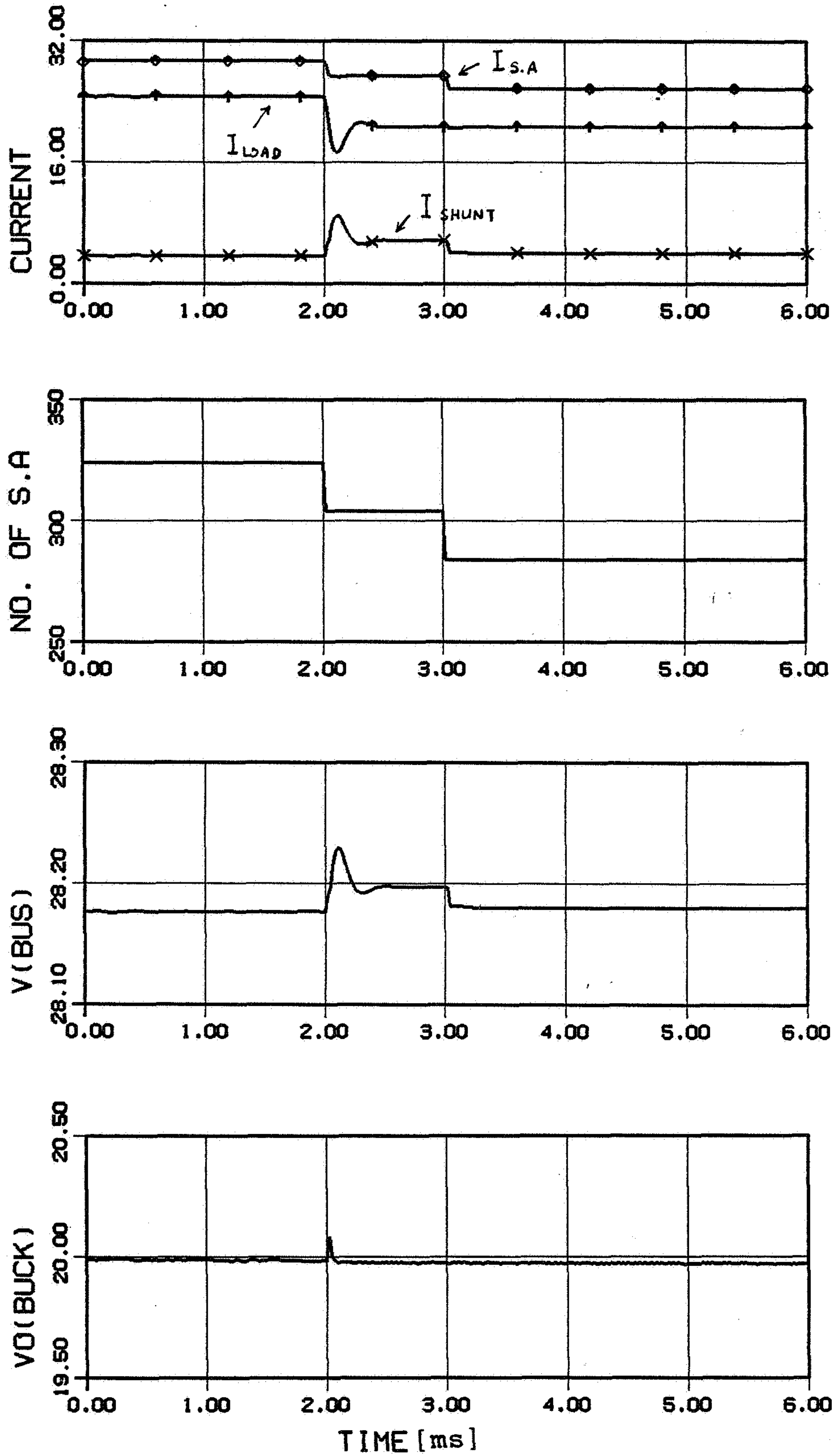


Fig.9 Simulation results