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Abstract

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The major contribution of these models is in the prediction of drum water level. The swell/shrink phenomena is quite accurately captured even though the models are only of third order.

Step responses and a comparison to plant data are presented to validate the performance of the models.

Program listing for the SIMNON system simulation language and the method used to calculate all unknown parameters in the models for a 160 MW unit are given.

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SIMPLIFIED MODELS OF BOILER-TURBINE UNITS

R.D. Bell and K.J. Åström

Contents

1. Introduction

Two simple models to represent the dynamics of fossil-fueled boiler-turbine units are derived in this report. These models are an extension of the work of Morton and Price [1977] and rely heavily on data and model developments presented in Eklund [1971], Åström and Eklund [1972, 1975] and Bell and Åström [1979].

The major contribution of these models is in the prediction of drum water level. The swell/shrink phenomena is quite accurately captured even though the models are only of third order.

Step responses and a comparison to plant data are presented to validate the performance of the models.

Program listings for the SIMNON system simulation language and the method used to calculate all unknown parameters in the models for a 160 MW unit are given.

2. Basic Model Development

The basic model structure is based on the work of Morton and Price [1977]. Some of the most important points in that paper are repeated here so that this report can be as self contained as possible.

DRUM PRESSURE

The fundamental assumption for the mathematical model of this section is that the rate of change of stored energy in the system is proportional to the rate of change of pressure.

i.e. rate of change of stored energy = $k_a \frac{dP}{dt}$, where P is the drum pressure, t is time and k_a a constant of proportionality.

The constant k_a relates the change in pressure to the stored energy. It can be evaluated from either dynamic tests on the boiler or, as is shown in section 4, can be calculated from the physical characteristics of the system.

In this assumption the time lags associated with changes in metal and water temperatures are considered to be very small compared to the time scale of the pressure changes. This has been independently verified by Åström and Eklund [1972].

For the circulation path it is assumed that the heat supplied by the fuel is used to,

(a) raise the incoming feedwater from economiser outlet temperature to saturation temperature,

(b) evaporate saturated water, and

(c) increase the energy stored in the water, metal and steam.

The energy balance equation is

$$e_f = (h_f - h_w)\, q_{fw} + h_{fg}\, q_e + k_a \frac{dP}{dt} \tag{2.1}$$

where e_f = heat supplied by the fuel (KWS)

q_{fw} = feedwater flow rate (Kg/sec)

q_e = evaporation rate (Kg/sec)

Equation (2.1) can be rearranged to give the evaporation rate as

$$q_e = k_b\, e_f - r\, q_{fw} - k_a\, k_b \frac{dP}{dt} \tag{2.2}$$

where $k_b = 1/h_{fg}$ and $r = (h_f - h_w)/h_{fg}$.

The rate of change of pressure in a given steam space is, for small changes, proportional to the rate of change in the mass of steam present

i.e. $$\frac{dP}{dt} = k_c (q_e - q_s) \tag{2.3}$$

where q_s is the steam flow rate out of the system.

Substituting from (2.3) into (2.2) gives

$$q_e = \frac{1}{(1+K)} (k_b\, e_f - r\, q_{fw}) + \frac{K}{(1+K)} q_s \tag{2.4}$$

where $K = k_a\, k_b\, k_c$.

The constant K can be considered as giving a measure of the change in mass of steam generated in the boiler per unit mass lost from the steam space.

Note from eqn (2.4) a change in evaporation rate will occur instantaneously with a change in steam flow out of the system (q_s) without changing the other inputs (ie. fuel or feedwater). This point is emphasised if the enthalphy changes for the water and steam when a pressure drop due to increased steam flow out of the system are calculated. The net energy released in the system during such a change is used to evaporate water into steam.

An expression for the rate of change of pressure can now be obtained by substituting eqn (2.4) into (2.3).

$$\frac{dP}{dt} = \frac{k_c}{(1+K)} (k_b\, e_f - r\, q_{fw} - q_s) \tag{2.5}$$

Note if K is reasonably large compared to unity then eqn (2.4) becomes

$$q_e = q_s \qquad (2.6)$$

i.e. the evaporation rate depends only on steam flow out of the system and that the other inputs fuel and feedwater only change the rate that the pressure will increase or decrease.

DRUM WATER LEVEL

The turbulent nature of the water at the steam water interface is not considered in this model. What is modelled is the reading that would appear in the drum if the water was still. It is effectively a mass of water measure, and as such will be lower than the top of the turbulence.

The mass of water in the drum is influenced by two factors.

1) The difference between feedwater flow and evaporation rate.

2) The displacement of water from the riser tubes due to a change in the steam being generated under the water level.

There is at high load a greater amount of steam in the riser tubes than there is at low load. So when the load changes (ie. variations in steam flow out of system) and the other inputs have been changed to exactly match these new conditions, then the drum water level will be higher or lower depending on the change. It will stay at this level unless appropriate correction is made to feedwater flow. This is the origin of shrink/swell as observed in all drum boiler systems.

If the evaporation rate changes then the mass of water transferred between drum and risers is given by $T_s \frac{dq_e}{dt}$ where T_s represents the time it would take to evaporate the mass transferred if the feedwater is kept constant. If this factor is combined with (1) above then the equation for the rate of change of mass of water in the drum becomes

$$\frac{dM_w}{dt} = q_{fw} - q_e + T_s \frac{dq_e}{dt} \qquad (2.7)$$

If it is assumed that the normal operating range for the drum water level does not vary substantially from the centre of the drum then

$$x_w = (M_w - M_{hf})\, V_f / a \qquad (2.8)$$

where V_f is the specific volume of saturated water,
a is the free water surface area
and M_{hf} is the mass of water when the drum is half full.

ELECTRICAL POWER OUTPUT

An energy balance for the complete turbine-alternator is considered

$$Po = k_t (q_s\, h_s - q_s\, h_o) \qquad (2.9)$$

where h_s and ho are the enthalphies of the steam entering and leaving the turbine.

For normal operating conditions the enthalpy of the inlet steam can be considered a linear function of steam pressure and the enthalpy of the outlet steam to be constant, eqn (2.9) then becomes

$$Po = k_{t1}\, q_s (P + k_{t2}) \qquad (2.10)$$

There are also significant dynamics involved in the transfer of steam energy into electrical power, mainly due to the mechanical components in the system. These can be approximated over quite a large operating range by a first order differential equation, and hence eqn (2.10) becomes

$$\frac{dPo}{dt} = (k_{t1}\, q_s (P + k_{t2}) - Po)/t_{c1} \qquad (2.11)$$

SUMMARISING THE MODEL EQUATIONS

The main equations to represent the dynamics of the system are eqns (2.4), (2.5), (2.7), (2.8) and (2.11). They are repeated here for clarity

$$\frac{dP}{dt} = \frac{k_c}{(1+K)}\{k_b\ e_f - r\ q_{fw} - q_s\} \qquad (2.12)$$

$$\frac{dM_w}{dt} = q_{fw} - q_e + T_s\ \frac{dq_e}{dt} \qquad (2.13)$$

$$\frac{dPo}{dt} = (k_{t1}\ q_s\,(P + k_{t2}) - Po)/t_{c1} \qquad (2.14)$$

$$q_e = \frac{1}{(1+K)}(k_b\ e_f - r\ q_{fw}) + \frac{K}{(1+K)}\ q_s \qquad (2.15)$$

$$x_w = (M_w - M_{bf})\ V_f/a \qquad (2.16)$$

As stated in the derivation eqn (2.15) can often be simplified to

$$q_e = q_s \qquad (2.17)$$

and this equation instead of (2.15) constitutes a simpler model for the system.

3. Extensions

A number of parameters in the basic model can be made functions of the operating conditions, and these are given in section 4 where parameter estimates are presented.

One of the other major limitations of the above model is in predicting drum water level under constant evaporation rate conditions. When this is present and there is an inbalance between steam flow out of the system and the evaporation rate, then a steady build up or decrease in steam occurs. This will result in a transfer of mass of water between the risers and drum causing a change in the drum water level. Such a characteristic is not captured by the model presented, but can be included by adding a term of the form $K_1(q_e - q_s)$ to eqn (2.13). The equations for the model in this case become eqns (2.12), (2.14), (2.15) and (2.16), with eqn (2.13) replaced by

$$\frac{dM_w}{dt} = q_{fw} - q_e + T_s \frac{dq_e}{dt} + K_1(q_e - q_s) \tag{3.1}$$

This additional factor should be based on the volume change of steam rather than the difference in mass flow rates. However, to include volumetric terms, an extra differential equation to keep account of the steam mass would be needed, and this complexity has not been justified for these simple models.

4. Parameter Estimates

The parameters or constants to be estimated for the models given in eqns (2.12) to (2.18) and (3.1) are

$K = k_a\ k_b\ k_c$, where

k_a is the increase in boiler energy storage per unit rise pressure.

k_b is the reciprocal of latent heat ($1/h_{fg}$).

k_c is the increase in pressure per unit mass of steam accumulated in the drum and associated parts.

r is the loss of fuel energy that would be used for evaporation per unit mass of feedwater entering the boiler. ($(h_f-h_w)/h_{fg}$)

k_{t1}, k_2 are coefficients evaluated by fitting a linear function to steam table data relating enthalpy to pressure for the normal plant operating conditions.

$k_{t2} = (k_2-k_3)/k_{t1}$, where

k_3 is the enthalpy of the fluid leaving the turbine.

t_{c1} is the time constant of the turbine alternator system.

V_f is the specific volume of saturated water.

a is the surface area of water in the drum at normal operating levels.

T_s is the fall of mass of water in boiler per unit increase in evaporation rate at normal operating level.

K_1 is the rate of change of mass of water in the drum for a steady increase in steam in the boiler.

The boiler-turbine unit that has been used to validate the models in this report has the following specifications:-

Rated power	160 MW oil fired
Steam flow at rated load	140 Kg/Sec
Drum steam pressure	140 Kg/cm^2
Superheated steam temperature	535°C
Volume of drum	40 m^3
Volume of downcomers	11 m^3
Volume of risers	38 m^3
Mass of water in system at normal operating conditions	40,000 Kg
Feedwater temperature	300°C
Mass of steam in system at normal operating conditions	2,000 Kg.

More details of the unit are available in Eklund [1971] and Eklund [1968]. This unit has been selected to validate the models because extensive dynamic data was collected from the plant in 1969. This data is also described in Eklund [1971]. The unit is still in operation for peak load purposes in Malmo Sweden. It is one of five units operated by Sydkraft AB at the Oresundsverket power station in Malmo Sweden.

Using the above plant specifications, the parameters in the model have been calculated in the following way:-

Parameter k_a

$$k_a = \frac{\Delta \text{ energy stored}}{\Delta \text{ pressure}}$$

$$= \frac{M_f \ \Delta h_f}{\Delta P}$$

$$= \frac{M_w \ \Delta h_w + M_s \ \Delta h_s}{\Delta P}$$

$$= \frac{40000 \times 42 - 2000 \times 18.2}{10} \quad / \text{ at } 100 \text{ Kg/cm}^2$$

$$= 164{,}360 \quad / \text{ at } 100 \text{ Kg/cm}^2$$

$$= \frac{40000 \times 41 - 2000 \times 25.6}{10} \quad / \text{ at } 130 \text{ Kg/cm}^2$$

$$= 158{,}880 \quad / \text{ at } 130 \text{ Kg/cm}^2$$

$$\therefore \ ka \approx M_w \frac{\Delta h}{\Delta P} = M_w \ 4.15 \qquad (4.1)$$

where M_w is the mass of water in the boiler and the 4.15 is an average value for over the pressure operating range of the boiler.

Since $M_w = 40{,}000$, $k_a = 166{,}000$ KJ/Kg/cm².

Parameter k_b.

This is the reciprocal of the latent heat of evaporation.

$$\text{i.e.} \quad k_b = 1/h_{fg} \qquad (4.2)$$

h_{fg} varies from 1319.4 KJ/Kg to 1066.6 KJ/Kg over the normal pressure operating conditions.

$\therefore$ k_b varies from 0.00076 to 0.00094.

A value of $k_b = 0.0008$ has been selected.

Parameter k_c.

$$k_c = \frac{\Delta P}{\Delta m}$$

Assuming that the volume of steam in the complete system at normal operating conditions is one half the total volume, then

$$\Delta m = V_{ss}\ \Delta\rho_s$$, where V_{ss} = volume occupied by steam

$$= 3859.6 \text{ at } 140 \text{ Kg/cm}^2$$

$$= 4243.0 \text{ at } 150 \text{ Kg/cm}^2$$

$$k_c = \frac{\Delta P}{V_{ss}\ \Delta\rho_s} \qquad (4.3)$$

$$= \frac{10}{4243.0 - 3859.6}$$

$$= 0.0261$$

Parameter r.

$$r = \frac{h_f - h_w}{h_{fg}} \qquad (4.4)$$

$$= \frac{1456.4 - 1345.0}{1250}$$

at 320°C for steam temp.
and 300°C for feedwater

$$= 0.08912$$

Parameters k_{t1} , k_{t2} , t_{c1} (these have been estimated from steam tables and the response time of the turbine alternator unit. No data was available about the weight or physical size of the turbine/alternator section so dynamic responses were used).

k_{t1} = 0.0063

k_{t2} = 0.5

t_{c1} = 10.0 seconds.

Parameters V_f , a

V_f = 0.0015 Specific volume of saturated water at 322°C

a = 27 m^2 Free surface area of water in drum (See Eklund [1968])

Parameter T_s.

Water displaced from risers = $(m_{sr2} - m_{sr1})\ v_s/v_w$,

where m_{sr2} = mass of steam in risers for evaporation rate q_{e2}

m_{sr1} = " " " " " " " " q_{e1}

v_s = specific volume of steam

v_w = specific volume of water.

Now $m_{sr} = V_{sr}\ \rho_s$, V_{sr} = volume occupied by steam

ρ_s = density of steam

assuming a linear relationship for steam volume along the risers, gives after some algebraic manipulation

$$m_{sr} = \frac{A_t\ l\ \rho_w\ q_e}{q_c}$$

where A_t is total area at the outlet of riser - assumed constant for length of riser

l is the lenglth of the risers

ρ_w is the density of water

q_e is the evaporation rate

q_c is the circulation flow rate

$$\text{Water displaced from risers} = \frac{A_t\ l\ \rho_w}{q_c}\ (q_{e2} - q_{e1})\ \frac{v_s}{v_w}$$

But water displaced $= T_s \; \Delta q_e$

$$\therefore \quad T_s = \frac{A_t \; l \; \rho_w}{q_c} \; \frac{v_s}{v_w} = \frac{V_r \; \rho_w^2 \; v_s}{q_c} \qquad (4.5)$$

$$= \frac{38 \times 0.015}{2000 \times 0.0015 \times 0.0015}$$ at normal operating conditions.

$$= 126.$$

Parameter K_1

If it is assumed that one third of the steam in the system is in the risers under normal operating conditions, then

$$K_1 = \frac{q_{disp}}{(q_e - q_s)} \, ,$$

q_e = evaporation rate

q_s = steam flow rate out of system

$$q_{disp} = \frac{1}{3} \frac{v_s}{v_w} (q_e - q_s)$$

where v_s = specific volume of steam
v_w = " " of water

$$K_1 = \frac{1}{3} \frac{v_s}{v_w} \qquad (4.6)$$

$$= \frac{1}{3} \frac{0.015}{0.0015}$$

$$\approx 3.0$$

Table 1, summarising parameters and their estimated values for the 160 MW unit

Parameter	Value	
k_a	166,000	KJ/Kg/cm²
k_b	0.0008	g/KJ
k_c	0.0261	Kg/cm²/Kg
r	0.08912	-
k_{t1}	0.0063	-
k_{t2}	0.5	-
t_{c1}	10.0	seconds
V_f	0.0015	m³/Kg
a	27	m²
T_s	126	sec.
K_1	3.0	-

The parameters given in table 1 can be related back to physical characteristics of the plant (volume of drum, riser (etc)) and plant operating conditions by utilising eqns (4.1) to (4.6) instead of the constants given in the table. This approach is useful for producing a generalised model that can easily be changed to a different drum-boiler-turbine unit.

Appendix A gives a summary of all variables and constants used in this report.

5. Step Responses

Figure 1 gives the step responses for the simple model for step changes in fuel (1), steam flow (2) and feedwater flow (3). The three main outputs of drum pressure, electrical output and drum water level are shown. The responses were obtained using the SIMNON simulation language. Listings of the SIMNON model, connect system and macros to produce this figure are given in appendix B.

Figure 2 gives the step responses for the complex model for step changes. The same notation as in figure 1 is used. The SIMNON model, connect system and macros to produce this figure are given in appendix C.

6. Comparison to Plant Data

The data used in this comparison is described by Eklund [1971]. It is for a 160 MW plant, and the parameters estimated in section 4 of this report are based on that plant.

Figures 3 to 5 compare the plant and model responses at low load conditions. Figure 3 is for fuel variations, figure 4 for steam flow variations, and figure 5 for feedwater flow variations.

Figures 6 to 8 compare the plant and model responses at high load. Figure 6 is for fuel variations, figure 7 for steam flow variations, and figure 8 for feedwater flow variations.

Figures 3 to 8 are for the simple model.

Figures 9 to 14 are for the complex model, and the same sequence of low and high load with corresponding input variations as that used in figures 3 to 8 applies to these figures.

Appendix D gives the connect system and figure macros used for these results.

7. Conclusions

Two comparatively simple boiler-turbine models have been derived in this report. They are an extension of the work presented in Morton and Price [1977] and have lead to models which give good responses when compared to plant data. In particular the drum water level shrink/ swell phenomena has been shown to be modelled quite accurately even though the complete model consists of three differential equations and two algebraic equations.

Included in this report is the method used to calculate the parameters in the model. An example of using this method for a 160 MW plant is also given.

SIMNON programming listings for both of the models as well as a series of connect systems and figure macros are given as appendicies.

8. Acknowledgement

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9. References

Eklund K. (1968): "Linear Mathematical Models of the Drum-Downcomer-Riser Loop of a Drum Boiler", TFRT-3005 Report, Lund Institute of Technology.

Eklund K. (1971): "Linear Drum Boiler-Turbine Models", Report TFRT-1001, Dept. of Automatic Control, Lund Institute of Technology, Sweden.

Åström K.J. and Eklund K. (1972): "A Simplified Non-linear Model of a Drum Boiler-Turbine Unit", Int. J. Control, vol.16, No.1, 145-169.

Åström K.J. and Eklund K. (1975): "A Simple Non-linear Drum Boiler Model", Int. J. Control, vol.22, No.5, 739-740.

Morton A.J. and Price P.H. (1977): "The Controllability of Steam Output, Pressure and Water Level in Drum Boilers", Proc. I. Mech. Eng. 1977 p75-84.

Bell R.D. and Åström K.J. (1979): "A Low Order Nonlinear Dynamic Model for Drum-Boiler-Turbine Alternator Units", TFRT-7162 Report, Dept. of Automatic Control, Lund Institute of Technology, Sweden.

10. Appendix A - Notation

a) Variables, inputs and outputs.

P	Drum steam	Kg/cm^2
t	Time	
e_f	Heat energy of fuel	KWs
q_f	Fuel mass flow rate	Kg/sec
q_{fw}	Feedwater mass flow rate	Kg/sec
q_s	Steam mass flow rate	Kg/sec
q_e	Evaporation mass flow rate	Kg/sec
Po	Electrical energy output	MWs
x_w	Drum water level	mm or m
M_w	Mass of water in system	Kg

b) Constants (See table 1 for values calculated for 160 MW unit).

k_a	The increase in boiler energy storage per unit rise in pressure.	$KJ/Kg/cm^2$
k_b	The reciprocal of latent heat $(1/h_{fg})$.	Kg/KJ
k_c	The increase in pressure per unit mass of steam accumulated in the drum and associated parts.	$Kg/cm^2/Kg$
r	The loss of fuel energy that would be used for evaporation per unit mass of feedwater entering the boiler $((h_f-h_w)/h_{fg})$.	-
h_{fg}	Latent heat of evaporation.	KJ/Kg
h_f	Enthalpy of saturated water.	KJ/Kg
h_w	Enthalpy of feedwater.	KJ/Kg
k_{t1} , k_2	Coefficients evaluated by fitting a linear function to steam table data relating enthalpy to pressure for the normal plant operating conditions.	-
k_{t2} =	$(k_2-k_3)/k_{t1}$, coefficient in electrical output equation.	-
k_3	Enthalpy of the fluid leaving the turbine.	KJ/Kg
t_{c1}	Time constant of the turbine/alternator system.	sec
V_f	Specific volume of saturated water.	m^3/Kg
a	Surface area of water in the drum at normal operating level.	m^2
T_s	The fall of mass of water in boiler per unit increase in evaporation rate at normal operating level.	sec
K_1	Rate of change of mass of water in the drum for a steady increase in steam in the boiler.	-

11. Appendix B - Program listing for simple model.

```
CONTINUOUS SYSTEM bt4

" 3rd order model based on the paper:-
" "The Controllability of Steam Output, Pressure and
"        Water Level in Drum Boilers",
"      Morton and Price, I.Mech.E, 1977

"Author : R.D.Bell 17/5/87

INPUT qf qs qfw pdp pop xwp
OUTPUT p po xw
STATE x1 x2 x3
DER d1 d2 d3

"Inputs
" qf - Fuel flow (0-10 kg/s)
" qs - Steam flow (0-140 kg/s)
" qfw - Feedwater mass flow rate (0-140 kg/s)
" ef - energy flow rate of fuel (kws)

"States and outputs
"p,x1 - Drum steam pressure (bar)
"xw,x2 - Drum water level (mm)
"po,x3 - Electrical power o/p (MWs)

"Constants
  dhdp:4.15 "Change in enthalpy of water per unit
            "pressure change. Calculated from steam
            "tables at p=120 bar.
  dpdvs:1.2 "Change in pressure per unit change in
            "specific volume. Calculated from steam
            "tables at p=120 bar.
  vss:40.0  "Volume in system occupied by steam at
            "normal operating conditions.
  r:0.08912 "(hf-hw)/hfg loss of evaporation per
            "unit mass of feed entering boiler.
  vf:0.0015 "Specific vol. of saturated water at
            "normal operating conditions (m3/kg).
  vs:0.015  "Specific vol. of saturated steam at
            "normal operating conditions (m3/kg).
  vr:38     "Volume of risers (m3).
  qc:2000   "Circulation flow rate (kg/s).
  a:27      "Free surface area of water in drum (m2)
  tc2:10.0  "Time constant for dynamics of turbines
            "and alternator.
  ce1:0.0063 "Constant for electrical o/p eqn.
  ce2:0.5   "     "     "      "      "   "
  cu11:20200.0 "Constant for converting fuel flow
               "to energy.
  cu12:-11700.0 "Constant for converting fuel flow
                "to energy.
  dw10:2900   "Zero reference for drum water level.
  kb:0.0008   "1/hfg reciprocal of latent heat at
              "normal operating conditions (kg/kj).
```

```
"Initial conditions
  x1:108
  x2:2.5
  x3:67.0

"Auxiliary equations
  mfd=a*x2/vf  "Mass of fluid in drum.
  ka=mfd*dhdp  "Increase in boiler energy storage
               "per unit rise in pressure (kj/bar).
  kc=dpdvs/vss "Increase in pressure per unit mass
               "of steam accumulated in drum and
               "associated parts (bar/kg).
  vstvf=vs/vf  "Ratio of specific volume of steam
               "to water at normal operating
               "conditions.
  ts=vstvf*vr/(qc*vf) "Increase in mass of water in
                      "drum per unit increase in
                      "evaporation rate at normal
                      "working level (s).
  ef=cu11*qf+cu12
  K=ka*kb*kc    "Additional mass of steam evaporated
                "per unit mass lost from system
                "(=ka*kb*kc).
  msd = qs "Rate of evaporation is equal to steam
           "flow (kg/s).

"Dynamics
  d1 = (kb*ef-r*qfw - qs)*kc/(1+K)
  d2 = (qfw - msd)*vf/a
  d3 = (qs*(ce1*p+ce2) - po)/tc2

"Outputs
  p = x1
  po= x3
  xw = (x2 + ts*msd*vf/a)*1e3-dwl0

END
-----------------------------------------------------------------
connecting system c1bt4
time t
qf[bt4]=if t<ts then qfll else qflu
qs[bt4]=if t<ts then qsll else qslu
qfw[bt4]=if t<ts then qfwll else qfwlu
pdp[bt4]=120
pop[bt4]=80
xwp[bt4]=0.0
ts:100
qfll:4.36
qflu:4.36
qsll:56.5
qslu:56.5
qfwll:56.5
qfwlu:56.5
end
-----------------------------------------------------------------
```

```
MACRO f2sllbt4
"Generates fig comparing step responses for fuel,control valve and feedwater
"at low load for bt4 model i.e. 3rd order Morton simple model.
write 'Has data been generated for this fig? (yes or no)'
read ans YESNO
if ans EQ  YES  goto start
f2fslbt4
f2cslbt4
f2wslbt4
label start
split 2 2
axes h 0 400 v 90 120
show p -mark/b1
show p -mark/b2
show p -mark/b3
text 'Drum pressure (kg/cm2)'
axes h 0 400 v 55 80
show po -mark/b1
show po -mark/b2
show po -mark/b3
text 'Electrical output (MWs)'
axes h 0 400 v -80 200
show xw -mark/b1
show xw -mark/b2
show xw -mark/b3
text 'Drum water level (m)'
axes h 0 400 v 55 80
show qs -mark/b1
show qs -mark/b2
show qs -mark/b3
text 'Steam flow (kg/s)'

END
-----------------------------------------------------------------

macro f2fslbt4
" Macro to obtain fuel step response for bt4 model
syst bt4 clbt4
store p po xw qs
par qflu:5.36
par qslu:56.5
par qfwlu:56.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b1

end
-----------------------------------------------------------------
```

```
macro f2cslbt4
" Macro to obtain control valve step response for bt4 model
syst bt4 c1bt4
store p po xw qs
par qflu:4.36
par qslu:66.5
par qfwlu:56.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b2

end
```

```
macro f2wslbt4
" Macro to obtain feedwater step response for bt4 model
syst bt4 c1bt4
store p po xw qs
par qflu:4.36
par qslu:56.5
par qfwlu:66.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b3

end
```

12. Appendix C - Program listing for complex model.

```
CONTINUOUS SYSTEM bt5
" 3rd order model based on paper by
" Morton and Price 1977

"Author : R.D.Bell 15/5/87 updated 4/6/87

INPUT qf qfw qs PDP POP xwP
OUTPUT P PO xw
STATE x1 x2 x3
DER d1 d2 d3

"Inputs
" qf - Fuel flow (0-10 kg/s)
" qfw - Feedwater mass flow rate (0-140 kg/s)
" qs - Steam mass flow rate (0-140 kg/s)
" ef - Energy flow rate of fuel (kws)

"States and outputs
"P,x1 - Drum steam pressure (bar)
"xw,x2 - Drum water level (mm)
"PO,x3 - Electrical o/p (MWs)

"Constants
  ka:166000  "Increase in boiler energy storage per
            "unit rise in pressure (kj/bar)
  kb:0.0008 "1/hfg reciprocal of latent heat (kg/kj)
  kc:0.0261 "Increase in pressure per unit mass of
            "steam accumulated in drum and
            "associated parts (bar/kg).
  r:0.08912 "(hf-hw)/hfg loss of evaporation
            "per unit mass of feed entering boiler.
  vf:0.0015 "Specific vol. of saturated water (m3/kg)
  a:27      "Free surface area of water in drum (m2)
  ts:126    "Fall in mass of water in boiler
            "per unit increase in evaporation rate
            "at normal working level (s).
  ce1:0.0063 "Constant for electrical o/p eqn
  ce2:0.5    "     "     "      "      "  "
  tc2:10.0   "Time constant for dynamics of turbines
             "and alternator.
  cu11:20200.0  "Constant for converting fuel flow
                "to energy.
  cu12:-11700.0 "Constant for converting fuel flow
                "to energy.
  sf1:1e3      "Scale factor for state eqn.
  mhf:40000    "Mass of water in system at normal
               "working level.
  dwl0:310     "Drum water level correction for
               "water displaced from risers.
  k1:2.0
"Initial conditions
  x1:110
  x2:40.0       "40.0e3/sf1
  x3:67
```

```
"Auxiliary equations
  ef=cu11*qf+cu12
  K=ka*kb*kc     "Additional mass of steam evaporated
                 "per unit mass lost from system
                 "(=ka*kb*kc).
  msd=(kb*ef-r*qfw)/(1+K) + qs*K/(1+K)  "Rate of
                                        "evaporation
                                        "(kg/s).
  disp=k1*(msd-qs)

"Dynamics
  d1 = (kb*ef - r*qfw - qs)*kc/(1+K)
  d2 = (qfw - msd + disp)/sf1
  d3 = (qs*(ce1*P + ce2) - PO)/tc2

"Outputs
  P = x1
  xw = ((x2*sf1-mhf + ts*msd)*vf/a)*1e3-dwl0
  PO = x3

END
----------------------------------------------------------------

connecting system c1bt5
time t
qf[bt5]=if t<ts then qfll else qflu
qs[bt5]=if t<ts then qsll else qslu
qfw[bt5]=if t<ts then qfwll else qfwlu
pdp[bt5]=120
pop[bt5]=80
xwp[bt5]=0.0

ts:100
qfll:4.36
qflu:4.36
qsll:56.5
qslu:56.5
qfwll:56.5
qfwlu:56.5

end
-----------------------------------------------------------------
```

```
MACRO f2sllbt5
"Generates fig comparing step responses for fuel,
"control valve and feedwater at low load for bt5
"model i.e. 3rd order Morton model.
write 'Has data been generated for this fig?(yes or no)'
read ans YESNO
if ans EQ  YES  goto start
f2fslbt5
f2cslbt5
f2wslbt5
label start
split 2 2
axes h 0 400 v 90 120
show p -mark/b1
show p -mark/b2
show p -mark/b3
text 'Drum pressure (kg/cm2)'
axes h 0 400 v 55 80
show po -mark/b1
show po -mark/b2
show po -mark/b3
text 'Electrical output (MWs)'
axes h 0 400 v -80 200
show xw -mark/b1
show xw -mark/b2
show xw -mark/b3
text 'Drum water level (m)'
axes h 0 400 v 55 80
show qs -mark/b1
show qs -mark/b2
show qs -mark/b3
text 'Steam flow (kg/s)'

END
------------------------------------------------------------------


macro f2fslbt5
" Macro to obtain fuel step response for bt5 model
syst bt5 clbt5
store p po xw qs
par qflu:5.36
par qslu:56.5
par qfwlu:56.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b1

end
-----------------------------------------------------------------
```

```
macro f2cslbt5
" Macro to obtain control valve step response
" for bt5 model.
syst bt5 c1bt5
store p po xw qs
par qflu:4.36
par qslu:66.5
par qfwlu:56.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b2

end
```

```
macro f2wslbt5
" Macro to obtain feedwater step response for bt5 model
syst bt5 c1bt5
store p po xw qs
par qflu:4.36
par qslu:56.5
par qfwlu:66.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b3

end
```

13. Appendix D - Connect system and figure macros for plant data.

```
CONNECTING SYSTEM c2bt4

TIME T

qf[bt4]=C9[IFILE]*qfcf
qs[bt4]=(c10[ifile]+c11[ifile])*qscf
qfw[bt4]=C2[IFILE]*qfwcf
PDP[bt4]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bt4]=C8[IFILE]
xwP[bt4]=c3[ifile]

qfcf:0.252
qscf:0.231
qfwcf:0.252

END
```

```
macro f1bd1bt4
"Generates fig comparing model and plant data.
" Uses plant data d107a low load fuel change.
" Uses bt4 model i.e. 3rd order Morton model (ev. rate = qs)

let n.ifile=13
,fname.ifile=bd107a
syst bt4 ifile c2bt4
par dt[ifile]:10.0
par dw10:2900
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 90 120
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
ashow xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'

end
```

```
macro f1bd2bt4
"Generates fig comparing model and plant data.
" Uses plant data d108a low load feedwater change.
" Uses bt4 model i.e. 3rd order Morton model (ev.rate=qs)

let n.ifile=13
,fname.ifile=bd108a
syst bt4 ifile c2bt4
par dt[ifile]:10.0
init x1:110             "Steam pressure initial condition
par dwl0:800           "Drum water level initial condition
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 107 112
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
ashow xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'

end
-----------------------------------------------------------------
```

```
macro f1bd3bt4
"Generates fig comparing model and plant data.
" Uses plant data d111a low load control valve change.
" Uses bt4 model i.e. 3rd order Morton model (ev.rate=qs)

let n.ifile=13
,fname.ifile=bd111a
syst bt4 ifile c2bt4
par dt[ifile]:10.0
init x1:110             "Steam pressure initial condition
init x3:69              "Electrical o/p     "        "
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 100 115
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
ashow xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'

end
-----------------------------------------------------------------
```

```
macro f1bd4bt4
"Generates fig comparing model and plant data.
" Uses plant data d201a high load fuel valve change.
" Uses bt4 model i.e. 3rd order Morton model (ev.rate=qs).
let n.ifile=13
,fname.ifile=bd201a
syst bt4 ifile c2bt4
par dt[ifile]:10.0
init x1:125              "Steam pressure initial condition
init x3:140              "Electrical o/p    "        "
par dwl0:3150            "Drum water level initial condition
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 115 140
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
axes h 0 3000 v -200 150
show xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'

end
-----------------------------------------------------------------
macro f1bd5bt4
"Generates fig comparing model and plant data.
" Uses plant data d102a high load feedwater valve change.
" Uses bt4 model i.e. 3rd order Morton model (ev.rate=qs)
let n.ifile=13
,fname.ifile=bd102a
syst bt4 ifile c2bt4
par dt[ifile]:10.0
init x1:126              "Steam pressure initial condition
init x3:140              "Electrical o/p    "        "
par r:0.0925
par dwl0:1100
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 123 128
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
axes h 0 3000 v -200 150
show xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'
end
-----------------------------------------------------------------
```

```
macro f1bd6bt4
"Generates fig comparing model and plant data.
" Uses plant data d105a high load control valve change.
" Uses bt4 model i.e. 3rd order Morton model (ev.rate=qs)

let n.ifile=13
,fname.ifile=bd105a
syst bt4 ifile c2bt4
par dt[ifile]:10.0
init x1:134             "Steam pressure initial condition
init x3:138             "Electrical o/p    "         "
par dwl0:3150           "Drum water level initial condition
par qscf:0.2447   "The steam flow measuring transducer seems in error
par ce2:0.44      "To allow for decreased losses from turbine at high loads
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 125 140
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
axes h 0 3000 v -100 200
show xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'

end
-----------------------------------------------------------------

CONNECTING SYSTEM c2bt5

TIME T

qf[bt5]=C9[IFILE]*qfcf
qs[bt5]=(c10[ifile]+c11[ifile])*qscf
qfw[bt5]=C2[IFILE]*qfwcf
PDP[bt5]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bt5]=C8[IFILE]
xwP[bt5]=c3[ifile]

qfcf:0.252
qscf:0.231
qfwcf:0.252

END
-----------------------------------------------------------------
```

```
macro f1bd1bt5
"Generates fig comparing model and plant data.
" Uses plant data d107a low load fuel change.
" Uses bt5 model i.e. 3rd order Morton model.

let n.ifile=13
,fname.ifile=bd107a
syst bt5 ifile c2bt5
par dt[ifile]:10.0
par dwl0:380
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 90 120
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
ashow xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'

end
------------------------------------------------------------------
macro f1bd2bt5
"Generates fig comparing model and plant data.
" Uses plant data d108a low load feedwater change.
" Uses bt5 model i.e. 3rd order Morton model.

let n.ifile=13
,fname.ifile=bd108a
syst bt5 ifile c2bt5
par dt[ifile]:10.0
init x1:110             "Steam pressure initial condition
par dwl0:400           "Drum water level initial condition
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 107 112
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
ashow xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'

end
------------------------------------------------------------------
```

```
macro f1bd3bt5
"Generates fig comparing model and plant data.
" Uses plant data d111a low load control valve change.
" Uses bt5 model i.e. 3rd order Morton model.

let n.ifile=13
,fname.ifile=bd111a
syst bt5 ifile c2bt5
par dt[ifile]:10.0
init x1:110              "Steam pressure initial condition
init x3:69               "Electrical o/p    "        "
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 100 115
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
ashow xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'

end
-----------------------------------------------------------------
macro f1bd4bt5
"Generates fig comparing model and plant data.
" Uses plant data d201a high load fuel valve change.
" Uses bt5 model i.e. 3rd order Morton model.

let n.ifile=13
,fname.ifile=bd201a
syst bt5 ifile c2bt5
par dt[ifile]:10.0
init x1:125              "Steam pressure initial condition
init x3:140              "Electrical o/p    "        "
par dw10:650            "Drum water level initial condition
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 115 140
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
axes h 0 3000 v -200 150
show xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'

end
-----------------------------------------------------------------
```

```
macro f1bd5bt5
"Generates fig comparing model and plant data.
" Uses plant data d102a high load feedwater valve change.
" Uses bt5 model i.e. 3rd order Morton model.
let n.ifile=13
,fname.ifile=bd102a
syst bt5 ifile c2bt5
par dt[ifile]:10.0
init x1:126             "Steam pressure initial condition
init x3:140             "Electrical o/p    "        "
par r:0.0925
par dw10:700
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 123 128
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
axes h 0 3000 v -200 150
show xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'
end
-----------------------------------------------------------------
macro f1bd6bt5
"Generates fig comparing model and plant data.
" Uses plant data d105a high load control valve change.
" Uses bt5 model i.e. 3rd order Morton model.
let n.ifile=13
,fname.ifile=bd105a
syst bt5 ifile c2bt5
par dt[ifile]:10.0
init x1:134             "Steam pressure initial condition
init x3:138             "Electrical o/p    "        "
par dw10:650           "Drum water level initial condition
par qscf:0.2447   "The steam flow measuring transducer seems in error
par ce2:0.44      "To allow for decreased losses from turbine at high loads
store p pdp po pop xw xwp qf qs qfw
split 1 1
axes h 0 3000 v 125 140
plot p pdp
simu 0 3000 /b1
split 3 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
axes h 0 3000 v -100 200
show xw xwp -mark/b1
text 'Drum water level. 1=model, 2=plant'
end
```

Figure 1. Step responses of simple model.
1 = fuel flow step (increase), 2 = control valve step (increase),
3 = feedwater flow step (increase).

87.06.02 - 17:24:44 nr: 8
hcopy

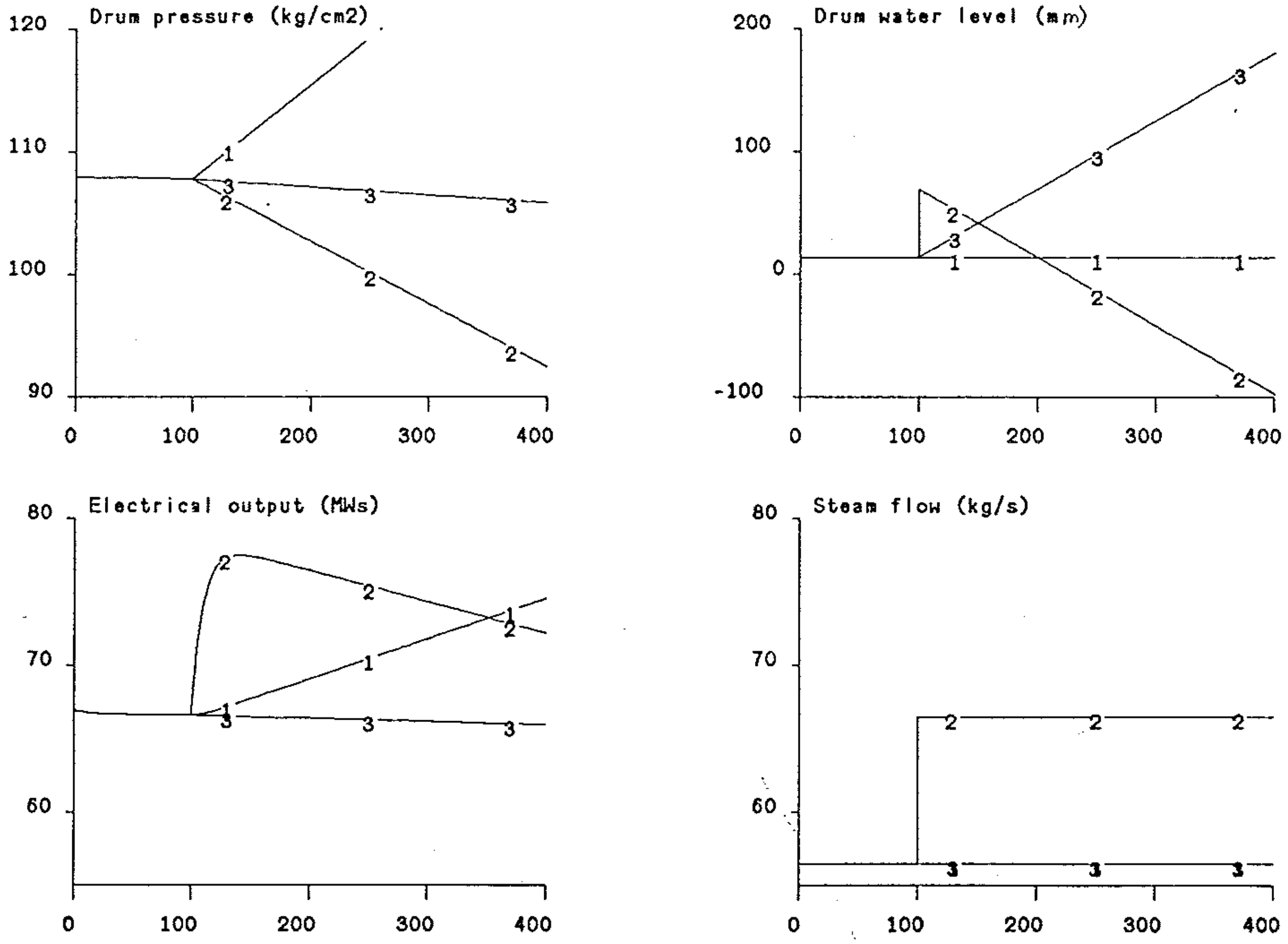

Figure 2. Step responses of complex model.
1 = fuel flow step (increase), 2 = control valve step (increase),
3 = feedwater flow step (increase).

87.06.05 - 09:07:10 nr: 1
hcopy

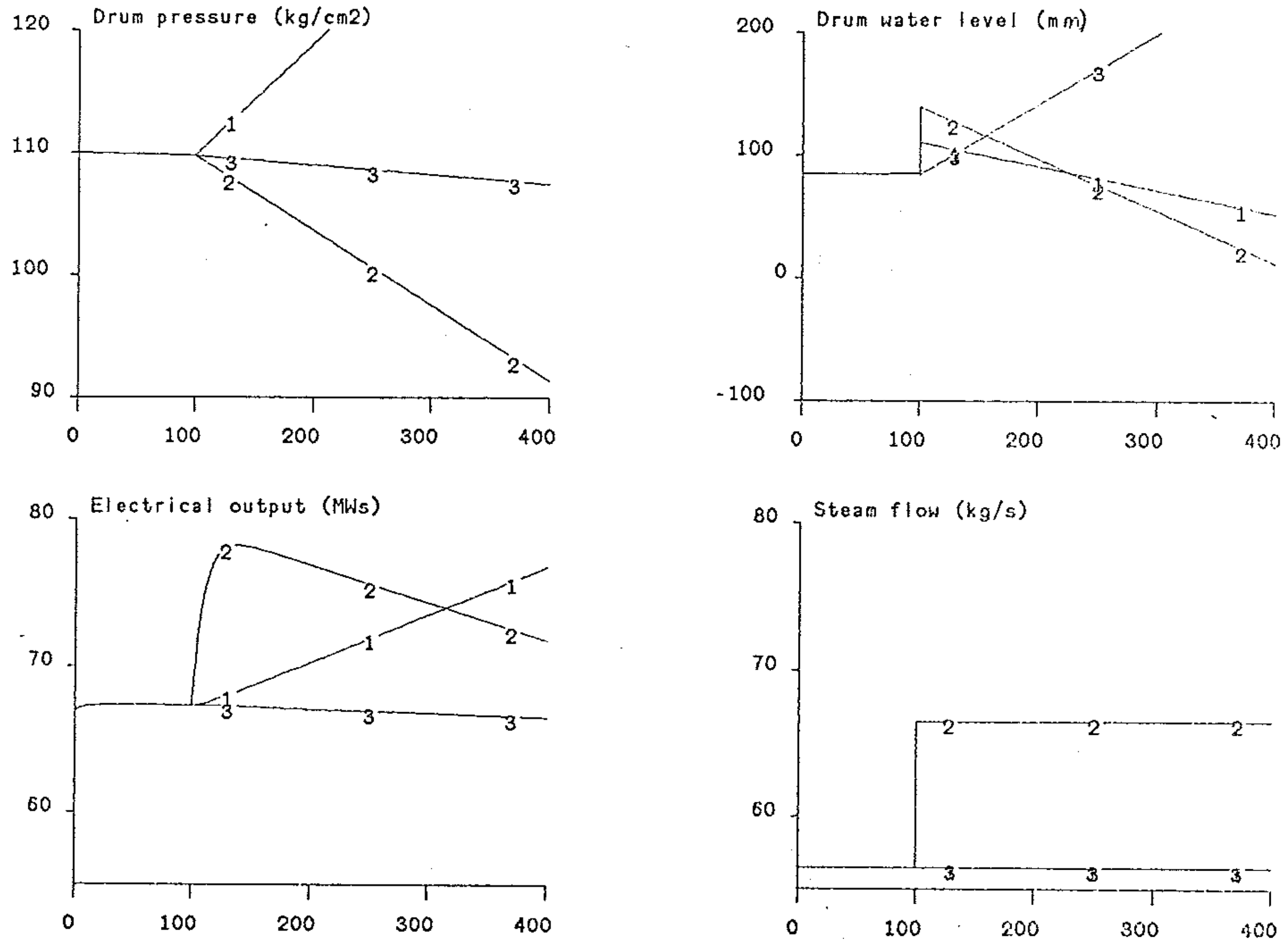

Figure 3. Comparison of plant and model responses, fuel flow changes, low load, simple model.

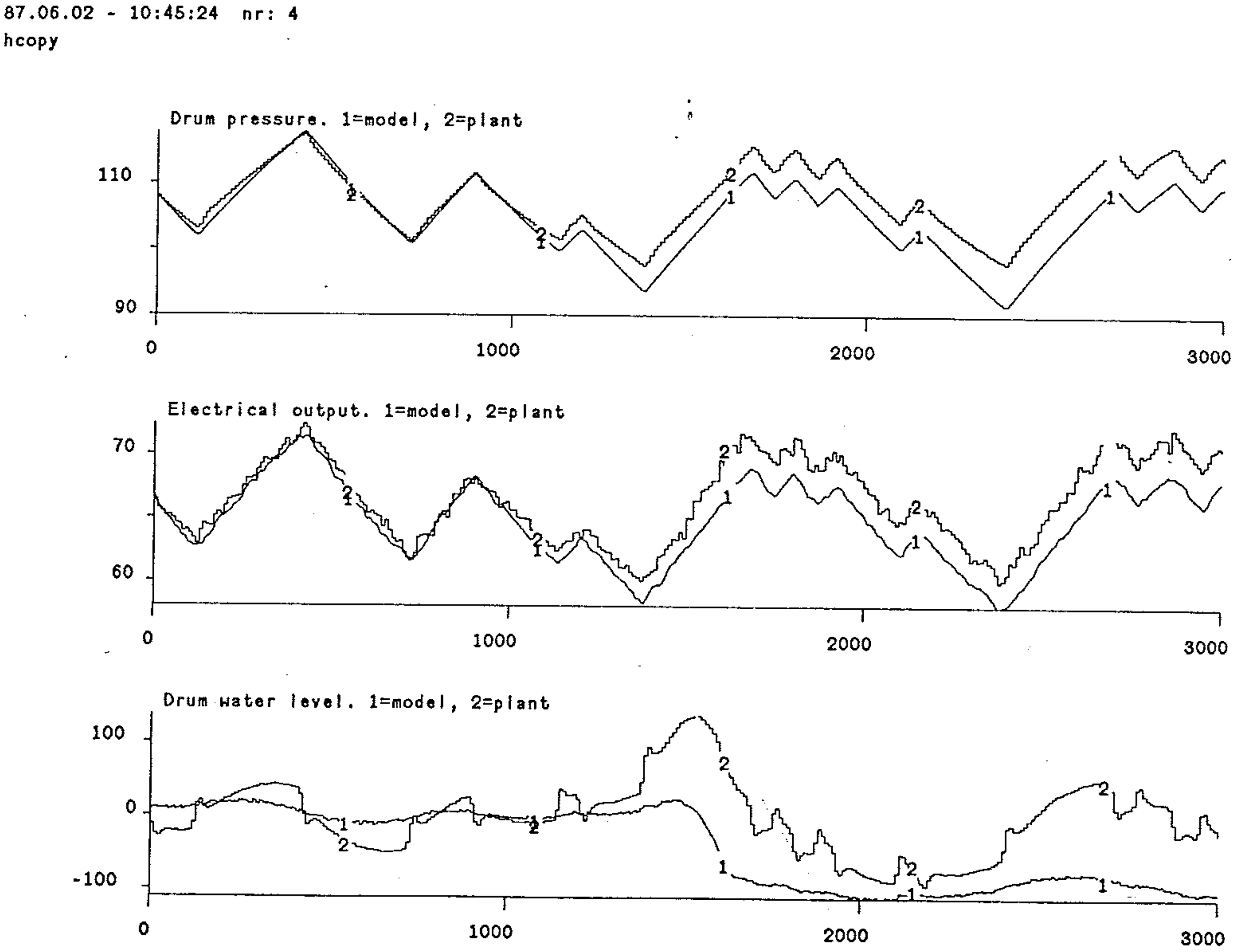

Figure 4. Comparison of plant and model responses, feedwater flow changes, low load, simple model.

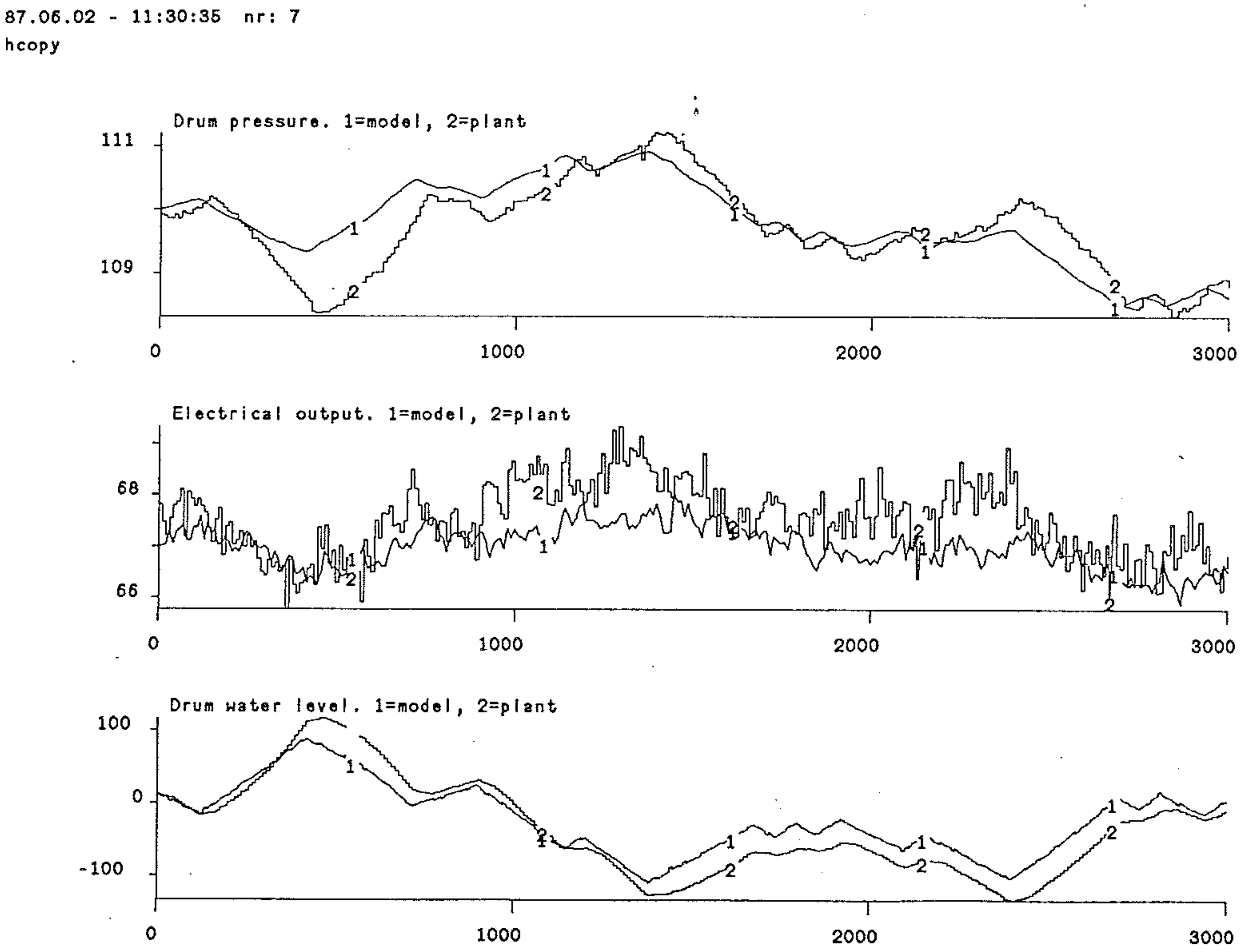

Figure 5. Comparison of plant and model responses, steam flow changes, low load, simple model.

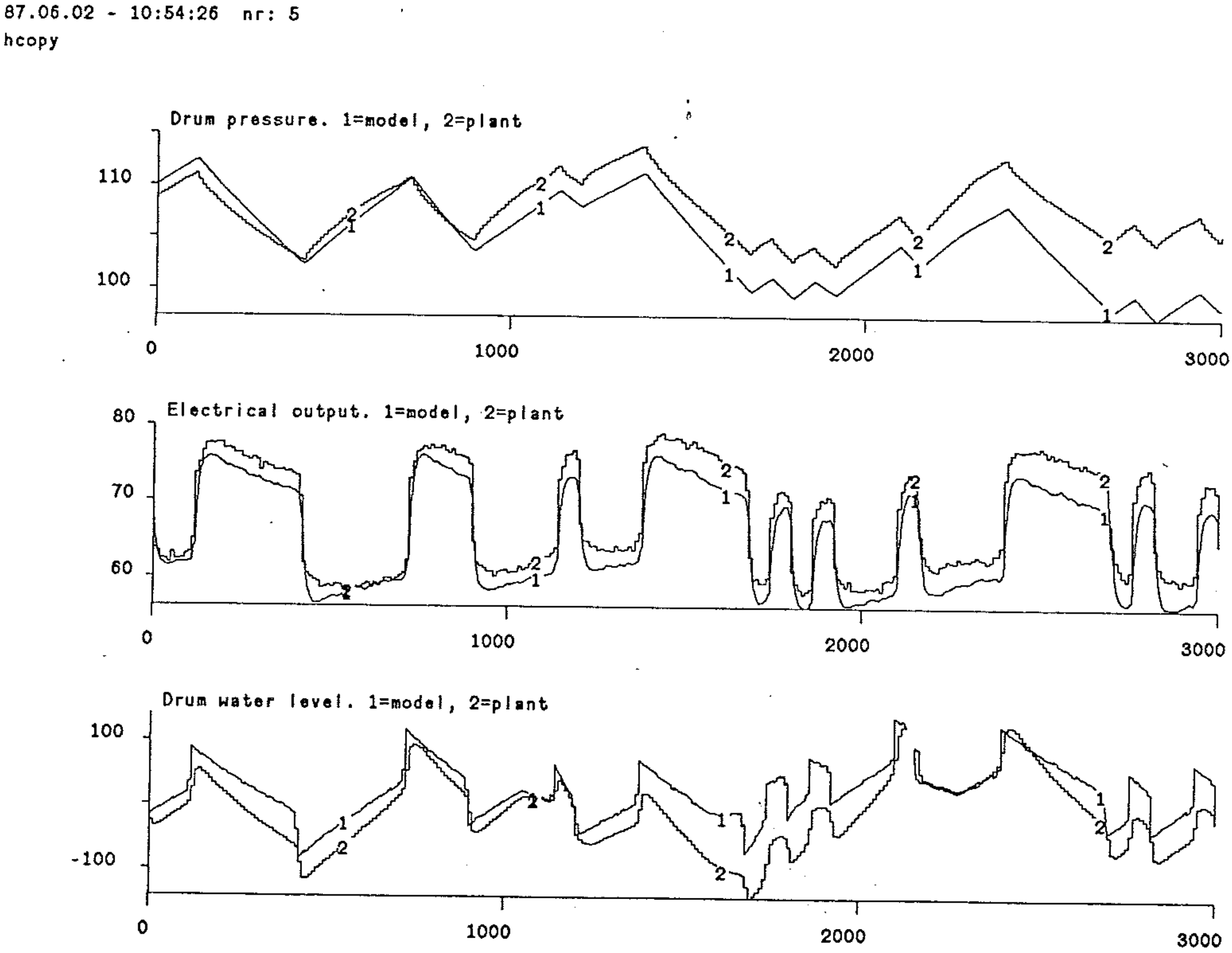

Figure 6. Comparison of plant and model responses, fuel flow changes, high load, simple model.

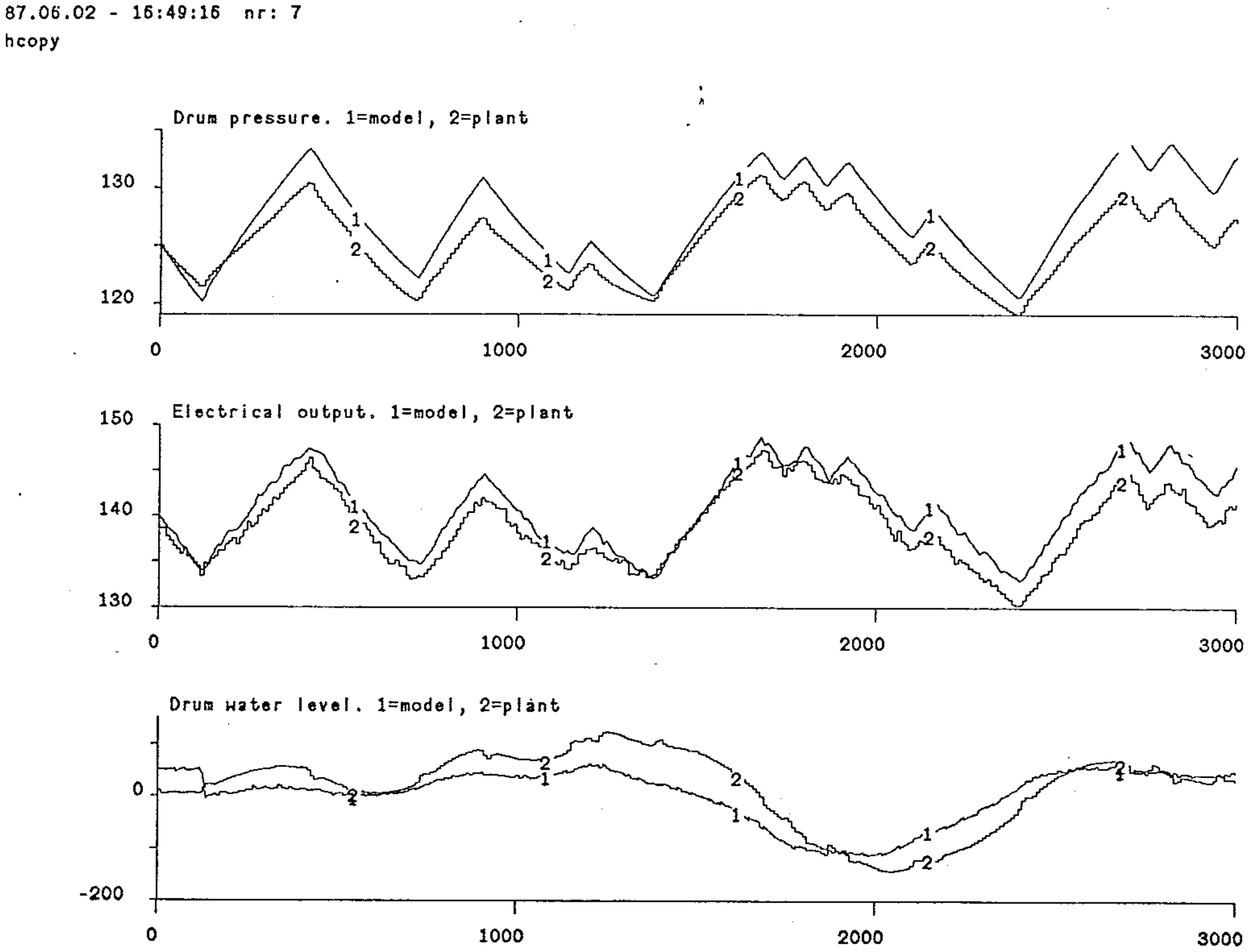

Figure 7. Comparison of plant and model responses, feedwater flow changes, high load, simple model.

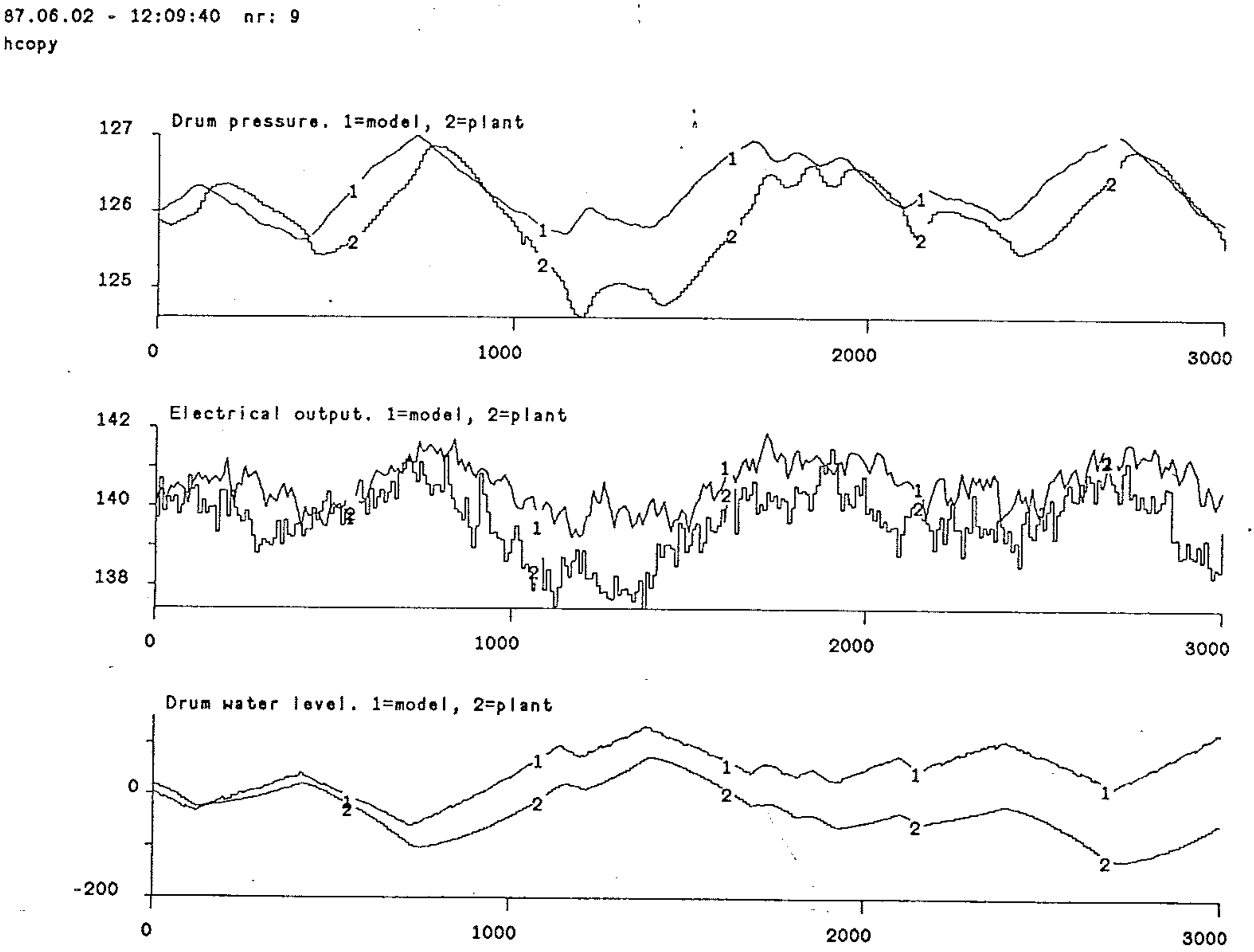

Figure 8. Comparison of plant and model responses, steam flow changes, high load, simple model.

87.06.02 - 16:29:57 nr: 5
hcopy

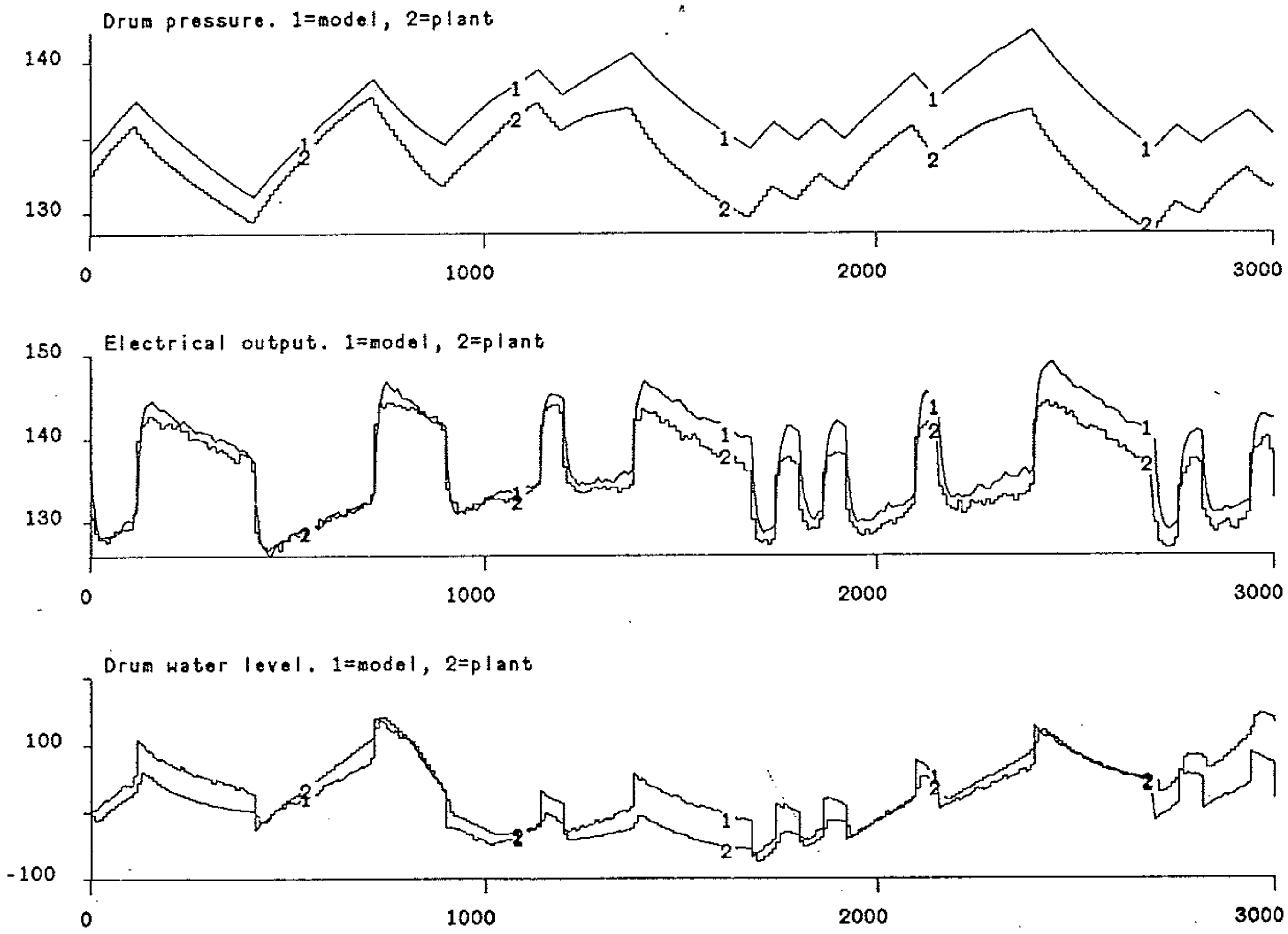

Figure 9. Comparison of plant and model responses, fuel flow changes, low load, advanced model.

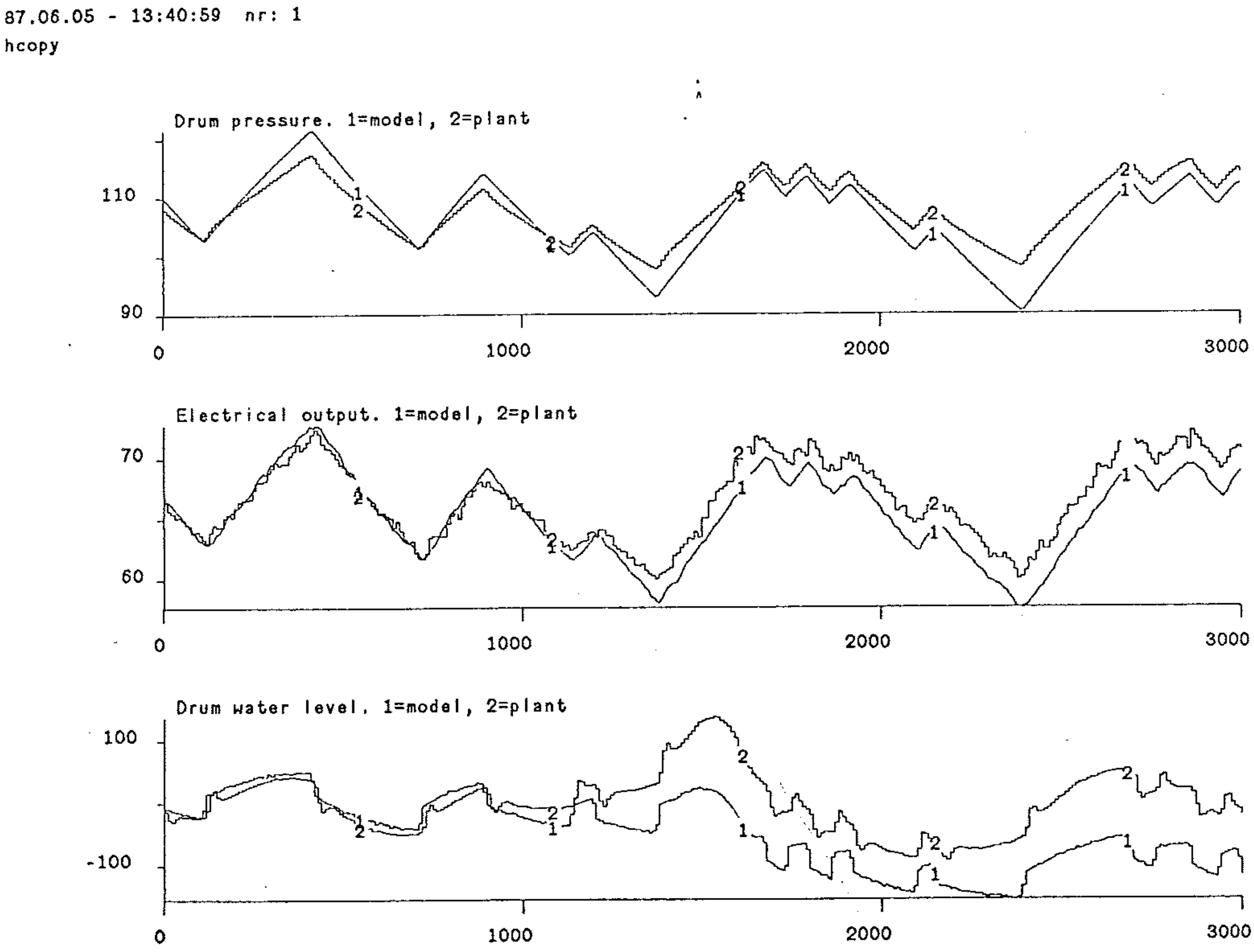

Figure 10. Comparison of plant and model responses, feedwater flow changes, low load, advanced model.

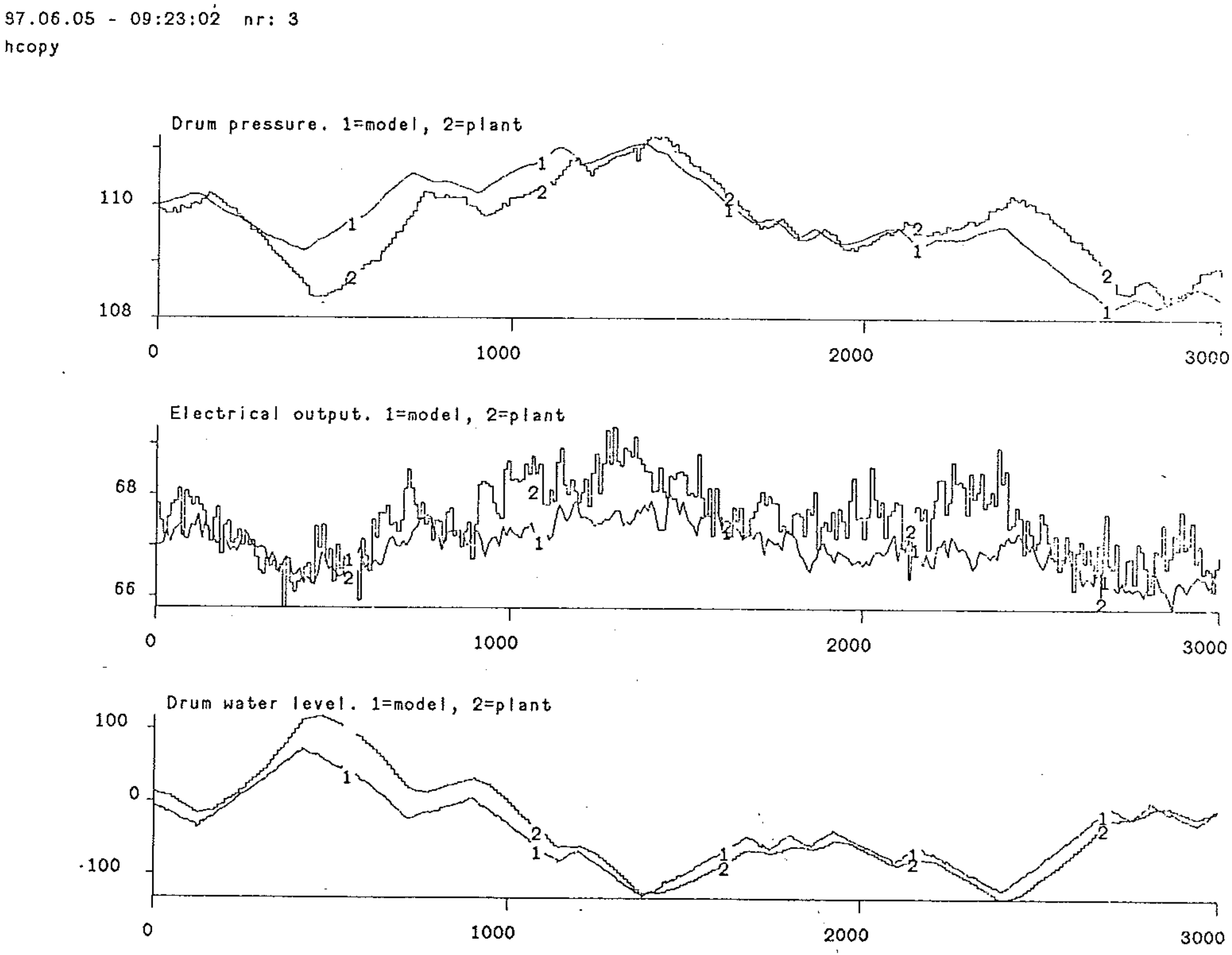

Figure 11. Comparison of plant and model responses, steam flow changes, high load, advanced model.

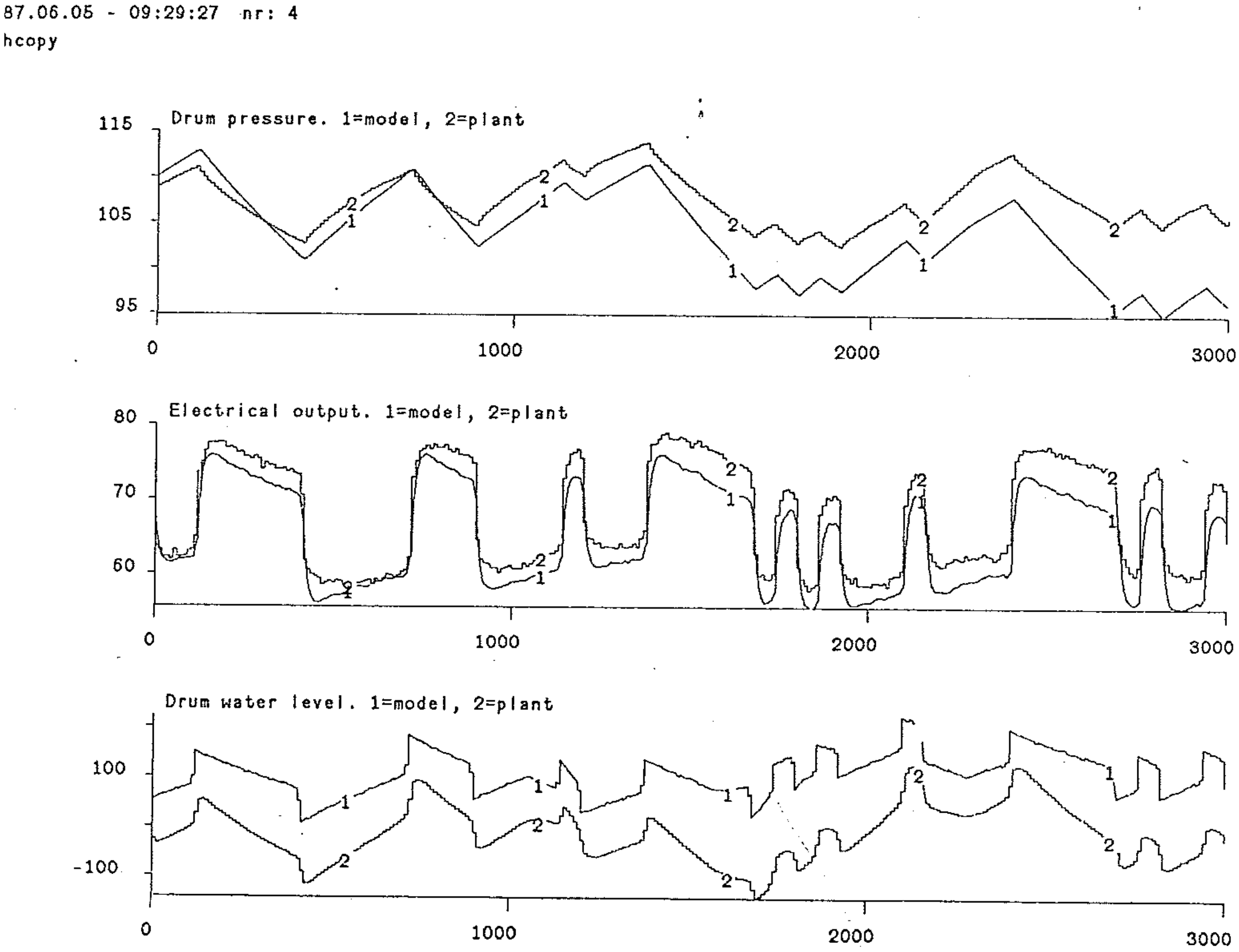

Figure 12. Comparison of plant and model responses, fuel flow changes, high load, advanced model.

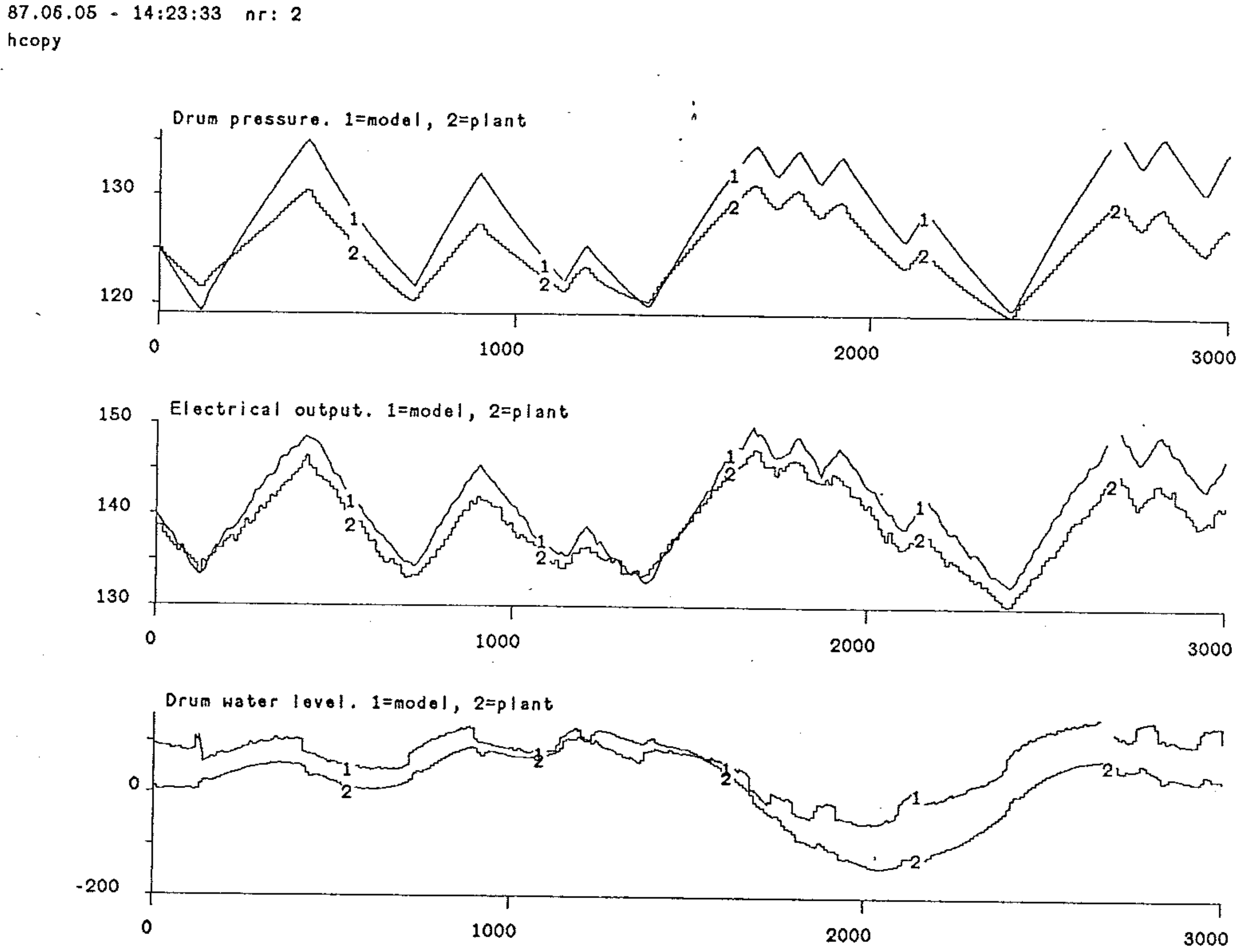

Figure 13. Comparison of plant and model responses, feedwater flow changes, high load, advanced model.

87.06.05 - 09:40:51 nr: 6
hcopy

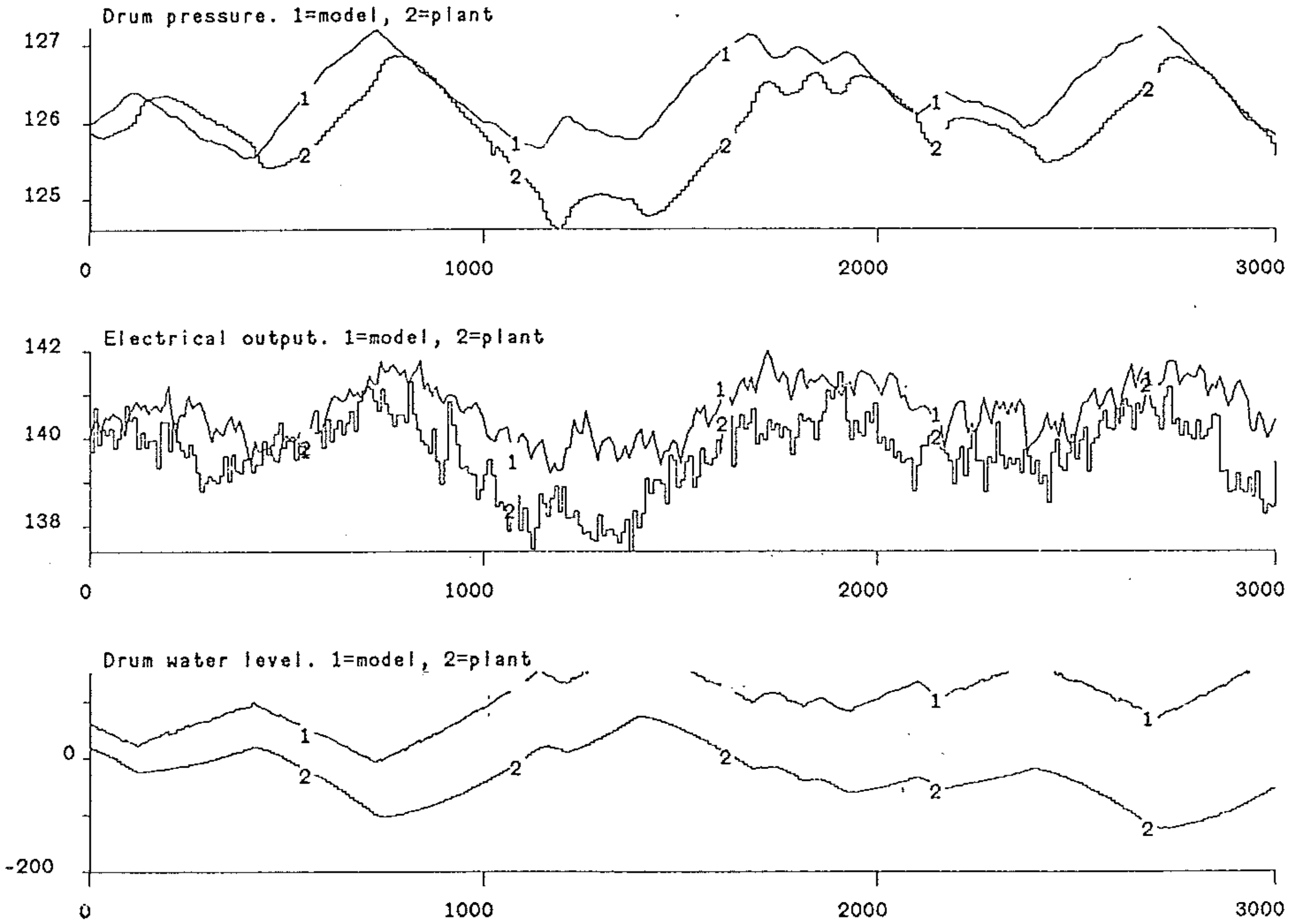

Figure 14. Comparison of plant and model responses, steam flow changes, high load, advanced model.