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Supplement 3 to BISON Topical Report RPA 90-90-P-A SAFIR Control System Simulator

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Supplement 3 to BISON Topical Report RPA 90-90-P-A SAFIR Control System Simulator

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ABSTRACT

The NRC first accepted the Westinghouse Boiling-Water-Reactor Transient Analysis Code, BISON, for referencing in US licensing applications in October 1989. The BISON code has since been extensively applied to the performance of plant transient analysis for licensing applications since that time.

Outside the US, BISON has been further used for transient analysis related to fuel reloads, extended power uprates, and plant modernizations. Plant control systems have also been modeled in detail using the SAFIR control system simulator and modeling tools and extensively validated. SAFIR is a code package containing a selection of standard control components and logical functions that can be coupled for use with any transient code such as BISON.

In the US, BISON has been mainly used in fuel reload licensing analysis and the plant control systems are not explicitly simulated. Instead, the effects of the control systems are simulated by the use of conservative time-dependent boundary conditions.

This report is the third supplement to RPA 90-90-P-A, "BISON – A One Dimensional Dynamic Analysis Code for Boiling Water reactors," Reference 1. The report documents the use of SAFIR, in conjunction with the approved transient analysis code, BISON, to model plant systems important to the balance-of-plant response, thus satisfying and eliminating Condition 6 of the BISON topical report by demonstrating that SAFIR is capable of modeling control systems consistent with the provisions of CENPD-300-P-A, "Reference Safety Report for Boiling Water Reactor Fuel," Reference 3.

This report also presents the process for control system model development, verification and validation using SAFIR in conjunction with an NRC approved transient code such as in this case BISON, as well as describing and demonstrating the SAFIR code itself.

The main purpose of this report is to obtain NRC approval of the SAFIR code and the process that will be used to develop, verify, and validate modeling of control systems using SAFIR in combination with an approved transient analysis code.

This report describes the standard components and logical functions included in SAFIR along with the validation and verification process that is followed for the addition of components and models. Application of the methodology to build-in control systems using basic SAFIR components is also presented including validation of the more complex plant system models.

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ACRONYMS

ACCBEG	Acceleration limiter
APRM	Average Power Range Monitor
APRMFilter	Signal for filtered APRM
ATWS	Anticipated Transients Without Scram
BAFR	Desired steam flow from reactor
BATD	Desired steam flow to bypass
BATDRV	Desired steam flow to bypass control valves
BATHTRV	Desired steam flow high pressure control valves
BATT	Desired steam flow to the turbine
BATVHBP	Desired steam flow to the VHBP
BOP	Balance of Plant
BPV	Bypass Valve
BWR	Boiling Water Reactor
DB	Bypass blockage
DBV	Bypass blockage valve
DRV	Bypass control valve
GRADIENT	Turbine speed time derivative
HPCI	High Pressure Coolant Injection
HTRV	High pressure control valve
HTSV	High pressure stop valve
LEDV_MOH	Reheater setpoint
LF	Load Rejection
LPCI	Low Pressure Coolant Injection
LTR	Licensing Topical Report
LTRV	Low pressure control valve
LTSV	Low pressure stop valve
MANPOS	Manual Position
MOHRV	Reheater control valve
MOHSV	Reheater stop valve
MSIV	Main Steam Isolation Valve
NERR	Control deviation
PI	Proportional, Integrating Controller
PIP	Proportional, Integrating, Proportional Controller
PSPA	Pressure Setpoint Adjustment
RFCS	Recirculation Flow Control System
SAFIR	Logics and control component toolbox
SRV	Safety Relief Valve
TCV	Turbine Control Valve
TS	Time Step
TSV	Turbine Stop Valve
VARVTAL	Turbine speed
VHBP	Capacity trimming
VHBPRV	Capacity trimming control valve
VHBPSV	Capacity trimming stop valve

1 INTRODUCTION

The Westinghouse transient analysis methods are described in the Licensing Topical Reports (LTRs) RPA 90-90-P-A, "BISON – A One Dimensional Dynamic Analysis Code for Boiling Water Reactors," Reference 1, CENPD-292-P-A, "BISON – One Dimensional Dynamic Analysis Code for Boiling Water Reactors: Supplement 1 to Code Description and Qualification", Reference 2, and WCAP-16606-P-A "Supplement 2 to BISON Topical Report RPA 90-90", Reference 4.

RPA 90-90-P-A describes the BISON transient code and the code qualification for BWR transient analyses and was approved for use in license applications by the U.S. NRC in 1989. CENPD-292-P-A was submitted to introduce changes and upgrades to the methods in order to address some of the SER restrictions on the original LTR. The second LTR was approved in 1995. WCAP-16606-P-A was submitted to introduce changes related to ATWS calculations and to increase the range of verification to higher pressures and steam qualities. This third LTR was approved in 2007.

The transient analysis design bases and overall reload methodology are summarized in the Reference Safety Analysis Report for BWR Reload Fuel, Reference 3. The methodology is currently used by Westinghouse for introducing new fuel designs into boiling water nuclear power plants in the U.S.

Outside the U.S., BISON has been used for transient analysis related to fuel reloads, extended power uprates and plant modernizations. Control systems have then been modeled in detail using SAFIR. Using these models SAFIR has also been extensively validated. SAFIR is a code package containing a selection of standard control components and logical functions that can be coupled to any transient code.

In the U.S. BISON, along with the hot channel model SLAVE, has long been found acceptable for licensing of reload transients used in fuel reload analysis. Control systems are not explicitly simulated by BISON, but the effects of the control systems are simulated by conservative time-dependent boundary conditions.

This report is the third supplement to RPA 90-90-P-A, "BISON – A One Dimensional Dynamic Analysis Code for Boiling Water Reactors," Reference 1, and aims to document how SAFIR is used in conjunction with BISON to model plant systems important to the balance-of-plant and thereby eliminate Condition 6 of the BISON topical report by demonstrating SAFIR is capable of modeling control systems consistent with the provisions of CENPD-300-P-A, "Reference Safety Report for Boiling Water Reactor Fuel," (Reference 3).

This Report describes the SAFIR control system simulator and generic modeling tools for use for performing licensing basis analysis. SAFIR is a stand-alone modeling tool for simulation of plant systems, including control systems, in conjunction with approved transient modeling codes such as BISON. As in the case of the SLAVE model, BISON output data is retrievable for further use for a SAFIR control system model. Qualification of the SAFIR control system simulator and turbine assembly model provides the necessary examples and documentation of the SAFIR modeling capabilities, performance, and qualifications for NRC staff review and approval. SAFIR is capable of modeling various types of transients which include, but not limited to, Load Rejection, Turbine Trip, Core Power or Pressure changes, and valve failures.

For this reason a process for model development, verification and validation using SAFIR and a NRC approved transient code, in this case BISON, is described and demonstrated as well as the SAFIR code itself.

- The Westinghouse definition of verification is to show the functionality and to ensure that requirements are fulfilled.
- The Westinghouse definition of validation is to show the behavior compared with reference data like e.g. measurement data.

The main purpose of this amendment is to license the SAFIR code and the process that uses the SAFIR code to develop, verify, and validate control systems in combination with licensed transient codes.

2 SUMMARY AND CONCLUSIONS

2.1 SUMMARY

SAFIR has been used for many years outside of the United States to model plant response both in steady-state and transient analysis. In this report the SAFIR model process is demonstrated against two BWR plants, [ ]^{a,c} in Sweden and Hamaoka-5 in Japan. The SAFIR model process will be demonstrated by:

- A description of SAFIR components and how they connect into models such as control systems including interaction with the transient code BISON is presented.
- A description of the SAFIR component verification and validation process including an example is presented.
- A description of the SAFIR model verification and validation process including two examples is presented.
    - A SAFIR built turbine controller model for the [ ]^{a,c} plant in Sweden is used to demonstrate the complete process of model development, verification and validation. In this case the final validation consists of a comparison between different measured and calculated internal controller signals as well as turbine valve positions vs. time.
    - Startup tests from the Japanese ABWR plant Hamaoka-5 are used to further demonstrate the validation process. In this validation the capabilities of BISON and SAFIR to simulate the plant response during transient startup tests are shown. In those simulations detailed models are used for the Recirculation Flow Control System, the Turbine Control System, and the Feedwater Control System.

2.2 CONCLUSIONS

The SAFIR plant models described in this report provide an accurate simulation against expected behavior (verification) and measurement data including actual plant transients (validation).

Based on the information provided in this report, it is concluded that:

- SAFIR is capable of simulating plant dynamic boundary conditions
- SAFIR is capable of modeling simple and complex plant systems including control systems
- SAFIR is compatible with approved NRC methodology codes
- Applications of SAFIR will be consistent with NRC approved methodology, e.g. for transient analysis as described in Reference 3.
- The development, verification and validation process ensures that SAFIR models can be developed to a desired functionality.

Therefore, SAFIR can be used to model plant control systems and analyze plant performance during steady-state operations as well as transient conditions.

The SAFIR code is a generic tool which can be used with any type of simulation code for any type of plant where the interaction of control systems with a simulated process is required. The only requirement is that there is an interface between the simulation code and SAFIR.

In this report, however, only application to BWRs is shown. In this case BISON is the transient code interacting with SAFIR, but other dynamic BWR codes that are approved for the application by the NRC may be used provided the model development and the verification and validation process is followed.

3 SAFIR BASIC DESCRIPTION

3.1 INTRODUCTION

SAFIR is a code with a selection of standard components that can be used to model BWR balance of plant responses, such as control systems. These components include mathematical operators (e.g. adder, multiplier), Boolean operators (e.g. and, not, or), filters (e.g. first- and second-order low pass filters), etc. Each component has a specific set of input and output parameters which can be tested against an expected solution. Components can be coupled together to form more complex systems or part of systems. When components are combined they are called a "macro" or a "model" as described in Section 3.4 and 3.5. Macros and models are not part of the source code, but specified as input by the user.

SAFIR is a code that through user input can be used to simulate most types of control systems or logical functions. SAFIR can be used both for simulation of digital systems like digital control systems as well as analog systems.

The flexibility of SAFIR allows for building in predefined system malfunctions that can be triggered from input.

The following type of building components are the bases for SAFIR:

- Components (basic components included in the source term)
- Macro components (combining two or more basic or macro components)
- Models (combining basic and macro components to build systems)
- Signals (connecting components)

For a transient code e.g. BISON, it is required that SAFIR is compiled and loaded as a part of the transient code. The communication interface between SAFIR and the transient code using signals has to be defined. For BISON this interface is described in Section 3.8

3.2 COMPONENTS

A component is a function that based on different inputs computes an algorithm and generates an output at a specific sampling time. The input connections may connect to a constant or a time dependent value (a "signal"), the output will be a time dependent value, calculated each TS second.

Consider the below example of a component "COMP" that compares the input values IN1 and IN2 at each TS second and then generates the output OUT. OUT is .FALSE. if IN1 <= IN2 or OUT is .TRUE. if IN1 > IN2. IN1, IN2 and TS are "input connectors" and OUT is an "output connector".

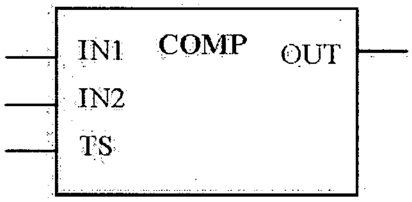

Figure 3-1 Component

3.3 INSTANCE

A component like COMP described above, can be seen essentially as a component type. Each component that is part of a macro or model is required to have a unique name. The name will form an instance of the component type and describes which connectors are used and what signals or values that are associated with each connector. In the example below an instance named #1 is defined as the COMP component with signals INA, INB, TS1 and Z attached. This can typically be drawn as:

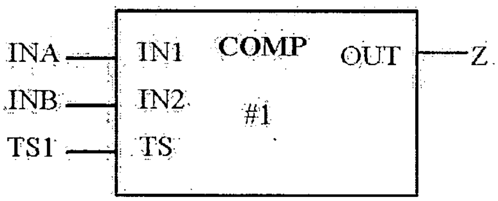

Figure 3-2 Instance of a component

3.4 MACRO

A macro is a user defined function consisting of a set of components. The defined macro can be used in the same way as one single component. Macro components can be less complex than models.

3.5 MODELS

A model is a combination of at least two components. Consider the COMP component from the definition above and imagine two COMP components put together. This forms a very simple model as shown below. It is now evident the need to have different names of the two components to be able to distinguish between them.

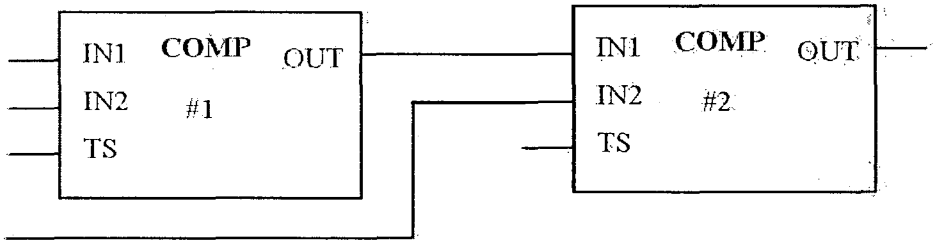

Figure 3-3 Model

3.6 SIGNALS

A signal is a variable that can change with time. Signals are used to connect components into models, as well as connections between models. Signals also serve as the connection between components/models and the transient code.

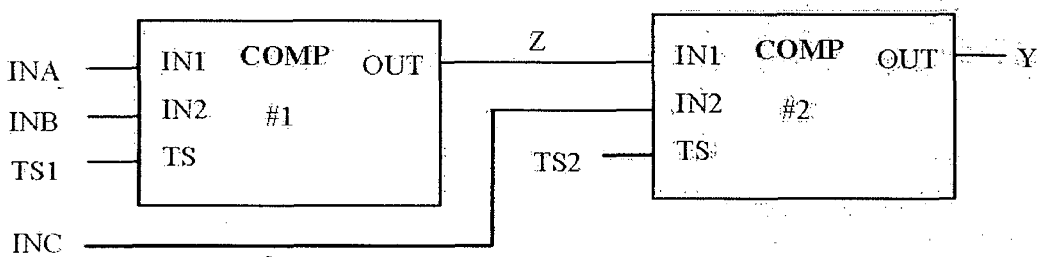

Figure 3-4 Signal

In the above example, a signal INA is connected to the input IN1 of COMP #1, INB to IN2 of COMP #1, INC to IN2 of COMP #2 and so on. The signal Z is slightly different since it connects the output OUT from COMP #1 to the input IN1 of COMP #2. The combined function uses the output from COMP #2 and connects this to signal Y.

The following signal definitions apply:

- An input signal is connected to one or several component(s) input connectors. It may be changed by the user and can be connected from an output of another component. INA, INB, INC, TS1, TS2 and Z are input signals in the above example.
- An output signal is connected to exactly one component output connector and will be calculated according to the component. An output signal may be assigned an initial value at time zero by the user. Z and Y are output signals in the above example.
- An internal signal connects between component output and input connectors. These signals are local in a model and will not interact with other models. Z is an internal signal in the above example.

3.7 INITIALIZATION OF SIGNALS

SAFIR automatically assigns values to model output signals for the steady-state solution based on known input signals and the standard component response.

Generally the output of a component changes only by changing the input signal(s).

There is however one exception to this, when a component that does not have a clear steady-state relationship between input and output because the history is unknown. Such components are typically

- Set/reset switches where last set or reset is not known (not initialized) so the output is unknown in the steady-state solution.
- All types of components that contain historical information, e.g. integrating control components, may have a different steady-state solution than zero as output.
- Components that feed back the output to an input.

For this reason SAFIR has the option to initialize the steady-state output of components to a prescribed value.

Initialization may be to a fixed number or to the steady-state value of a signal that is user defined or an output signal defined by a previous SAFIR model or the transient code.

3.8 MODEL COMMUNICATION

Communication between models can only be made with signals that connect outputs from one model to inputs of other models.

In this sense the transient code that uses SAFIR is considered to be a model with outputs and inputs which are communicated with SAFIR. The input signals from BISON to SAFIR are listed in Table 3-1 below as well as the outputs from SAFIR to BISON.

For the BISON code implementation of SAFIR the input and output signal connections consist of, but are not limited to, the signals in Table 3-1 below.

Table 3-1 BISON Input and Output Signals

Parameter	IN	OUT	Comment (usage in a model)
Transient time		X	For time control
Steam dome pressure		X	Typically for measurement
Pressure at specified elevation in the downcomer		X	Typically for level measurement
Average Power Range Monitor		X	Typically for measurement
Recirculation flow		X	Typically for measurement
Recirculation pump speed for each pump	X	X	Can not be set in steady-state. Typically for power control
Recirculation pump motor momentum for each pump		X	Typically for power control
Recirculation pump angular speed for each pump		X	Typically for power control
Nominal recirculation flow		X	For normalization
Nominal steam flow		X	For normalization
Nominal electrical power output		X	For normalization
Nominal steam dome pressure		X	For normalization

Nominal thermal power		X	For normalization
Electrical power output		X	Typically for power control
Reactor two-phase water level		X	Typically for water level indication
Feedwater temperature	X	X	Can not be set in steady-state since it is calculated by the energy balance
Feedwater flow	X	X	Can not be set in steady-state since it is calculated by the energy balance
Core support plate pressure drop		X	Typically for flow measurement
Scram signal (.TRUE./.FALSE.)	X	X	Set also by BISON if built-in models are activated.
Recirculation pump runback signal (.TRUE./.FALSE.)	X	X	Set also by BISON if built-in models are activated.
Recirculation pump trip signal for each pump (.TRUE./.FALSE.)	X	X	Set also by BISON if built-in models are activated.
Pressure in all steam line nodes		X	Typically for pressure control
Flow in all steam line nodes		X	Typically for pressure control
Pressure in all steam line valves		X	Typically for modeling self closure and relief valves actuated on local pressure
Flow in flow controlled steam line valves (e.g. TCV,TSV,BPV,SRV)	X	X	Not in steady-state. To control valve flows
Areas of area controlled main steam line valves (e.g. MSIVs)	X		To control MSIV closure
Auxiliary feedwater etc start signal, flow and enthalpy	X		Typically for HPCI, LPCI etc
Boron solution start signal and flow	X		Typically for ATWS boron shutdown

If a new input or output connector is requested this will be added to the code using the standard code update procedures.

3.9 NUMERICS

3.9.1 Sampling Time

All SAFIR components can have their own individual sampling time.

For digital control systems different models or even components can have individual sampling times.

- For a digital control system the requirement on individual component sampling time shall be that of the real plant component.

For an analog system a similar sampling time does not exist. However, the transient code itself is digital so this determines the requirement for the component sampling time.

- For an analog control system the sampling time shall not be longer than the transient code time step.

3.10 AVAILABLE COMPONENTS

The available verified and validated basic components are listed in Table 3-2 below. More components can be added to the code following the Westinghouse standard quality assurance processes for code changes.

Common for all components is the sampling time TS. Most components also have a maximum and minimum limitation defined by MAX and MIN.

Many components can also perform a balancing function denoted "following" which means that the output signal connection OUT will follow the external reference signal connected to the input connection F. Following is started when component input connector CF is set to .TRUE. and stops when CF is reset to .FALSE.

Following means that the output OUT is set to the signal or value connected to the input connection F as long as CF is .TRUE.

Boolean .FALSE. and .TRUE. are simulated with floating number where .FALSE. is 0 and .TRUE. is 1, the threshold between .FALSE. and .TRUE. is set to 0.5 where floating numbers less than 0.5 are considered .FALSE.

SAFIR components are described in Table 3-2 below. In the table "t" denotes simulation time in the digital output.

Table 3-2 SAFIR Components

Function	Description	Input	Output
INT	Integrator INT (INTegrator) is used to give an integration effect. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference and permits a bumpless return to the normal function. The main property when controlling is that the output signal retains its value when the input signal IN(t) = 0.	IN, K, TI, TS, MIN, MAX, F, CF	Transfer function G(s) = K • (1/(sTI)) OUT(t) = K(t) • TS/TI(t) • IN(t) + OUT(t-TS)

PI	PI-controller PI (Proportional Integrating) is used as a standard PI-regulator for serial compensation in feedback systems. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference and permits a bumpless return to the normal function.	IN, K, TI, TS, MIN, MAX, F, CF	Transfer function $G(s) = K \cdot (1 + 1/(sTI))$ $OUT(t) = K(t) \cdot (1+TS/TI(t)) \cdot IN(t) - K(t) \cdot IN(t-TS) + OUT(t-TS)$
PIP	PIP-controller PIP (Proportional Integrating Proportional) is used to give a proportional effect and a limited integration effect. The output signal in steady-state is proportional to the input signal. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference and permits a bumpless return to the normal function.	IN, K, T1, T2, TS, MIN, MAX, F, CF	The transfer function $G(s) = K \cdot (1+sT1) / (1+sT2)$, where $T1 < T2$ $OUT(t) = K(t) \cdot (C1 \cdot IN(t) - C2 \cdot IN(t-TS)) + C3 \cdot OUT(t-TS)$, where $T1 < T2$ where $C1 = (2 \cdot T1(t) + TS) / (2 \cdot T2(t) + TS)$ $C2 = (2 \cdot T1(t) - TS) / (2 \cdot T2(t) + TS)$ $C3 = (2 \cdot T2(t) - TS) / (2 \cdot T2(t) + TS)$
PDP	PDP-controller PDP (Proportional Derivating Proportional) is used to give a proportional effect and a limited derivation effect. The output signal in steady-state is proportional to the input signal. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference and permits a bumpless return to the normal function.	IN, K, T1, T2, TS, MIN, MAX, F, CF	Transfer function $G(s) = K \cdot (1+sT1) / (1+sT2)$, where $T1 > T2$ $OUT(t) = K(t) \cdot (C1 \cdot IN(t) - C2 \cdot IN(t-TS)) + C3 \cdot OUT(t-TS)$, where $T1 > T2$ where $C1 = (2 \cdot T1(t) + TS) / (2 \cdot T2(t) + TS)$ $C2 = (2 \cdot T1(t) - TS) / (2 \cdot T2(t) + TS)$ $C3 = (2 \cdot T2(t) - TS) / (2 \cdot T2(t) + TS)$
DERIV	Physical derivative	IN, K, TD,	Transfer function

	DERIV (DERIVator) is used to give a derivation effect. The derivation effect can be limited with the filter function, which serves as a low pass filter. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference and permits a bumpless return to the normal function.	TF, TS, MIN, MAX, F, CF	G(s) = K • sTD/(1+sTF) OUT(t) = K(t) • (C1 • IN(t) + C2 • IN(t-TS)) + C3 • OUT(t-TS) where C1 = 2 • TD(t) / (2 • TF(t) + TS) C2 = –C1 C3 = (2 • TF(t) – TS) / (2 • TF(t) + TS)
LOWP1	1st order low pass filter LOWP1 (LOW Pass filter 1-pole) is used as a single pole low pass filter. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference and permits a bumpless return to the normal function.	IN, K, T, TS, MIN, MAX, F, CF	Transfer function G(s) = K • 1/(1+sT) OUT(t) = K(t) • (C1 • IN(t) + C2 • IN(t-TS)) + C3 • OUT(t-TS) where C1 = TS(t) / (2 • T(t) + TS) C2 = C1 C3 = (2 • T(t) – TS) / (2 • T(t) + TS)
LOWP2	2nd order low pass filter LOWP2 (LOW Pass filter 2-pole) is used as a 2-pole low pass filter. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference and permits a bumpless return to the normal function.	IN, K, T1, T2, D, TS, MIN, MAX, F, CF	Transfer function $G(s) = K \cdot (1+sT1) / ((1+2 \cdot D \cdot sT2)+sT2^2)$ OUT(t) = K(t) • (C1 • IN(t) + C2 • IN(t-TS) + C3 • IN(t - 2 • TS)) + C4 • OUT(t-TS) + C5 • OUT(t - 2 • TS) where $C1 = Q \cdot ((TS / T2(t))^2 + 2 \cdot T1(t) \cdot TS / T2(t)^2)$ $C2 = Q \cdot 2 \cdot (TS / T2(t))^2$ $C3 = Q \cdot ((TS / T2(t))^2 - 2 \cdot T1(t) \cdot TS / T2(t)^2)$ $C4 = Q \cdot (8 - 2 \cdot (TS / T2(t))^2)$ $C5 = Q \cdot (4 \cdot D(t) \cdot TS / T2(t) - (TS / T2(t))^2 - 4)$ $Q = 1 / ((TS / T2(t))^2 + 4 \cdot D(t) \cdot TS / T2(t) + 4)$
AMP	Amplifier AMP (AMPlifier) is used as an amplifier in feedback systems. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the	IN, K, TS, MIN, MAX, F, CF	Transfer function G(s) = K OUT(t) = K(t) • IN(t)

	output signal to follow an external reference.		
DB	Dead band filter DB (Dead Band filter) is used as a low amplitude filter for signal changes less than a specified dead band. The output signal can be limited to limit values specified by input MIN and MAX.	IN, K, DEADB, TS, MIN, MAX	OUT is dependent on the difference between the input signal and the output signal of the previous sample. The input signal change related to the output signal is calculated as abs (IN(t) - OUT(t - TS)). If the input signal change is greater than or equal to DEADB, the input signal is not processed: OUT(t) = IN(t). The input signal change is amplified with a factor K if the input signal change is less than DEADB OUT(t)=OUT(t-TS)+K(t) • (IN(t)-OUT(t-TS)), that is, an output signal change which is dependent on the difference between the input signal and the output signal of the previous sample. This function corresponds to a first order filter.
RAMP	Ramp function RAMP (RAMP function) is used to limit the speed of change of a signal. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference. The main property of a RAMP function is that the output signal follows the input signal while the input signal is not changed more than the value specified at the step inputs (STP and STN). If the input signal is changed more than so, the output signal is first changed by STP or STN - depending on the direction of change and the by SLP or SLN – per second until the value at the input and output are equal.	IN, PSLP, NSLP, PSTP, NSTP, TS, MIN, MAX, F, CF	The output signal is calculated, with respect to three different cases. IN(t) = OUT(t-TS) No changes and the output signal is equal to the input signal IN(t) > OUT(t-TS) OUT(t) = min(I(t), PSLP(t)•TS + VP(t-TS) + PSTP(t)) IN(t) < OUT(t-TS) OUT(t) = max(I(t), SLN(t)•TS + VN(t-TS) – NSTP(t)) where VP(t) = min(OUT(t),VP(t-TS)+PSLP(t)•TS) VN(t) = max(OUT(t),VN(t-TS)-NSLP(t)•TS)
FUNK	Function generator FUNK (FUNction generator – 1 variable) is used for generation	IN, TAB(X), TS, MIN,	The output signal is calculated as a piece by piece linear function determined by TAB(X). For each X-value in TAB there is a

	of an optional function of 1 variable, y = f(x). The function is described by a number of co-ordinates. Linear interpolation is used for values between these co-ordinates. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference.	MAX, F, CF	corresponding Y-value. The output signal is calculated by means of interpolation between the two Y-values corresponding to the two X-values in TAB which surround the value of the input signal IN(t). OUT(t) = TAB(IN(t)) If the input signal is outside the range defined by TAB(X), the output signal is set to the first or last value in TAB(X) which is nearest the value of the input signal IN(t).
PROF	Profile generator A function generator – time is used for generating a signal, the value of which varies with time in accordance with an optional function. It is used in applications in which a process signal is to be controlled in accordance with a predetermined sequence (profile) specified from a start time. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference.	IN, TAB(T), START, RESET, HOLD, DSTART, EN, TS, MIN, MAX, TS, F, CF	The output signal is calculated as a piece by piece linear function determined by TAB(T). For each T-value in TAB there is a corresponding Y-value. The output signal is calculated by means of interpolation between the two Y-values corresponding to the two T-values in TAB(T) which are nearest the value of the internal time. When either START or EN is set, the internal timing. Internal time stops when HOLD is set or EN is reset. When START or EN is set .TRUE. internal timing commences and t_{START} is set to t. OUT(t) = TAB(t-t_{START}) When HOLD is set .TRUE. or EN is set .FALSE. OUT(t) is frozen When HOLD is set .FALSE. OUT(t) continues to follow TAB When RESET is set .TRUE. Internal time is reset to zero and OUT(t) = TAB(0) DSTART may be used to reset the internal timing t_{START} to t when disengaging the following function. The output signal will be frozen until OUT(t) = TAB(t-t_{START}).
OMK	Switch OMK is used as a connection element for data. The output signal can be limited to limit values specified by input MIN and MAX.	IN1, IN2, GATE, TS, MIN, MAX	GATE is .FALSE. => OUT(t) = IN2(t). GATE is .TRUE. => OUT(t) = IN1(t).
GVB	Limiter with hysteresis GVB is used for limit value monitoring of real numbers.	IN, HIGH, LOW, TS	Hysteresis can not be explicitly given, but are set to the difference between HIGH and LOW. HIGH >= LOW

			OUT(t) is .TRUE. when IN(t) is greater than HIGH OUT(t) = .FALSE. when IN(t) is less than LOW <u>HIGH < LOW</u> OUT(t) = .FALSE. when IN(t) is greater than LOW OUT(t) = .TRUE. when IN(t) is less than HIGH
M2G	At least two gate M2G is used to determine when at least two Boolean signals are set. The output signal can be limited to limit values specified by input MIN and MAX.	IN_1, IN_2, …, IN_N, TS, MIN, MAX	Determines if at least two of $IN_1(t)$, $IN_2(t)$,…, $IN_N(t)$ are .TRUE. If that is the case, OUT(t) = .TRUE.
MVV	Midvalue selector MVV is used to calculate the median value of a maximum of four input signals. The output signal can be limited to limit values specified by input MIN and MAX.	IN_1, IN_2, IN_3, IN_4, TS, MIN, MAX	<u>One or three input signal(s)</u> OUT(t) = is set to the middlemost input signal value. <u>Two or four input signals</u> OUT(t) is calculated as the arithmetic mean of the two middlemost input signal values.
SUM	Adder SUM is used for addition of an optional number input values. The output signal can be limited to limit values specified by input MIN and MAX.	IN_1, IN_2, …, IN_N, TS, MIN, MAX	$OUT(t) = IN_1(t) + IN_2(t) + , \ldots, + IN_N(t))$
SUB	Subtractor SUB is used for subtraction of two input values. The output signal can be limited to limit values specified by input MIN and MAX.	IN_1, IN_2, TS, MIN, MAX	$OUT(t) = IN_1(t) - IN_2(t)$
MULT	Multiplier MULT is used for multiplication of an optional number input values. The output signal can be limited to limit values specified by input MIN and MAX.	IN_1, IN_2, …, IN_N, TS, MIN, MAX	$OUT(t) = IN_1(t) \bullet IN_2(t) \ldots \bullet IN_N(t)$
DIV	Divider DIV is used for division of two input values. The output signal can be limited to limit values specified by input MIN and MAX.	IN_1, IN_2, TS, MIN, MAX	$OUT(t) = IN_1(t) / IN_2(t)$

AND	AND gate AND is used to form general combinatory expressions with Boolean variables.	IN_1, IN_2, ..., IN_N, TS	Boolean algebra notation $OUT(t) = IN_1(t) \bullet IN_2(t) \bullet ... \bullet IN_N(t)$ The output is only set to .TRUE. when all input signals are set to .TRUE..
OR	OR gate OR is used to form general combinatory expressions with Boolean variables.	IN_1, IN_2, ..., IN_N, TS	Boolean algebra notation $OUT(t) = IN_1(t) + IN_2(t) + ... + IN_N(t)$ The output is set to .TRUE. if one input signal is set to .TRUE.
NOT	Inverter NOT is used for inverting Boolean variables.	IN, TS	Boolean algebra notation $OUT(t) = ! IN(t)$ The output is set to .TRUE. if the input signal is .FALSE..
SR	Set/Reset switch SR (Set Reset) is used as a memory for Boolean variables.	SET, RESET, TS	OUT(t) = .TRUE. if SET = .TRUE. at the same time that the RESET = .FALSE. OUT(t) = .FALSE. if RESET = .TRUE.
DELAY	Delay element Time delay on and off of Boolean variables for use in connection with combined expressions.	IN, TDON, TDOFF, TS	When IN(t) changes from .FALSE. to .TRUE., OUT(t) = .TRUE. with a delay of TDON sec. When IN(t) changes from .TRUE. to .FALSE., OUT(t) = .FALSE. with a delay of TDOFF sec.
MAX	Maximizer MAX is used to select the largest value of an optional number of inputs. The output signal can be limited to limit values specified by input MIN and MAX.	IN_1, IN_2, ..., IN_N, TS, MIN, MAX	$OUT(t) = max(IN_1(t), IN_2(t), ..., IN_N(t))$
MIN	Minimizer MIN is used to select the smallest value of an optional number of inputs. The output signal can be limited to limit values specified by input MIN and MAX.	IN_1, IN_2, ..., IN_N, TS, MIN, MAX	$OUT(t) = min(IN_1(t), IN_2(t), ..., IN_N(t))$
COMP	Comparator COMP (COMParator) is used to compare two values. Output signal is Boolean.	IN1, IN2, TS	If IN1(t) > IN2(t) => OUT(t) = .TRUE. If IN1(t) <= IN2(t) => OUT(t) = .FALSE.
ALARM	Alarm ALARM is a comparator of two values used with a printout function. Output signal is Boolean.	IN, ABOVE, BELOW, ALARM, TS	Alarm printing function. The string to be printed is given as input to connection ALARM. <u>If ABOVE is given:</u> If IN(t) > ABOVE ALARM is printed <u>If BELOW is given:</u> If IN(t) < BELOW ALARM is printed OUT(t) = .TRUE. if ALARM has been printed

ABS	Amplifier with absolute value output ABS is used to form the absolute value of the input signal. The absolute value can be multiplied with an optional value. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference.	IN, K, MIN, MAX, F, CF	OUT(t) = K(t) • abs(IN(t))
SIN	Sinus generator SIN (SINus generator) is used to generate a sinus oscillation. The output signal can be limited to limit values specified by input MIN and MAX.	AMPL, FREQ, AVER, START, TS, MIN, MAX	When START is set .FALSE. OUT(t) = AVER When START is set .TRUE. t_{START} is set to t. OUT(t) = AVER + AMPL• sin(2π • (t- t_{START}) • FREQ)
TRI	Triangular wave generator TRI (TRIangular wave generator) is used to generate a triangular wave oscillation. The output signal can be limited to limit values specified by input MIN and MAX.	AMPL, FREQ, AVER, START, TS, MIN, MAX	When START is set .FALSE. OUT(t) = AVER An ongoing wave will continue until the AVER value is reached, the output signal will thereafter freeze at value AVER. When START is set .TRUE. t_{START} is set to t. X = mod(t- t_{START} , 1/FREQ) If X < 1 / (4 • FREQ) OUT(t) = X / (1 / (4 • FREQ)) • AMPL + AVER If X < 2 / (4 • FREQ) OUT(t) = - (X – 1 / (4 • FREQ)) / (1 / (4 • FREQ)) • AMPL + AMPL + AVER If X < 3 / (4 • FREQ) OUT(t) = - (X – 1 / (2 • FREQ)) / (1 / (4 • FREQ)) • AMPL + AVER otherwise OUT(t) = X – 3 / (4 • FREQ)) / (1 / (4 • FREQ)) • AMPL - AMPL + AVER
RECT	Rectangle wave generator RECT (RECTangular wave generator) is used to generate a rectangular wave oscillation. The output signal can be limited to limit values specified by input MIN and MAX.	AMPL, FREQ, AVER, START, TS, MIN, MAX	When START is set .FALSE. OUT(t) = AVER When START is set .TRUE. t_{START} is set to t. X = mod(t- t_{START} , 1/FREQ) – 0.5/FREQ If X < 0 => FX = 1, otherwise FX = -1 OUT(t) = AVER + AMPL • FX

UNI	Uniform noise generator UNI (UNIform noise generator) is used to generate uniform distributed noise. The output signal can be limited to limit values specified by input MIN and MAX.	A, B, START, TS, MIN, MAX	The generated noise is uniformly distributed between A and B. The noise generator is started when START is set to .TRUE.. If START is set to .FALSE., the noise generator gives the average value (A + B)/2 as the output. If the generator has been started and the start signal is set back to .FALSE., the generator will immediately stop generating noise and the output will be the average value (A + B)/2.
NORM	Normal noise generator NORM (NORMal noise generator) is used to generate normal distributed noise. The output signal can be limited to limit values specified by input MIN and MAX.	AVER, SIGMA, ANT, START, TS, MIN, MAX	OUT(t) = normal distributed noise with an average value AVER and a standard deviation SIGMA. NORM is started when START is set to .TRUE. If START is set to .FALSE., OUT(t) = AVER. ANT denotes the number of random values used for generating each sample of noise.
PRBS	PRBS noise generator PRBS (Pseudo Random Binary Sequence generator) is used to generate PRBS. The output signal can be limited to limit values specified by input MIN and MAX.	A, B, ORDER, START, TS, MIN, MAX	OUT(t) = pseudo-random binary sequences (PRBS). PRBS generates a signal which is either A or B. PRBS is started when START is set to .TRUE. If START is set to .FALSE., OUT(t) = 0.
SQRT	Square root function SQRT (SQuare RooT) is used to calculate the square root of the input signal. The result can be multiplied with an optional value. The output signal can be limited to limit values specified by input MIN and MAX. The balancing function permits the output signal to follow an external reference.	IN, K, TS, MIN, MAX, F, CF	OUT(t) = K(t) • sqrt(IN(t)) If input signal is less than or equal to zero. OUT(t) = 0 and ERR(t) = 1
EXP	Exponential EXP (EXPonential) is used to calculate the exponential of the input signal. The result can be multiplied with an optional value. The output signal can be	IN1, IN2, TS, MIN, MAX	OUT(t) = IN2(t) exp(IN1(t))

	limited to limit values specified by input MIN and MAX.		
PUMP	Pump function PUMP calculates pressure setup as a function of flow and angular velocity. The pump curve is specified as a table with pressure setup (Y) versus flow (X). The input signal RPM shall be normalized so that the maximum angular velocity is 1.0.	RPM, FLOW, TAB(X), TS, MIN, MAX	DP(t) = RPM • abs(RPM) • (Y1 + (FLOW / RPM - X1) • (Y2 – Y1)/(X2 – X1) For each X-value in TAB there is a corresponding Y-value. The output signal is calculated by means of interpolation between the two Y-values corresponding to the two X-values in TAB.

3.11 LIMITATIONS

Within SAFIR the following general limitations are applied:

- A signal can only be connected to one single output
- A model must have at least one input signal
- An instance of a component must have a unique name within a model

4 COMPONENT VERIFICATION AND VALIDATION PROCESS

4.1 INTRODUCTION

The addition of a component to SAFIR follows the Westinghouse standard quality assurance processes both for the implementation verification and validation when required.

Components that may be added by the described procedure shall only consist of a simple transfer function.

An example of verification for a component is shown in Section 4.4 below.

4.2 VERIFICATION

The Westinghouse definition of verification is to show the functionality of the component and to ensure that the component fulfills the requirements.

Once a component is defined and implemented it has to be verified. The verification is designed to show the implementation of the component is in agreement with the functional requirements and the algorithm is correctly implemented.

For simple components e.g. an AND gate or a SUM component only a small set of verifications are needed.

For more complex components the verification becomes more extensive to verify the functionality. Such verification can consist of comparisons with:

- Theoretical solution
- Code to code comparison
- Other methods of solutions

4.3 VALIDATION

The Westinghouse definition of validation is to show the component behavior coincides with the reference data, e.g. measurement data.

Validation is only required for complex components which are empirical or designed to fit measurement data. Such validation will be performed using comparisons to measurement data.

4.4 VERIFICATION EXAMPLE

4.4.1 PI component

4.4.1.1 Function

Component PI is used to give a proportional effect and an integration effect. The output signal will be constant if the input signal is 0. The output signal can be limited within limit values. The balancing function permits the output signal to follow an external reference and permits a smooth and bumpless return to the normal function.

The PI component main property in control mode is that it permits the integral section (portion) of the function to retain its value when the input signal is 0, which keeps the output signal at a constant level.

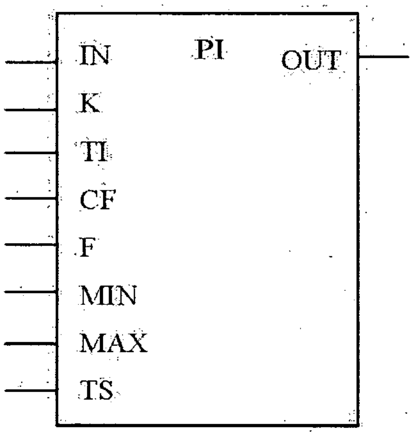

Figure 4-1 The PI component

IN represents the input signal name or value. K can be used for amplification if needed. TI is the time constant for integration. TI is not allowed to be smaller than TS, and if TI < TS, TI is automatically set equal to TS. CF is the logical signal name that initiates following. If CF is set to 1 (.TRUE.), the component immediately starts to follow the reference value of the input F and the output is set to the value of the input F. If the value at F is not within the output signal limits, the output is set to the limit value concerned. On return to the normal function, the value of output during the last sample in following remains during one sample time, after which integration will be performed from this value. TS denotes the sampling time (s). MAX specifies the maximum value of the output signal and MIN specifies the minimum value of the output signal. OUT is the output signal. The transfer function, G(s), for the PI component is:

$$G(s) = K + \frac{K}{s \cdot TI}$$

4.4.1.2 Requirements

The requirements for this component are as follows:

a,c

[ ]

4.4.1.3 Verification

For the PI component, two separate time-dependent verifications were performed. The first verification tested the function as a time-dependent case with the optional following option engaged.

The second verification tested the component in a time-dependent case without the following option engaged. Both positive and negative numbers were incorporated into the test cases. Boolean numbers were also used to turn the following option on or off. In choosing these two verifications, all relevant aspects of the component were able to be accurately tested.

4.4.1.3.1 Time-Dependent PI with Following – Time Constant Test

The PI component may be executed as a time-dependent function with following. Three signals were created – A, C and D. They changed over a five-second period. See Figure 4-2 and Figure 4-3.

- Signal A was fed into the input connector (IN).
- Signal C represented the time constant for integration (input connector TI).
- Signal D represented the Boolean signal to enable a following function (input connector CF), with the reference value for following (input connector F) set to 2.

The amplification (K) was held constant at 1, and the output (output connector OUT) was initialized to 0.

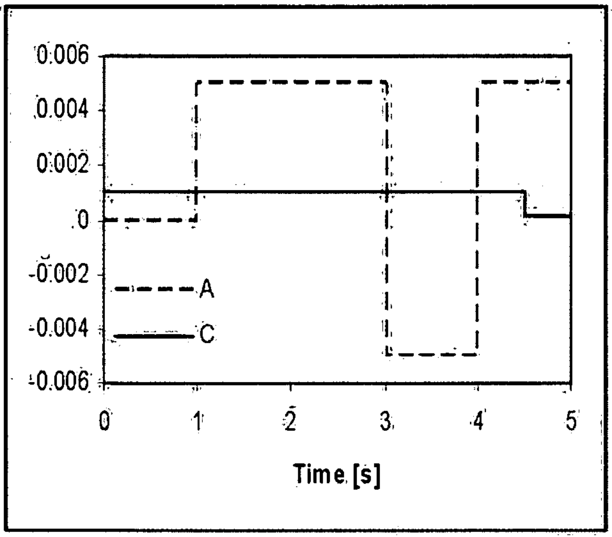

Figure 4-2 Signals A and C

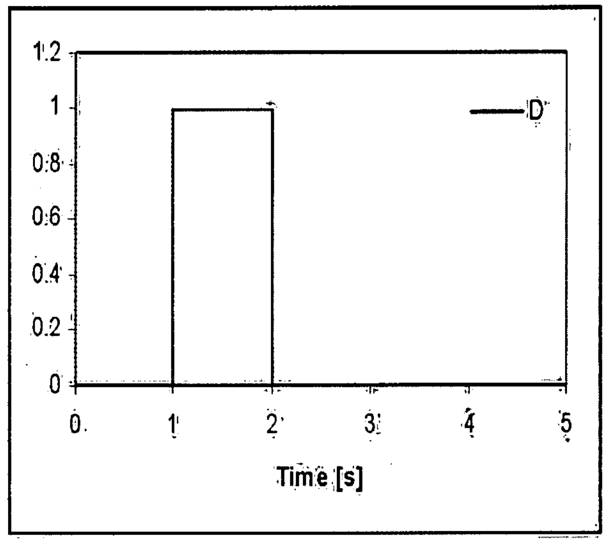

Figure 4-3 Signal D

Also tested in this verification were the maximum (MAX) and minimum (MIN) output limitations, as well as results for setting the time constant (TI) for integration to a value that was less than the sampling time (TS). The change in TI occurs at 4.5 seconds. No slope change in the output occurs at this time, and therefore the requirement that TI must not be less than TS is satisfied.

Graphical results for this time-dependent case with the following option can be found in Figure 4-4 and Figure 4-5.

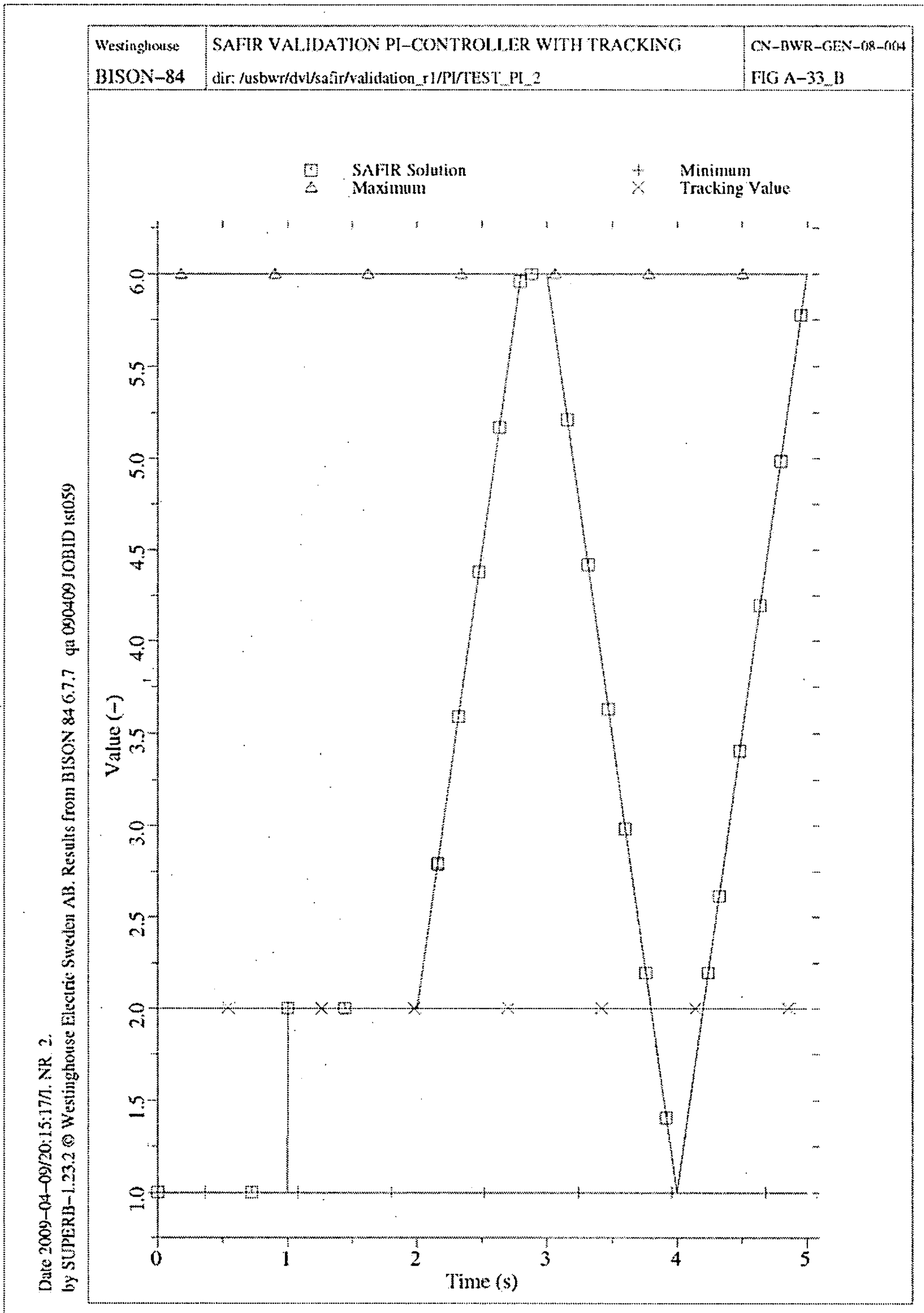

Figure 4-4 PI controller with following

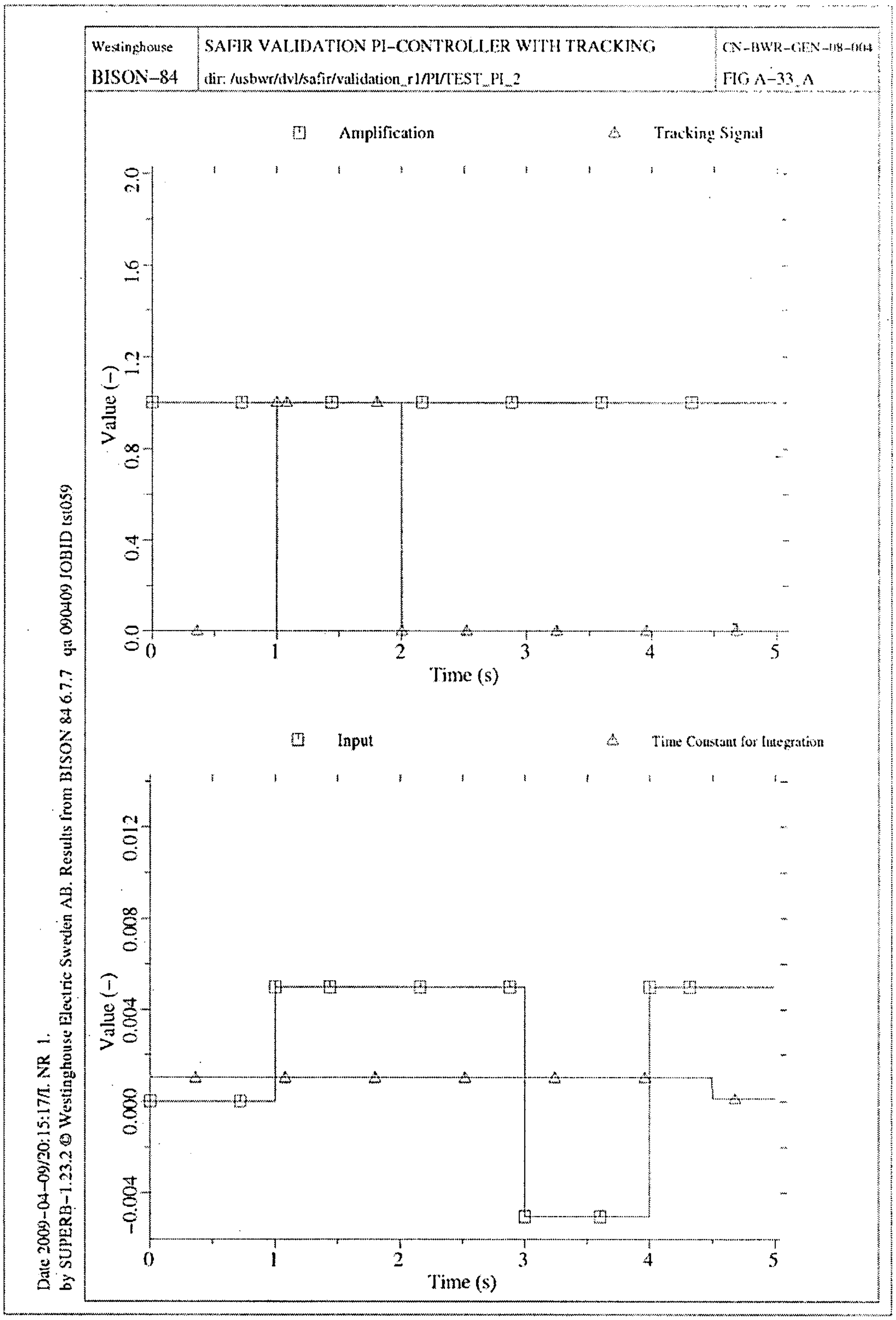

Figure 4-5 PI controller with following

4.4.1.3.2 Time-Dependent PI without Following

The PI component may also be executed as a time-dependent function without following engaged. Two signals A and B were generated as shown in Figure 4-6.

- Signal A was connected to the input (input connector IN)
- Signal B was connected to the amplification (input connector K).

The time constant for integration (input connector TI) was held constant at 4. The output (output connector OUT) was initialized to zero:

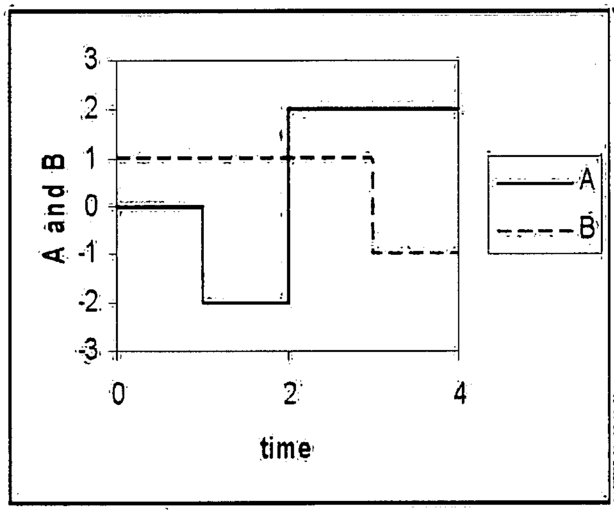

Figure 4-6 Input signals

Graphical results for this case can be found in Figure 4-7.

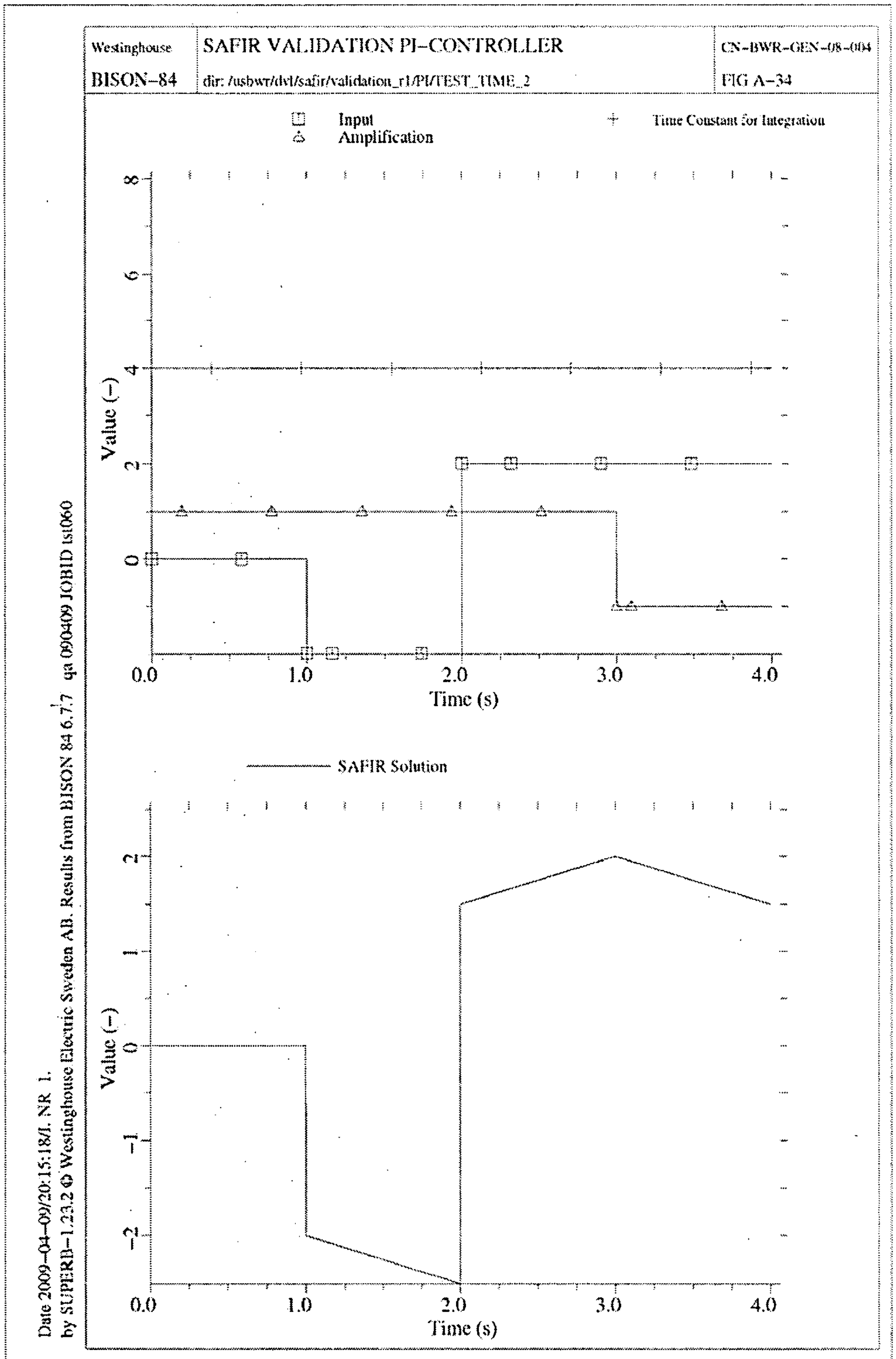

Figure 4-7 PI-controller without following

4.4.1.3.3 Analytical solution of PI

The implementation of the PI component in SAFIR was verified by comparing the output from SAFIR to the analytical solution described below, using the two input signals A and B as shown in Figure 4-6. The used algorithm is:

OUT(t) = K(t) • (1 + TS / TI) • IN(t) – K(t) • IN(t-TS) + OUT(t-TS)

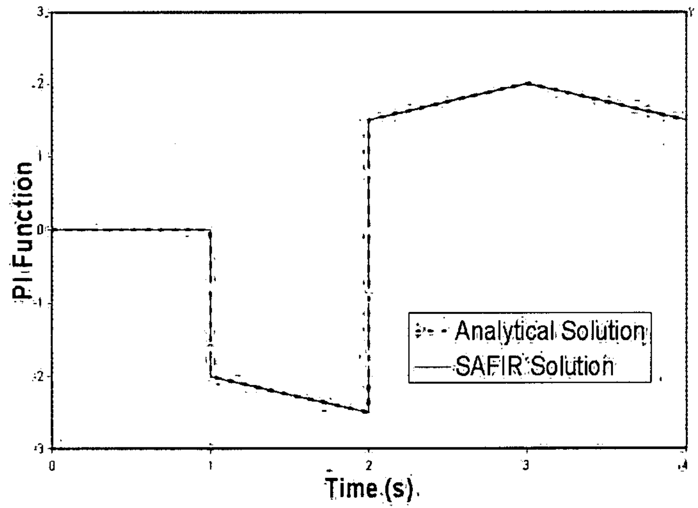

Figure 4-8 PI-controller without following

4.4.2 Conclusions for PI

After the completion of the verification, it has been determined that the PI component performs as expected. All SAFIR solutions were in agreement with the expected analytical solutions.

The performed verification cases are sufficient to cover the requirements for this function.

5 MODEL DEVELOPMENT, VERIFICATION AND VALIDATION PROCESS

5.1 INTRODUCTION

The generation of a SAFIR model follows the Westinghouse standard quality assurance processes both for the implementation verification and validation when required.

This process is almost identical with the verification and validation of a component with the exception that no software upgrades are involved since models are built entirely through code inputs.

The process for SAFIR model development consists of three main steps:

- Development
- Verification
- Validation

This is an iterative process where feedback from verification and validation steps may require changes in the development phase.

Examples in which the development, verification and validation process is used for different models are shown in Section 6.

5.2 DEVELOPMENT

The model development process consists of the following steps:

- Requirements
  - Desired functionality including possible intended conservatisms
  - Limitations and assumptions
  - Communication with adjacent systems
  - Communication with the transient code
- Design
- Implementation

5.3 VERIFICATION

The Westinghouse definition of verification is to show the functionality of the model and to ensure that the model fulfills the requirements.

An example of how a verification process is performed for a turbine controller is shown in Section 6.1.4.

5.4 VALIDATION

The Westinghouse definition of validation is to show the model behavior compared with reference data like e.g. measurement data.

Validation of models is performed against available data and code to code comparison, for instance with the information presented in the FSAR. Recorded plant data during startup tests or operational occurrences are used when available.

In Section 6.1.5 the validation process is illustrated for a relatively complex system; the turbine controller model. The reactor response is simulated with boundary conditions, i.e. without any feedback from the BISON code.

In Section 6.2 an example of validation using different reactor parameter setpoint disturbances from startup tests using BISON and multiple control system models is given.

6 MODEL VERIFICATION AND VALIDATION

6.1 TURBINE CONTROLLER AND VALVE PROCESS MODEL

6.1.1 Introduction

The BWR [ ]^{a,c} in Sweden began commercial operation in 1985. In 2001 the pressure controller was replaced. Before startup a test program was performed in order to demonstrate correct functionality. One of the tests performed was a load rejection that is used for the validation of the pressure control system. The model described in this section consists of three coupled SAFIR models and serves as an example of model requirements, design, verification and validation to demonstrate a procedure to qualify a model for use.

Basic plant data for [ ]^{a,c} are compiled in Table 6-1.

Table 6-1 Specifications of [ ]^{a,c}

Reactor Thermal Output	3,300 MWt (109.3 %)
Reactor Pressure	7.00 MPa[abs]
Steam Flow	2,120 kg/sec
Core Flow	13,100 kg/sec
Number of Fuel Assemblies	700
Number of Control Rods	169
Coolant Recirculation	8 Internal Pumps
Control Rod Drive	Electric Motor (Normal) Hydraulic Drive (Scram)

6.1.2 The design of the model

The turbine controller model is described by one control channel (of two) with stress on pressure control. The turbine control model controls the high pressure turbine control valve, the bypass control valves, the reheater control valves and the capacity trimming control valve, see Figure 6-1.

The turbine controller uses neutron flux and steam dome pressure to calculate valve setpoints. The valve process model calculates steam flow through valves in a steam line model.

The performances of the models are best estimate according to the available data and manufacture information. The models have predefined malfunctions that can be triggered from input.

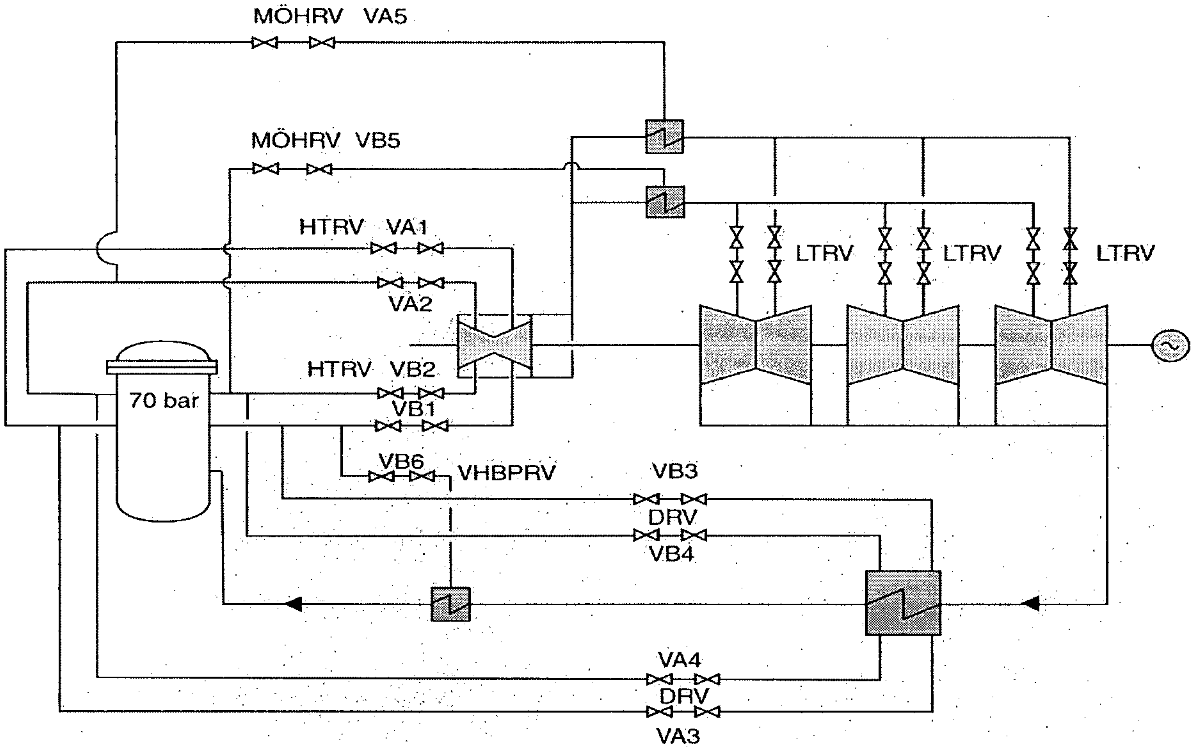

Figure 6-1 Process

6.1.2.1 Requirements

The model for the [ ]^{a,c} plant includes a turbine controller, valve process models for high pressure valves, bypass valves, reheater valves, capacity trimming valve, and one simple turbine model. The turbine controller model and valve process models are modeled with clear interface. The turbine control model's structure and extent is briefly shown in Figure 6-2.

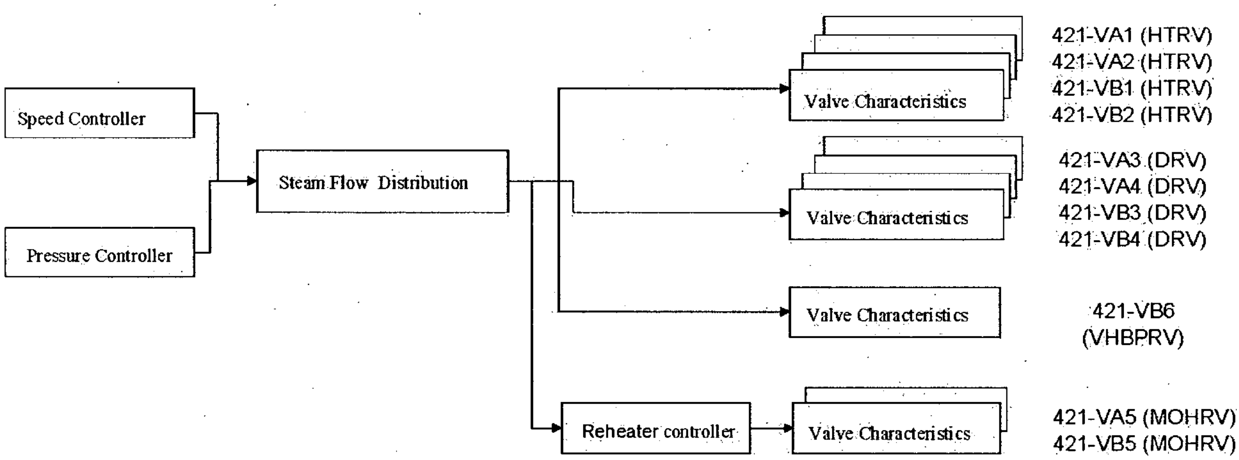

Figure 6-2 Brief controller structure (model)

6.1.2.1.1 Turbine control model

The turbine controller model is analyzed to handle the following situations of operation:

- Full turbine speed
- Events at nominal reactor pressure at load
  which start with capacity trimming control valve closed (neutron flux ≤ 102 %)
  which start with capacity trimming control valve open (neutron flux > 102 %)
- Pressure control with high pressure control valves and capacity trimming control valve
- Pressure control with bypass control valves. Those are required for example at turbine trip or inadvertent closure of one or more high pressure control valves.
- Disturbance of reactor pressure or power.

6.1.2.1.2 Valve process model

The valve process model includes the following valves:

- High pressure turbine control valves (HTRV)
- High pressure turbine stop valves (HTSV)
- Bypass control valves (DRV)
- Bypass blockage valves (DBV)
- Reheater control valve (MOHRV)
- Reheater stop valve (MOHSV)
- Capacity trimming control valve (VHBPRV)
- Capacity trimming stop valve (VHBPSV)

The valve process models are capable of converting desired valve position (setpoint) to flow through the valve by using the defined valve characteristics.

The valves should be modeled individually with regards to capacity, characteristics and stroke time.

Disturbance of individual valve behavior shall be possible.

6.1.2.1.3 Turbine model

The turbine model is designed to calculate:

- Generator power
- Turbine speed change at load rejection

6.1.2.2 Assumptions and Limitations

Assumptions and limitations in the turbine control model and the valve process models are:

a,c

[ ]

6.1.2.3 Communication and connecting systems

6.1.2.3.1 Turbine control model

The turbine control model has the following input:

- Narrow range pressure in the reactor vessel
- Pressure setpoint (narrow range pressure)
- Neutron flux
- Turbine speed
- Turbine protection logics; turbine trip, bypass blockage

The turbine control model has following output:

- Setpoints for control valves

Connecting systems which communicate with the turbine control model are:

- Turbine (SAFIR model)
- Steam lines (BISON model)
- Neutron flux measurement (SAFIR model)
- Instrumentation in the reactor vessel (SAFIR model)
- Turbine protection system (SAFIR model)

The model description in Section 6.1.3.1 gives a more detailed description how the turbine control model is communicating and is controlled by connecting systems or through signals from the user.

6.1.2.3.2 Valve process model

The valve process model has the following input:

- Signals from the turbine controller (setpoints) and individual valve characteristics for control valves
- Signals from the turbine protection system and valve characteristics for stop valves
- Manual valve control signals for control and stop valves

The valve process model has the following output:

- Valve flows
- Valve positions
- Valve status user information (open/closed)

Connecting systems which communicate with the valve process models are:

- Steam lines (BISON model)
- Turbine protection system (SAFIR model)
- Turbine controller (SAFIR model)

6.1.2.3.3 Turbine model

The turbine model has the following input:

- Steam flow through the high pressure turbine control valves
- Turbine protection logics; load rejection

The turbine model has the following output:

- Generator power
- Turbine speed

Connecting systems which communicate with the turbine model are:

- Steam lines (BISON model)
- Reactor power controller (SAFIR model)
- Turbine controller (SAFIR model)

6.1.2.4 The functionality of the model

The turbine control model and the valve process models are used for the following functions:

- Control, closure and opening of individual control valves
- Closure of individual stop valves

The turbine control model and valve process models are able to handle load rejection, turbine trip and turbine trip without bypass including failure of one or more valves.

The turbine model is limited to calculate:

- Generator power to the power controller
- Turbine speed to the turbine controller at load rejection

6.1.2.5 Verification and validation of the model

The model has been verified against following events:

- Neutron flux disturbance
- Pressure disturbance
- Pressure setpoint disturbance
- Turbine trip
- Verification of turbine model against BISON and load rejection tests
- Turbine trip without bypass
- Inadvertent closure of a high pressure turbine control valve
- Inadvertent opening of a bypass control valve
- Failure of a single valve

Only the 5 initial verification cases are presented in this report.

The model has been validated against the following event:

- Load rejection test

The model for a particular plant is normally validated against startup tests and other plant event data if available.

6.1.3 Implementation of the model

6.1.3.1 Description

Generally the turbine control model has the same structure as the real turbine controller. Hence, it is relatively simple to understand the design of the model from the graphical presentation of the model in Figure 6-3 and the controller's logic circuit. Extension of the model functionality is possible due to the degree of detail included in the model.

a,c

Figure 6-3 Turbine Controller

The turbine controller consists of two control channels. Each control channel in the turbine controller includes pressure controller, speed/power controller, steam flow distributor and valve characteristics. Only one control channel is modeled in the turbine control model. The sample time in the controller is 20 milliseconds.

The turbine controller controls the high pressure turbine control valves (HTRV), bypass control valves (DRV), reheater control valves (MOHRV), capacity trimming control valve (VHBPRV) and low pressure turbine control valves (LTRV) in addition to other components. Only control function of the control valves is modeled in the turbine control model. The turbine control model consequently controls the following valves:

- 421VA1, 421VA2, 421VB1 and 421VB2 (HTRV)
- 421VA3, 421VA4, 421VB3 and 421VB4 (DRV)
- 421VA5 and 421VB5 (MOHRV)
- 421VB6 (VHBPRV)

The different sub models in the turbine control model are further described below.

6.1.3.1.1 The pressure controller

The pressure controller consists of a wide range pressure controller and a narrow range pressure controller. Only the narrow range pressure controller is modeled. The narrow range pressure controller is a PI controller with a neutron flux feed forward.

The pressure controller gets the following input signals; narrow range pressure in the reactor vessel, reactor power, pressure setpoint, output from speed controller and forced closure signal for bypass valves.

Output signals from the pressure controller are desired steam flow from the reactor (BAFR), desired steam flow to the turbine (BATT), filtered reactor power and control deviation (NERR).

Because of the steam line's length, pressure changes could cause resonance. Such resonance results in pressure waves which are transferred in the system. A 2-pole filter, the steam line resonance filter, prevents those waves from impacting the creation of the desired steam flow from the reactor. The narrow range pressure is filtered through the steam line resonance filter and creates a control deviation by subtracting the pressure setpoint. The neutron flux feed forward consists of filtered neutron flux, where the time constant of the filter corresponds to the time constant of the fuel. The feed forward, which is used to speed up the control at power changes, is added to the PI controller's output signal. The sum gives the desired steam flow from the reactor.

The pressure controller delivers the desired steam flow to the turbine. This signal is formed through selecting minimum BAFR or the output signal from the speed controller. The desired steam flow to the turbine is limited between -5 % and 110 %. At full reactor power (109.3 %) BATT corresponds to about 96.4 %. If BAFR > 110 % and BATT at the same time reaches its upper limit 110 %, bypass valves will start to open.

The pressure controller is modeled as presented in Figure 6-4.

a,c

Figure 6-4 Pressure controller

6.1.3.1.2. Acceleration limiter

The main task of the acceleration limiter is to protect the turbine against over-speed at load rejection. Figure 6-5 below shows a simplified logic circuit for the acceleration limiter using turbine speed (VARVTAL) and turbine speed time derivative (GRADIENT) as input to generate the acceleration limitation (ACCBEG).

a,c

Figure 6-5 Logic circuit for the acceleration limiter

Two different conditions can make the acceleration limiter go in operation:

- turbine speed > 106 %
- turbine speed > 102 % and the rate of speed change >15 Hz/min

The acceleration limiter is presented in Figure 6-6. The rate is calculated with help of three integrators, as shown in Figure 6-6.

a,c

Figure 6-6 Acceleration limiter

The acceleration limiter gets the following input signals: turbine speed, desired steam flow from the reactor, desired steam flow to the turbine, turbine trip signal and turbine off load signal. Turbine overspeed is detected and the speed controller is monitored based on the input signals.

Output signals from the acceleration limiter are filtered turbine speed and a number of logical signals to the speed controller.

6.1.3.1.3 Speed/power controller

The controller's main task is to control the steam flow which can be received by the turbine. The speed/power controller consists of a power controller, which controls using the steam flow from the turbine as input, and a speed controller which controls using turbine speed as input. The output signals from the controller are summarized to a load setpoint which goes to a PIP controller. The output from the PIP controller is at full load above desired steam flow from the reactor and is then deselected in a minimum selector which gives the speed/power controller's output signal. Hence, at full load the setpoint from the speed /power controller is identical to the setpoint from the pressure controller.

At turbine trip the output signal from the speed/power controller is set to –5 % through a switch at the same time as the time constant in the PIP controller is set to 0. A description of the signals at load rejection is further described in Section 6.1.3.6.

The speed/power controller is modeled as presented in Figure 6-7.

a,c

Figure 6-7 Speed/power controller

6.1.3.1.4 Steam flow distribution and reheater control

The task of the steam flow distributor is to distribute the steam flow from the reactor between the turbine control valves. The steam flow distributor has three input signals from the pressure controller:

- desired steam flow from the reactor (BAFR)
- desired steam flow to the turbine (BATT)
- filtered reactor power (APRMFilter).

The output signal from the steam flow distributor is:

- desired steam flow to the high pressure turbine control valves (BATHTRV)
- desired steam flow to the to bypass (BATD)
- desired steam flow to the capacity trimming control valve (BATVHBP).

The capacity trimming control valve opens to 15% position at 102 % reactor power and takes over the pressure control from the high pressure turbine control valves. When the power is below 101 % the capacity trimming control valve is closed and control is only made with the high pressure turbine control valves.

Power changes which result in a more permanent change of the steam flow are slowly redistributed from the capacity trimming control valve to the high pressure turbine control valves. The capacity trimming control valve then returns to 15 % open. The redistribution between desired steam flow to the capacity trimming control valve and to the high pressure turbine control valves is made with two integrators with different time constants. The first integrator handles the pressure control and is part of a filter. If the capacity trimming control valve is in operation, it will get the increase. At the same time the input signal to the other integrator, gets positive which then slowly integrates and redistributes the steam flow to the high pressure turbine control valves.

If the input signal for desired steam flow to the turbine goes below the desired steam flow from the reactor, the desired steam flow is momentarily redistributed from the high pressure turbine control valves to the bypass valves.

The steam flow distributor model is presented in Figure 6-8.

a,c

Figure 6-8 Steam flow distributor

The control of the reheater control valves is made in a separate macro which has the input signals "desired steam flow to the turbine" and "setpoint for the reheater control valves". The valves start to open at 7 % and are completely open at 40 % of desired steam flow to the turbine. The output signal is the setpoint for the reheater control valves.

The reheater control model is presented in Figure 6-9. a,c

Figure 6-9 Reheater control model

6.1.3.1.5 Valve control

The turbine controller calculates desired steam flows to the control valves which are converted into setpoints (control signals) to the control valves through the inverse valve characteristics (desired steam flow to valve position setpoint) in the form of tables. The flow through the valves can not exceed 100 %.

There is a common model for control of each valve type. See also Figure 6-10. a,c

Figure 6-10 Valve control model

6.1.3.1.6 Bypass valve control

The bypass valve control model initiates closing of the bypass control valves and has the following input signals:

- Desired steam flow to the bypass (BATD)
- Bypass blockage with a delay

Output signals are:

- Desired steam flow to the bypass control valves (BATDRV, which is identical to BATD except for bypass blockage when it is set to -100 %)

In the model there is also a possibility to set a delay for the bypass blockage signal.

The bypass valve control model is presented in Figure 6-11.

a,c

Figure 6-11 Bypass valve control model

Turbine controller initialization model

The steam flow distribution model requires help to resolve initial condition and the turbine controller initialization model calculates initial desired steam flow from the reactor, desired demand to high pressure turbine control valves, and initial demand to the capacity trimming control valves. The turbine controller initialization model has the following input signals:

- Calculated steam flow from the reactor
- Reactor power
- Setpoints to invoke the capacity trimming control valves

Output signals are:

- Initial desired steam flow from the reactor
- Initial desired demand of the capacity trimming valves
- Initial conditions for demand to the high pressure turbine control valves

The turbine controller initialization model is presented in Figure 6-12.

a,c

Figure 6-12 Turbine controller initialization model

6.1.3.1.7 Valve process models

The valve process models for control valves also include stop valves. These valves are not controlled by the turbine controller, but from the turbine protection system. The valve process models consequently include the following valves:

- 421VA1.V1, 421VA2.V1, 421VB1.V1, 421VB2.V1 (High pressure turbine control valves)
- 421VA1.V2, 421VA2.V2, 421VB1.V2, 421VB2.V2 (High pressure turbine stop valves)
- 421VA3.V1, 421VA4.V1, 421VB3.V1, 421VB4.V1 (Bypass control valves)
- 421VA3.V2, 421VA4.V2, 421VB3.V2, 421VB4.V2 (Bypass stop valves)
- 421VA5.V1, 421VB5.V1 (Reheater control valves)
- 421VA5.V2, 421VB5.V2 (Reheater stop valves)
- 421VB6.V1 (Capacity trimming control valve)
- 421VB6.V2 (Capacity trimming stop valve)

The graphical presentations of the models are given in Figure 6-13, Figure 6-14, and Figure 6-15. a,c

Figure 6-13 High pressure turbine control and stop valves

a,c

Figure 6-14 Bypass control and stop valves

a,c

Figure 6-15 Reheater and capacity trimming control and stop valves

The control valves are modeled as a ramp device in series with a low pass filter to simulate the dynamics of the valves. The conversion from valve position to flow is made through the valve characteristics. The valve position can be fixed or be manually controlled by the user. The valves can also be requested to open or close by a setpoint disturbance signal.

The stop valves are modeled only as time function (flow) specified by the user.

All valves are modeled with the valve model, see Figure 6-16.

a,c

Figure 6-16 Valve model

6.1.3.1.8 The turbine model

The turbine model takes the steam flow through the high pressure turbine control valves as input and calculates generator power and turbine speed.

The turbine model has five input signals:

- steam flow through each of the four high pressure turbine control valves
- load rejection signal

The turbine model has two output signals:

- generator power
- turbine speed (only calculated at load rejection, otherwise kept constant)

The turbine model is shown in Figure 6-17.

a,c

Figure 6-17 Turbine model

6.1.3.2 Control

The turbine controller model is controlled through a number of input signals. Disturbance signals can be added to the narrow range pressure, pressure setpoint, and neutron flux within the turbine control model. Disturbance signals can also be added to each valve setpoint in the valve process models.

The turbine control model is controlled through following input signals:

- Disturbance signals for narrow range pressure, neutron flux, and pressure setpoint
- Change of setting parameters (time constants and gains) to the model

6.1.3.3 Input

Input to the model is given as time constants, gains, upper and lower limits, and valve opening and closing characteristics.

6.1.3.4 Output

The output signals from the model are flows through control valves and stop valves.

6.1.4 Verification of the model

The verification of the models was performed without BISON activated; i.e. only the SAFIR models were executed. This means that no consideration was taken to the plants response to a disturbance.

6.1.4.1 Step in neutron flux (APRM) up to 130 %

At 10 seconds a step in APRM from 109 % to 130 % occurs (see Figure 6-18). The other input signals are kept constant. The narrow range pressure also remains constant (see Figure 6-19). As expected an increased flow from the reactor is requested (BAFR, see Figure 6-20). The capacity trimming valve is requested to open quickly (BATVHBP, see Figure 6-21) to compensate for the rapid increase in desired steam flow from the reactor. Also the high pressure turbine control valves are requested to open (BATHTRV, see Figure 6-22) but with a lower speed than the capacity trimming valve. When the desired steam flow from the reactor reaches the limit for desired steam flow to the turbine (BATT, see Figure 6-23), 110 %, the bypass control valves are requested to open (BATD > 0, see Figure 6-23). The capacity trimming valve reaches its maximum value very fast because of the step in APRM. Since there has been a static change of APRM there is redistribution between the capacity trimming control valve and the high pressure turbine control valves, over time the capacity trimming control valve returns to its original value.

At 90 seconds another step in APRM occurs, from 130 % to 109 %. As a result the desired steam flow from the reactor rapidly decreases. The desired steam flow to the capacity trimming control valve is then decreasing fast at a limit of -3 %. When the desired steam flow from the reactor reaches 110 %, the bypass control valves are closing (DRV, see Figure 6-24 and Figure 6-25). Pressure control is performed with the high pressure turbine control valves (HTRV, see Figure 6-26 and Figure 6-27) when the bypass control valves and the capacity trimming valve have closed. Because no flow is passing through capacity trimming control valve (VHBPRV, see Figure 6-28 and Figure 6-29), desired steam flow to the high pressure turbine control valves is going to be slightly above its original value. About 140 seconds after the step change the integrator's output signals in the steam flow distributor has reached the limit for redistribution which results in that the capacity trimming control valve opens and the high pressure turbine control valves close and later reach its original values. The reheater control valves are fully open during the entire perturbation (MOHRV, see Figure 6-30 and Figure 6-31)

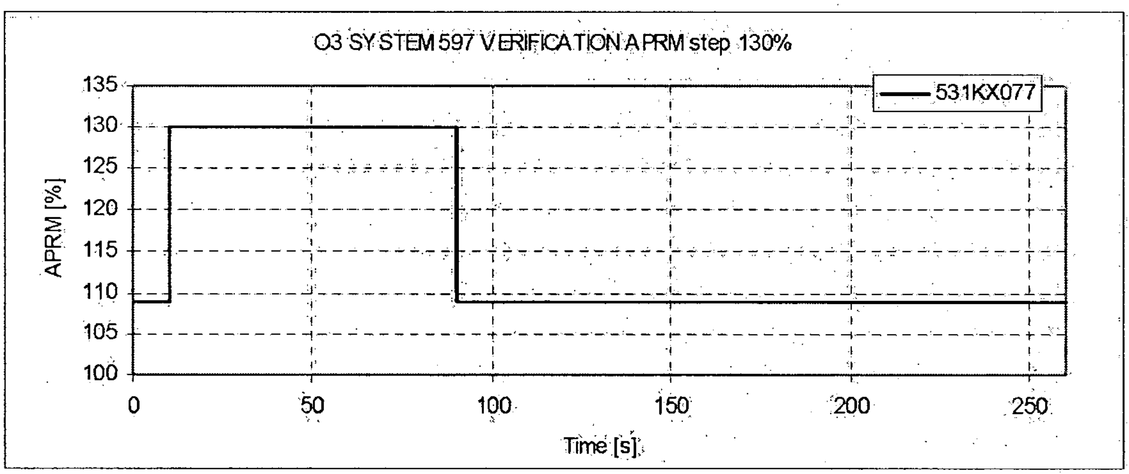

Figure 6-18 APRM (%)

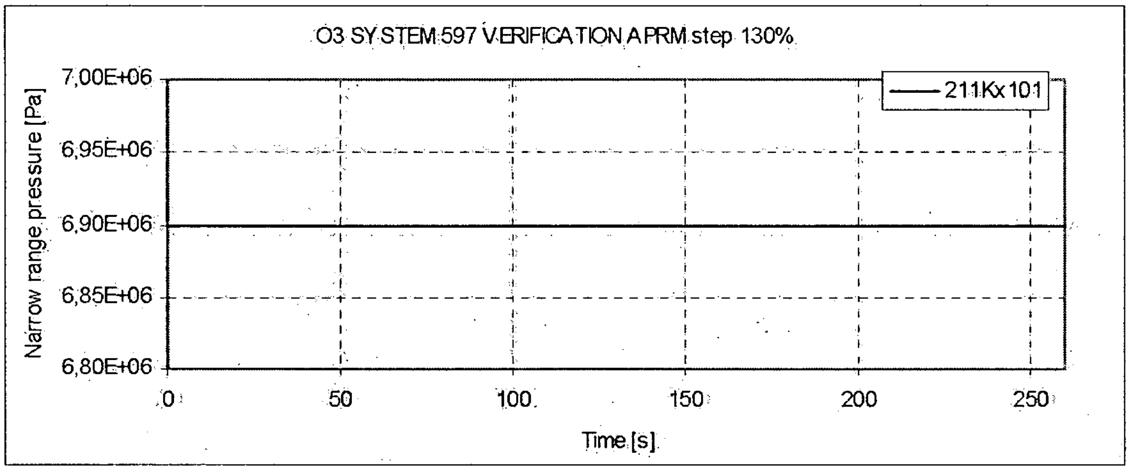

Figure 6-19 **Narrow range pressure (Pa)**

a,c

[ ]

Figure 6-20 **BAFR (%)**

a,c

[ ]

Figure 6-21 **BATVHBP (%)**

a,c

Figure 6-22 BATHTRV (%)

a,c

Figure 6-23 BATT and BATD (%)

a,c

Figure 6-24 DRV position (%)

a,c

Figure 6-25 DRV flow (kg/s)

a,c

Figure 6-26 HTRV positions (%)

a,c

Figure 6-27 HTRV flow (kg/s)

a,c

Figure 6-28 VHBPRV position (%)

a,c

Figure 6-29 VHBPRV flow (kg/s)

a,c

Figure 6-30 MOHRV position (%)

a,c

[ ]

Figure 6-31 MOHRV flow (kg/s)

6.1.4.2 1 % ramp in desired steam flow from the reactor

To be able to create a ramp in desired steam flow from the reactor, neutron flux filter has been disabled. The perturbation is modeled as a ramp in neutron flux (APRM, see Figure 6-32), which results in a similar ramp in the desired steam flow from the reactor (BAFR, see Figure 6-34). The narrow range pressure also remains constant (see Figure 6-33). It is verified how the desired steam flow to the capacity trimming control valve (BATVHBP, see Figure 6-35) and the desired steam flow to the high pressure turbine control valves (BATHTRV, see Figure 6-36) is controlling as the desired steam flow from the reactor changes. The desired steam flow to the turbine (BATT) and to the bypass (BATD) are presented in Figure 6-37

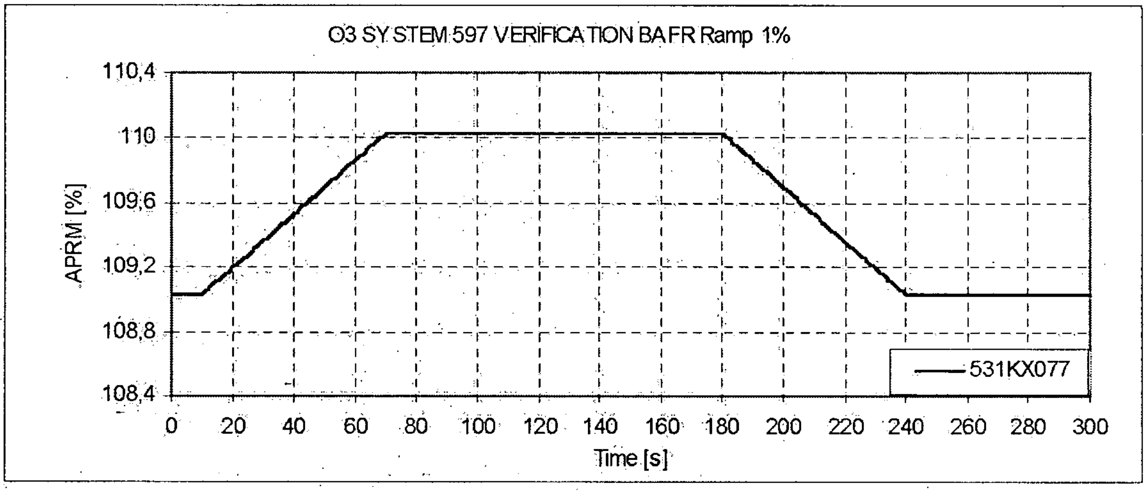

Figure 6-32 APRM (%)

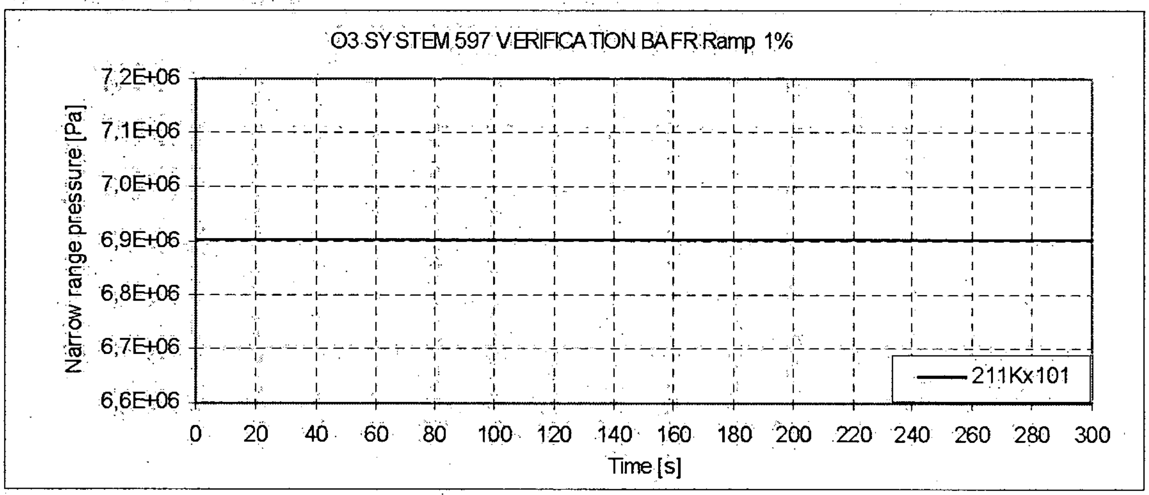

Figure 6-33 Narrow range pressure (Pa)

a,c

[ ]

Figure 6-34 BAFR (%)

a,c

[ ]

Figure 6-35 BATVHBP (%)

a,c

[ ]

Figure 6-36 BATHTRV (%)

a,c

[ ]

Figure 6-37 BATT and BATD (%)

6.1.4.3 Opening of the capacity trimming control valve

In the figures below it is verified that the capacity trimming valve opens when APRM exceeds 102 %.

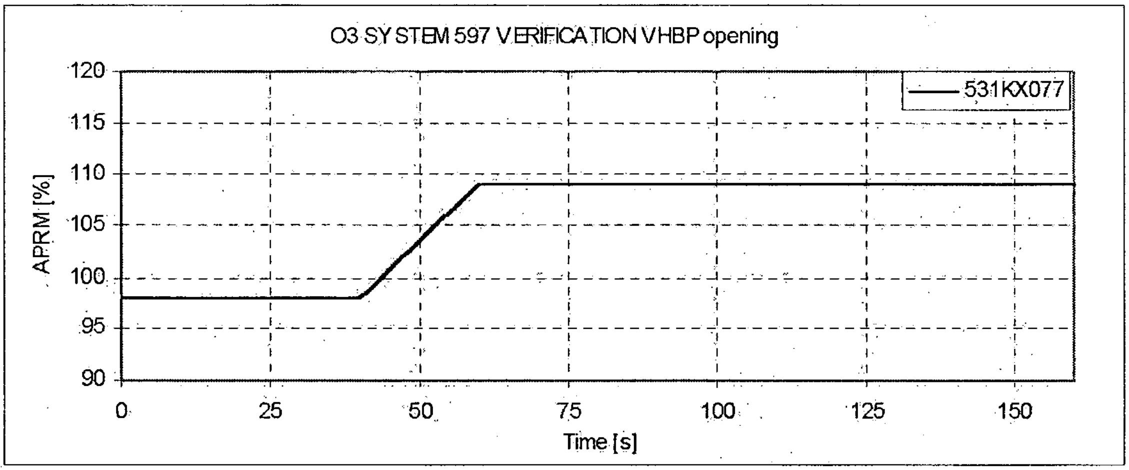

Figure 6-38 APRM (%)

a,c

Figure 6-39 BAFR (%)

a,c

Figure 6-40 Narrow range pressure (Pa)

a,c

Figure 6-41 BATT and BATD (%)

a,c

Figure 6-42 BATHTRV (%)

a,c

Figure 6-43 HTRV positions (%)

a,c

Figure 6-44 BATVHBP (%)

a,c

Figure 6-45 DRV position (%)

a,c

Figure 6-46 VHBPRV position (%)

6.1.4.4 Step response for a narrow range pressure increase with 0.02 MPa

At 10 seconds a step in the narrow range pressure (see Figure 6-49) from 6.9 MPa to 6.92 MPa occurs (this is equivalent with a step in the pressure setpoint from 6.9 MPa to 6.88 MPa). The other input signals are kept constant. As expected an increased flow from the reactor (BAFR, see Figure 6-48) is requested. Because there is no feedback from the plant, the desired steam flow from the reactor will continue to increase until the signal is limited or the disturbance disappears. The increase in the desired steam flow from the reactor causes an increased flow through the capacity control trimming valve and the high pressure turbine control valves. The capacity trimming control valve opens rapidly to compensate the fast pressure increase. At the same time the high pressure turbine control valves start to open. The capacity trimming valve and the high pressure turbine control valves continue to open until the control deviation disappears or until the valves are completely open. Since the desired steam flow from the reactor is not exceeding 110 %, the bypass control valves are not going to open.

At 20 seconds the disturbance disappears. The capacity trimming control valve has opened to 65 % and the high pressure turbine control valves are completely or almost completely open. The desired steam flow from the reactor will decrease to a constant value, which is higher than the initial value because the output from the pressure controller's PI component has increased. The desired steam flow to the capacity trimming control valve is decreasing rapidly to compensate the fast decrease in the desired steam flow from the reactor, followed by redistribution to static control. The capacity trimming control valve returns to the original value and the high pressure turbine control valves are completely open.

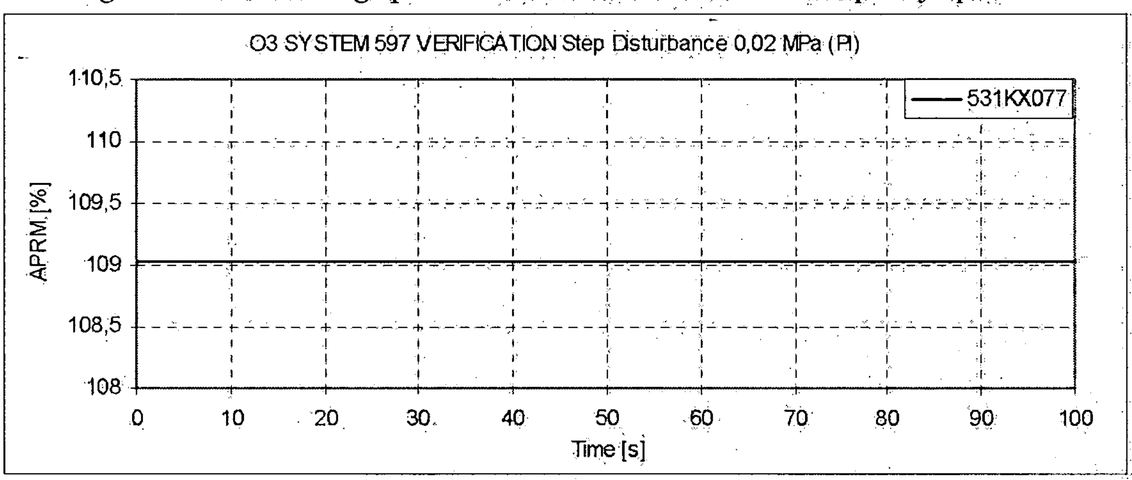

Figure 6-47 APRM (%)

a,c

[ ]

Figure 6-48 BAFR (%)

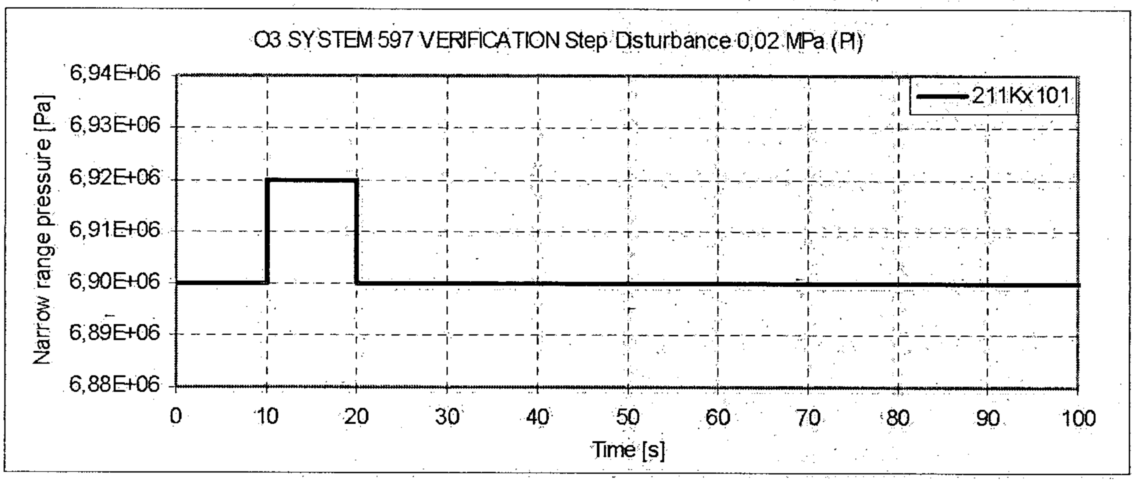

Figure 6-49 Narrow range pressure (Pa)

a,c

[ ]

Figure 6-50 BATT and BATD (%)

a,c

Figure 6-51 BATHTRV (%)

a,c

Figure 6-52 HTRV positions (%)

a,c

Figure 6-53 BATVHBP (%)

a,c

Figure 6-54 DRV position (%)

a,c

Figure 6-55 MOHRV position (%)

a,c

Figure 6-56 VHBPRV position (%)

6.1.4.5 Turbine trip

At 10 seconds a turbine trip is requested. The other input signals are kept constant. Desired flow to the turbine (BATT, see Figure 6-60), desired flow to the capacity trimming valve (BATVHBP, see Figure 6-63) and desired flow to the reheater valves (MOHRV, see Figure 6-65) are immediately set to a negative value and the flow is redirected to the condenser (BATD, see Figure 6-60). At the same time the high pressure turbine control valves are requested to close, the stop valves are requested to close. Because the stop valves have a faster closure time the flow will be limited by their characteristics.

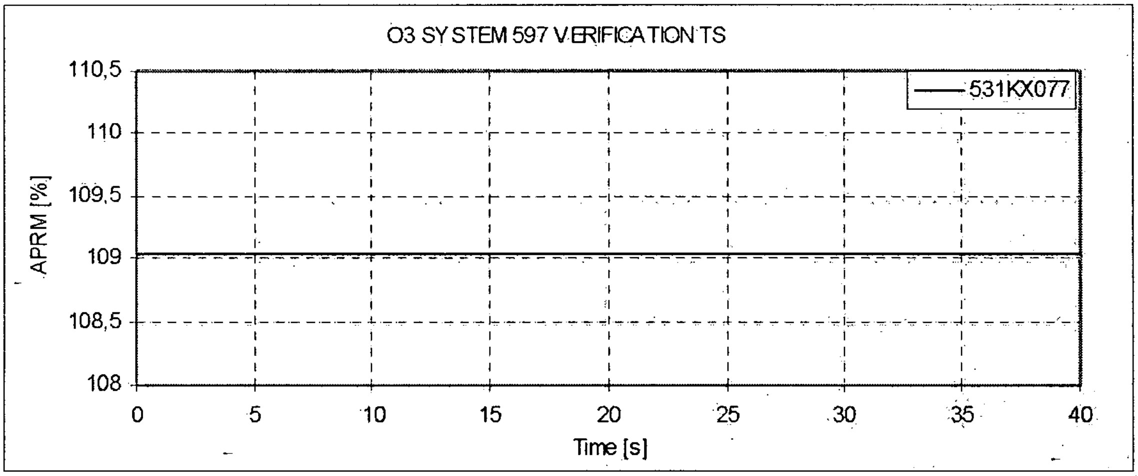

Figure 6-57 APRM (%)

a,c

Figure 6-58 BAFR (%)

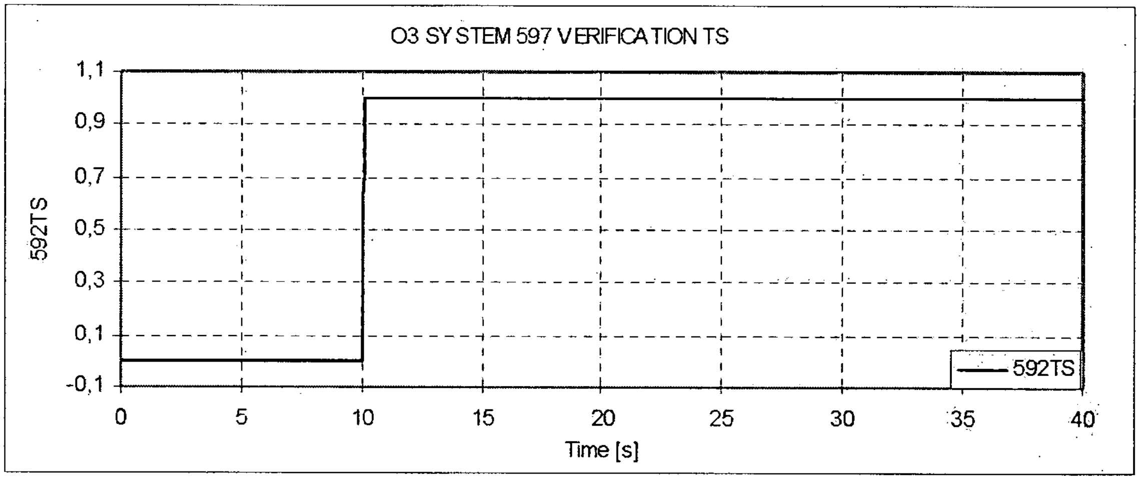

Figure 6-59 592TS

a,c

[ ]

Figure 6-60 BATT and BATD (%)

a,c

[ ]

Figure 6-61 BATHTRV (%)

a,c

Figure 6-62 HTRV positions (%)

a,c

Figure 6-63 BATVHBP (%)

a,c

Figure 6-64 DRV position (%)

a,c

Figure 6-65 MOHRV position (%)

a,c

Figure 6-66 HTRV flow (kg/s)

a,c

Figure 6-67 VHBPRV position (%)

a,c

Figure 6-68 DRV flow (kg/s)

a,c

Figure 6-69 MOHRV flow (kg/s)

a,c

Figure 6-70 VHBPRV flow (kg/s)

6.1.4.6 Verification of the turbine model against load rejection in BISON/BOP

The verification is performed vs. a more detailed built-in model for [ ]^{a,c}. Figure 6-71 to Figure 6-73 shows a simulation of load rejection in BISON with the model activated. The flow through the high pressure turbine control vales is then given as boundary value to the SAFIR model and the turbine speed and generator power is presented in the same figures.

a,c

Figure 6-71 Steam flow to high pressure control valves

a,c

Figure 6-72 Comparison of turbine speed, SAFIR (solid line) and Balance of Plant model (dashed line)

a,c

Figure 6-73 Comparison of generator power, SAFIR (solid line) and Balance of Plant model (dashed line)

Because the SAFIR model is a simplified model compared to the built-in [ ]^{a,c} turbine model differences are expected. The results are acceptable within the desirable application range and the simple turbine model is judged to be suitable for [ ]^{a,c}.

6.1.5 Validation of the model

On June 2nd, 2001, a load rejection test was performed at [ ]^{a,c}. The conditions before the test were 98 % reactor power and 13,000 kg/s recirculation flow. The load rejection was initiated through switching off the plant breaker.

The measured data used are from the data recorder in the process computer. The data sample time was 50 Hz. For the validation the first 59 seconds in the recorded data has been excluded, which makes the time zero to correspond to 59 seconds in the recorded data.

The following signals have been used as boundary conditions in the simulation, see Table 6-2.

Table 6-2 Boundary conditions for validation of the turbine control model

Description	BISON	Data recorder
Neutron flux	531KX077	Average of 531Kx077 train A-D
Turbine speed	TSPEED	597KA701
Narrow range pressure	211KX101	Average of 211Kx101 train A-D

Before the load rejection is initiated, the time constant (TIDOMK) is equal to 0 second and the load feed forward signal (LASTFRAMK) is about 40 % above the desired steam flow from the reactor (BAFR). This gives that the values desired steam flow to the turbine (BATT) and desired steam flow from the reactor (BAFR) are the same. When the plant breaker is switched off, the turbine speed is increasing (see Figure 6-74 below). A control deviation is built up in the speed controller (TURBRAV) which rapidly reduces the load feed forward (LASTFRAMK) down to it is equal to the desired steam flow from the reactor (BAFR). When load feed forward (LASTFRAMK) goes below the desired steam flow from the reactor (BAFR), the Boolean signal LMTID is set to TRUE (=1). This changes the time constant (TIDOMK) to 8 seconds and the desired steam flow from the reactor (BAFR) is slowly ramped down, which can be seen in Figure 6-75.

a,b,c

Figure 6-74 **Measured turbine speed [rpm] at the load rejection test**

a,b,c

Figure 6-75 **Desired steam flow to the turbine (BATT (%)) vs. time (Tid (s)) at the load rejection test**

About 0.3 second after desired steam flow to the turbine has started to decrease, the acceleration limiter goes in operation. This is caused by the speed exceeding 102 % and the speed change rate is higher than 15 Hz/min. A description of the acceleration limiter is shown in Section 6.1.3.1.2.

The acceleration limiter reduces the desired steam flow to the turbine to -5 % and sets the time constant in the integrator (LASTINT) to zero. At the same time, the output signal from the integrator (BATTINT) is set to zero.

Boundary signals to the model are narrow range pressure (Figure 6-76) and APRM (Figure 6-77).

a,b,c

Figure 6-76 Narrow range pressure (Pa) at the load rejection test

a,b,c

Figure 6-77 APRM (%) at the load rejection test

Measured (solid line) and calculated (dashed line) filtered APRM (APRMFilter) are shown in Figure 6-78 and desired steam flow from the reactor (BAFR) in Figure 6-79.

a,b,c

Figure 6-78 Meas./calc. APRMFilter (%)

a,b,c

Figure 6-79 Meas./calc. BAFR (%)

Measured (solid line) and calculated (dashed line) pressure controller output are shown in Figure 6-80 and desired steam flow to the turbine (BATT) in Figure 6-81.

a,b,c

Figure 6-80 Meas./calc. PI Controller output (%)

a,b,c

Figure 6-81 Meas./calc. BATT (%)

Measured (solid line) and calculated (dashed line) TCV positions are shown in Figure 6-82 (V421VA1), Figure 6-83 (V421VA2), Figure 6-84 (V421VB1), and Figure 6-85 (V421VB2). Measured BPV positions (solid lines) for 421VA3, 421VA4, 421VB3, and 421VB4 and calculated valve positions (dashed line, all bypass valves modeled have identical positions) in Figure 6-86.

a,b,c

Figure 6-82 Meas./calc. 421VA1 (%) position

Figure 6-83 Meas./calc. 421VA2 (%) position

a,b,c

a,b,c

Figure 6-84 Meas./calc. 421VB1 (%) position

a,b,c

Figure 6-85 Meas./calc. 421VB2 (%) position

Figure 6-86 Meas./calc. BPV (%) positions

For the signals in the turbine controller there is good agreement between measurement and simulation results.

Also, the valve positions are in good agreement. The position for one high pressure turbine control valve (421VA1, Figure 6-82), is more open than the other (about 65 % compared to the others 60 %). This is caused by the characteristics used, which has been based on measured data, where this valve deviates from the other with the same signal from the pressure controller.

In reality the bypass valves have individual characteristics. All valves have the same characteristics in this validation and this common characteristic has been used in the model for all four bypass control valves.

Figure 6-87 shows a comparison between measured (dashed line) and simulated (solid line) turbine speed.

a,b,c

[ ]

Figure 6-87 Meas./calc. Turbine speed (rpm)

6.2 VALIDATION AGAINST STARTUP TESTS

6.2.1 Introduction*

The ABWR (Advanced BWR), Hamaoka-5 in Japan began commercial operation in January 2005. A startup test program was performed in order to demonstrate safe and stable plant operation in the presence of anticipated operational occurrences (AOO). Basic plant data for Hamaoka-5 is compiled in Table 6-3.

Table 6-3. Specifications of Hamaoka-5*

Reactor Thermal Output	3,926 MWt
Reactor Pressure	7.17 MPa[abs]
Steam Flow	2,120 kg/sec
Core Flow	14,500 kg/sec
Number of Fuel Assemblies	872
Number of Control Rods	205
Coolant Recirculation	10 Internal Pumps
Control Rod Drive	Electric Motor (Normal) Hydraulic Drive (Scram)

6.2.2 Transient Analysis of Startup Tests

Some of the Hamaoka-5 startup tests have been simulated with the BISON code including the SAFIR control system simulator as reported in Reference 5. Startup tests were performed at rated condition. Of special interest for control system simulation are several tests with transient setpoint changes.

6.2.2.1 Simulation Model

The simulation model using BISON with SAFIR built control systems of Hamaoka-5 has been developed by TOSHIBA using Westinghouse methodology. The overall ABWR reactor control systems schematics, not presented in Reference 5, are shown in Figure 6-88. The control systems and adjacent models consist of:

- Recirculation Flow Control System:
  - Main controller
  - Flow Controller
  - Adjustable Speed Drive (ASD)
- Turbine Control System:
  - Pressure Controller (EHC)
  - Turbine Control Valves (TCV)
  - Turbine Bypass Valves (TBV)
  - Turbine Stop Valves (TSV)
- Feedwater Control System:
  - Level Controller
  - Flow Controller
  - Valve Controller

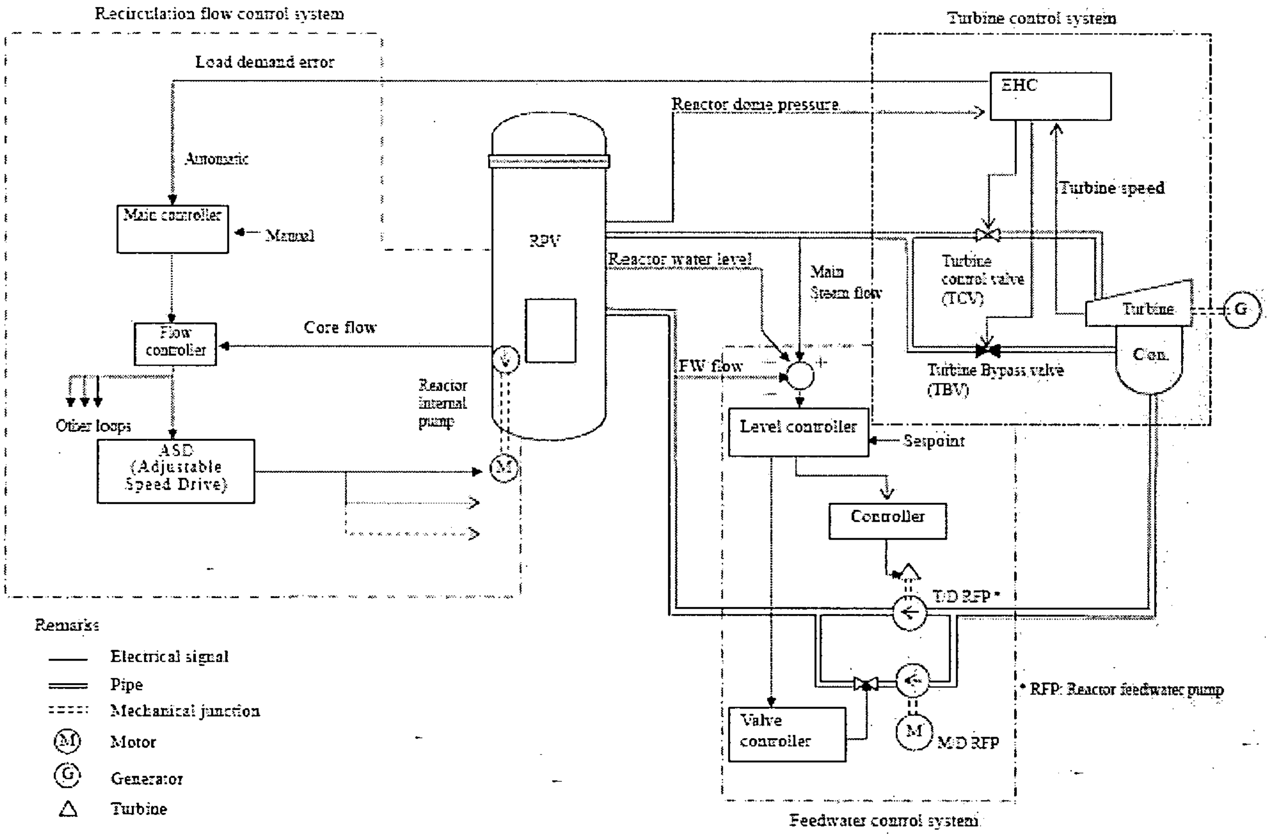

Figure 6-88 Reactor Control Systems Schematics (ABWR)

Details of the recirculation flow control system are shown in Figure 6-89.

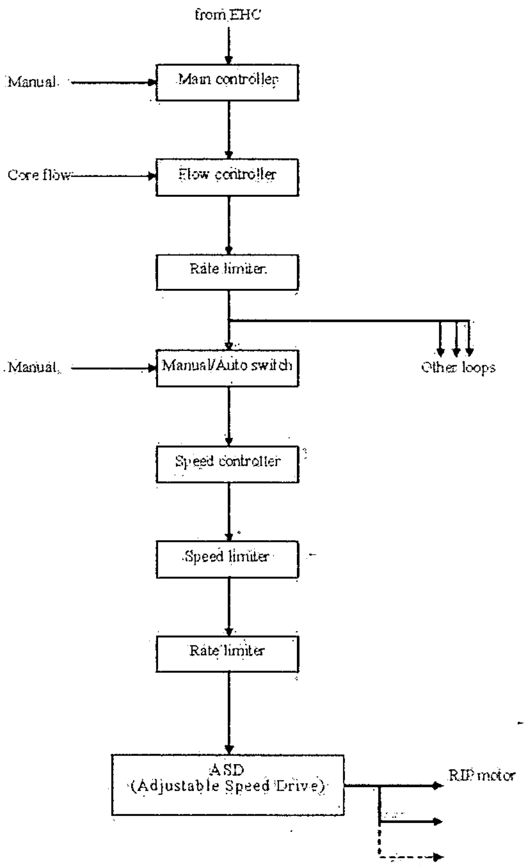

Figure 6-89 Recirculation Flow Control System

Input signals to the recirculation flow control system are load demand error from the turbine control system and measured core flow. Output signal is the recirculation pump speed.

Details of the turbine control system are shown in Figure 6-90.

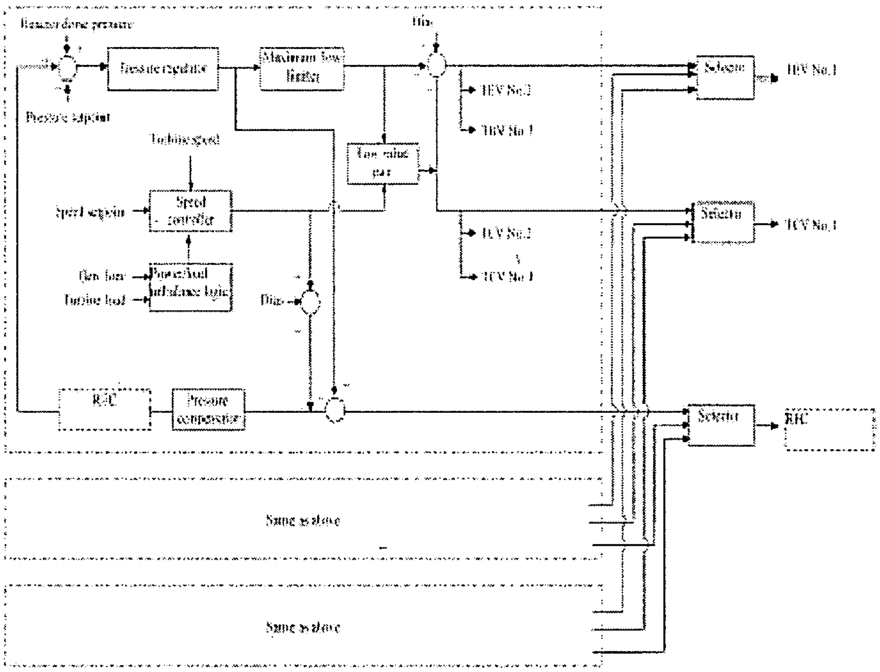

Figure 6-90 Turbine Control System

Input signals to the turbine control system are reactor dome pressure and turbine speed. Output signals are TCV, TSV, and TBV valve positions and the load demand error.

Details of the feedwater control system are shown in Figure 6-91.

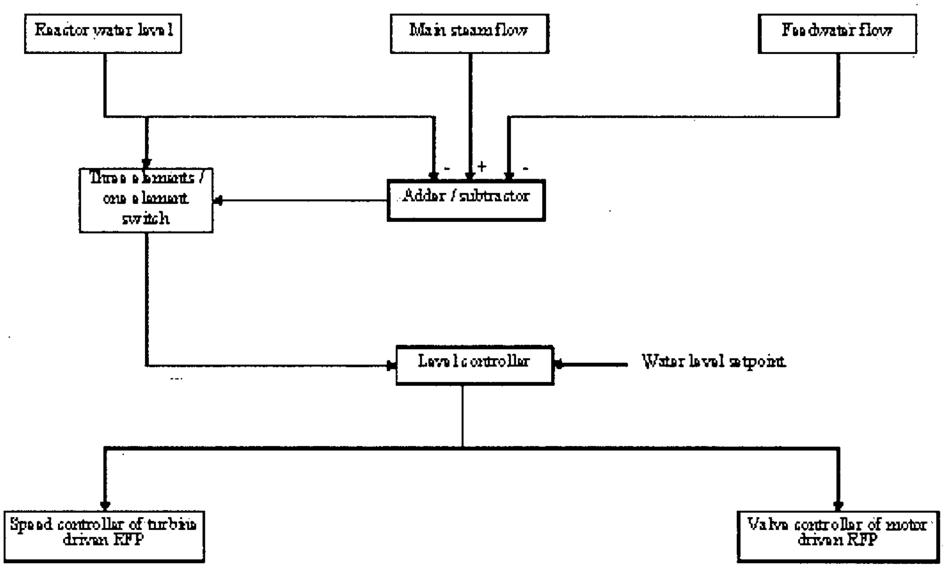

Figure 6-91 Feedwater Control System

Input signals to the feedwater control system are water level setpoint, reactor water level, steam flow, and feedwater flow. Output signals are feedwater pump speed and valve positions.

These models were implemented using SAFIR along with the BISON model of the Hamaoka-5 ABWR plant.

6.2.2.2 Pressure Control System Step Change*

The objective of the Steam Bypass & Pressure Control System (SB&PCS) is to control reactor vessel pressure by turbine control and/or steam bypass valves. For normal operation, the turbine control valves (TCVs) regulate steam pressure. However, if the total steam flow demand from the pressure controller exceeds the effective TCV steam flow demand, the SB&PCS sends the excess steam flow directly to the main condenser, through the turbine bypass valves. This test is performed by addition of the -/+0.069 MPa step change of the reactor pressure setpoint. The purpose of this test is to measure the response of the reactor (reactor pressure, neutron flux, main steam flow) and to adjust the performance of SB&PCS in order to achieve a stable response. Figure 6-92 and Figure 6-93 show a comparison of the analysis result and test data. If the pressure setpoint is changed by a -0.069 MPa, main steam flow initially increases in order to reduce the reactor pressure. Reduction in reactor pressure generates more voids in the core which causes a reduction in reactor power and the vessel water level increase. After the reactor pressure has decreased almost 0.069 MPa from the initial pressure, it is settled down by control of the SB&PCS and vessel water level is controlled by the feedwater control system (FWCS). As for the step change of positive disturbance, the transient shows an almost inverse response of the negative disturbance. In Figure 6-92 and Figure 6-93, the analysis results show good agreement with the test data.

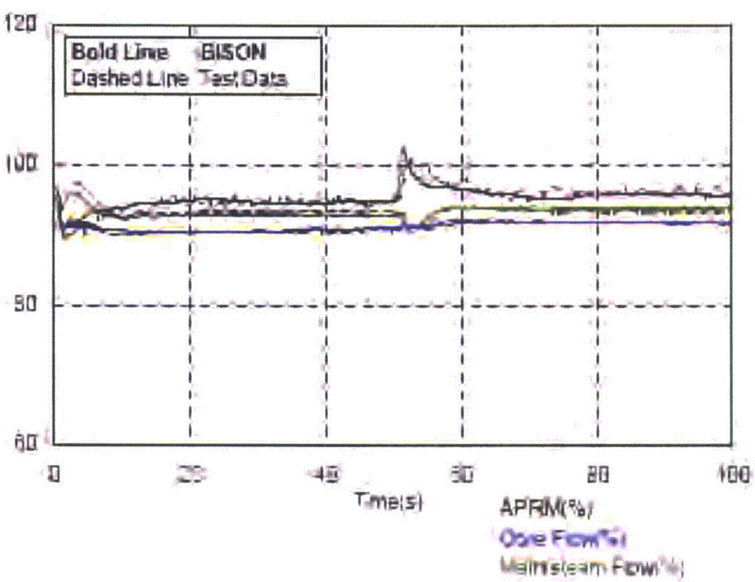

Figure 6-92. Pressure control (step change) – APRM, core flow, main steam flow*

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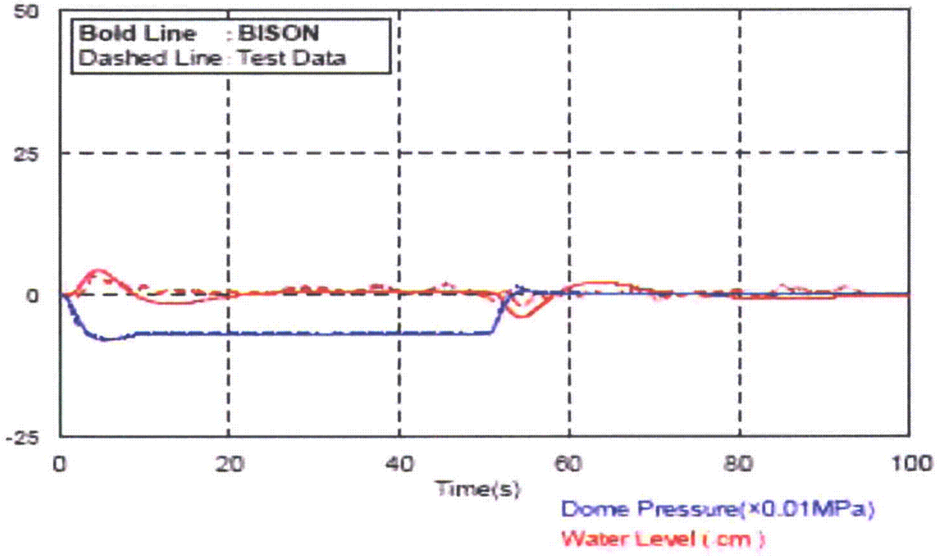

Figure 6-93 Pressure control (step change) – dome pressure and water level*

6.2.2.3 Feedwater Control System Step Change*

The Feedwater Control System (FWCS) controls the flow of feedwater into the reactor pressure vessel to maintain water level in the vessel. At rated condition, it is controlled using three elements: measured water level, feedwater flow, and main steam flow. This test is performed by addition of the -/+15 cm step change of reactor water level setpoint. The purpose of this test is to measure the response of the reactor (vessel water level and feedwater flow) and adjust the performance of FWCS in order to achieve a stable response.

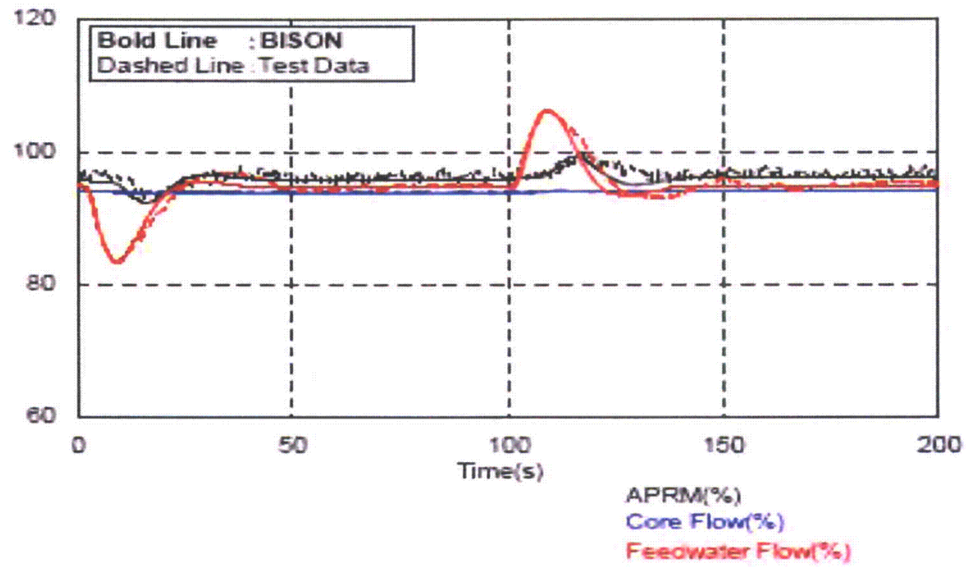

Figure 6-94 Feedwater control (step change) – APRM, core flow, feedwater flow*

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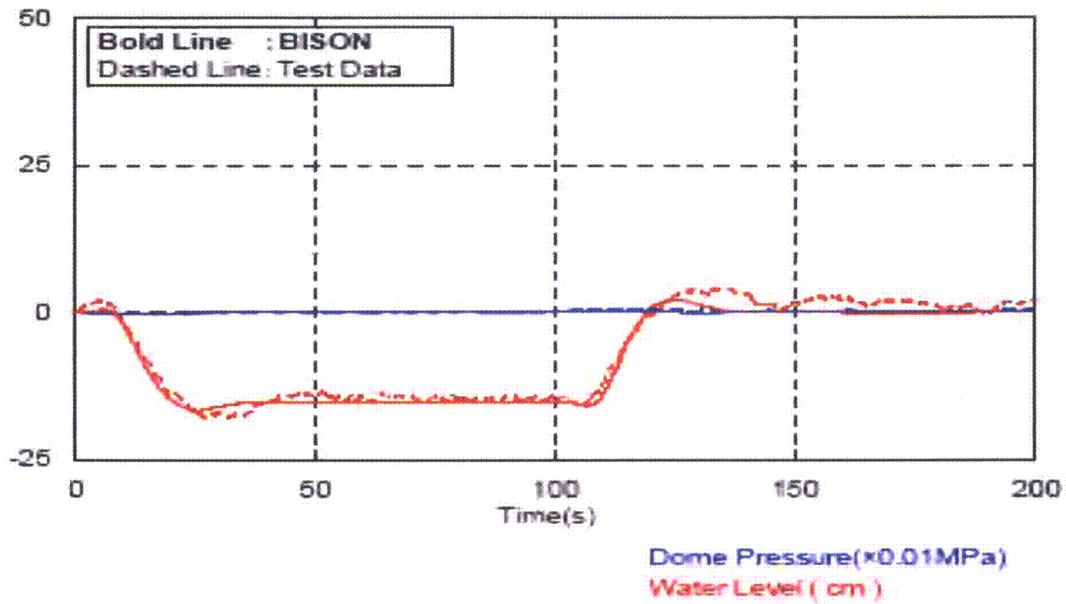

Figure 6-95 Feedwater control (step change) – dome pressure and water level*

Figure 6-94 and Figure 6-95 show a comparison of the analysis result and test data. If the vessel water level setpoint is changed by -15 cm, feedwater flow is initially decreased in order to reduce the water level. The feedwater flow reduction causes a decrease in the core inlet sub cooling which causes a neutron flux reduction. The vessel water level is decreased monotonously and settles down to - 15 cm from the initial level. After 20 seconds, feedwater flow settles to approximately its initial flow. As for the step change of positive disturbance, the transient shows an almost inverse response of the negative disturbance. In Figure 6-94 and Figure 6-95, the analysis results show good agreement with the test data.

6.2.2.4 Recirculation Flow Control System Ramp Change*

The objective of the recirculation flow control system (RFCS) is to control reactor power by controlling the flow rate of the core flow. This test is performed by addition of ramp input of a -/+10% change of the reactor power (load) setpoint. The purpose of this test is to measure the response of the reactor (core flow, neutron flux) and adjust the performance of the recirculation control system in order to achieve a stable response.

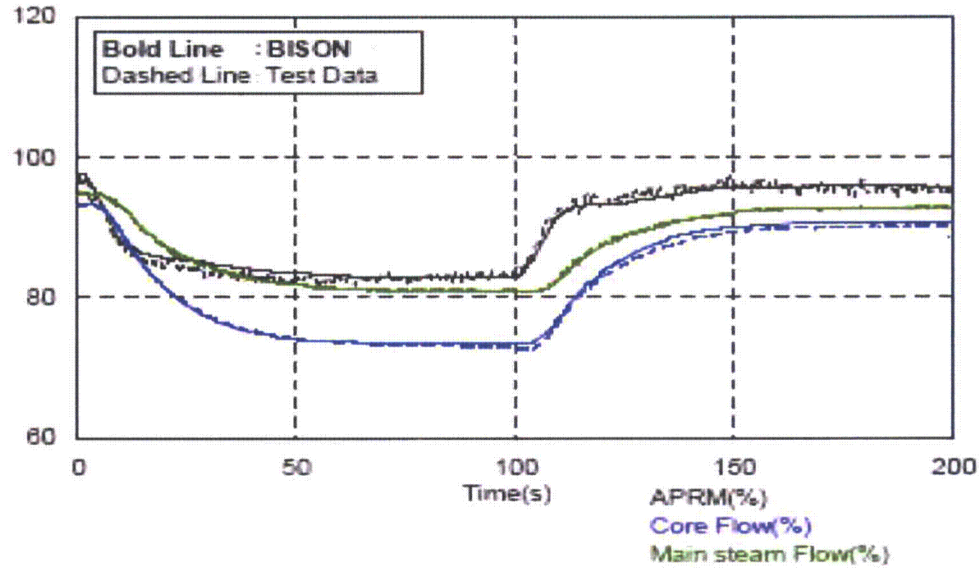

Figure 6-96 Recirculation control (ramp change) – APRM, core flow, main steam flow*

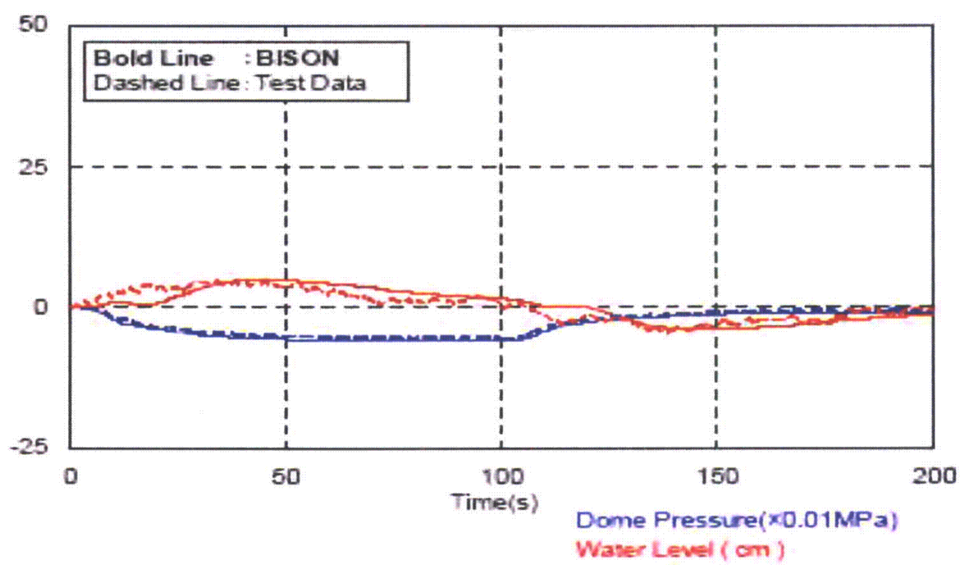

Figure 6-97 Recirculation control (ramp change) – dome pressure and water level*

Figure 6-96 and Figure 6-97 show a comparison of the analysis result and test data. If the load setpoint is changed by -10%, the core flow decreases in order to reduce the reactor power. The reactor pressure decreases due to the power reduction, which generates more voids in the reactor, and the vessel water level initially increase. After about 60 seconds, the reactor has reached a new stable steady-state condition. As for the ramp change of positive disturbance, the transient shows an almost inverse response of the negative disturbance. In Figure 6-96 and Figure 6-97, the analysis results show good agreement with the test data.

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