Using Damadics Actuator Benchmark Library (DABLib)

Michał Bartyś, Michał Syfert

Final, ver. 1.22

April 26, 2002

1. Version Info

version #	Remarks	Date
draft		March 02, 2002
1.0 final	• Changes in library block structure – two additional, hidden blocks were added • Change in f9 and f10 simulations	March 17, 2002
1.01	• Correction of a bad link • Correction of a look-up table in Water Control Valve Block in Core Actuator.	March 22, 2002
1.2	• Rearrangement in block structure - 'DABLib Utilities' introduction • Correction in blocks 'Act' and 'ExtAct' connected with P1' and P2' in case of fault f17 • 'PICalc' block introduction • 'Process Blocks' block group introduction • Example V introduction • Corrections in General Description Section	April 12, 2002
1.21	• Correction in blocks 'Act' and 'ExtAct' connected with T1' in case of fault f7 • Changes in Example IV according to f7 correction	April 25, 2002
1.22	• Correction in blocks 'DGen'. In case of fault with negative direction (f12, f14, f19) the value of "f(i)" output of the block was not correct – no fault value was indicated	April 26, 2002

2. Start up

- The **‘DABLIB’** library is created for use with Matlab 5.2 / Simulink 2.2 environment or higher versions.

- Installation. To use **‘DABLIB’** library please add DABLib directory to your Matlab path. Then, the *DAMADICS Actuator Benchmark Library* will appear in your Simulink library launcher.

- Simulation parameters. When using **‘DABLIB’** components, please set the following solver options: Type / fixed-step, ode4 (Runge-Kutta), Fixed-step size / 0.0025s.

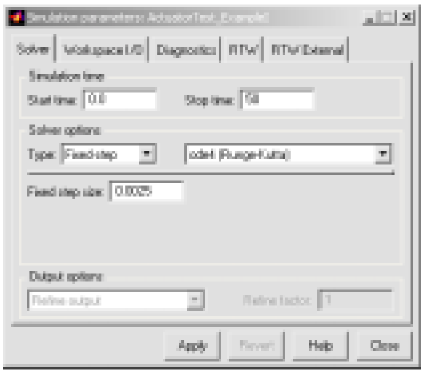

*Figure 1. Required solver options settings for **‘DABLIB’***

3. General descritpion

The Damadics Actuator Benchmark Library (**DABLIB**) was created to fulfil the requirements of model benchmark within the EC FP5 Research Training Network - Development and Application of Methods for Actuator Diagnosis in Industrial Control Systems (DAMADICS). The aim of the benchmark is to compare, evaluate and rank different actuator fault diagnosis algorithms.

The **DABLIB** consists of several blocks.

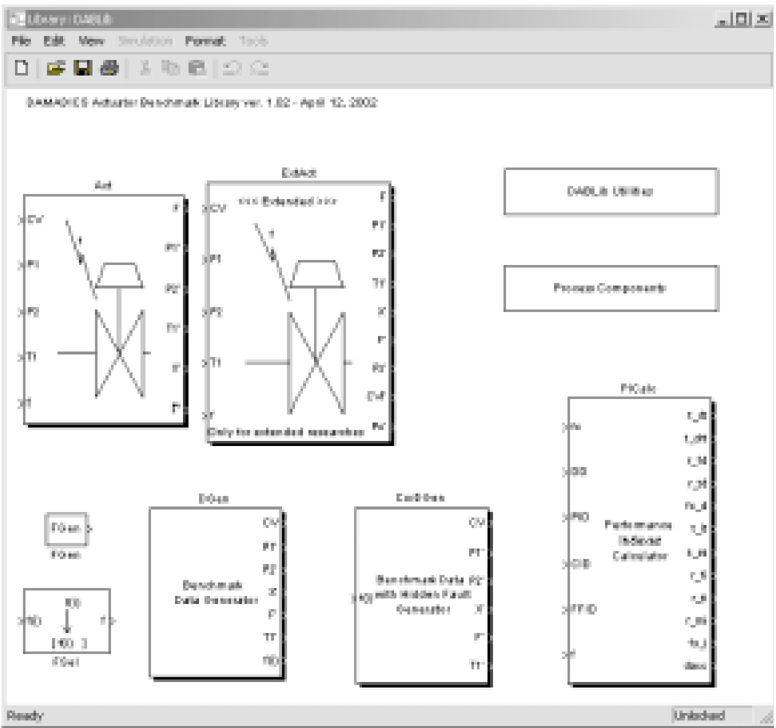

*Figure 2. **‘DABLIB’** components*

Fault generator (**FGEN**) is a fault strength setting device.

Fault selector (**FSEL**) selects desired fault and assigns fault attributes.

Data generator (**DGEN**) generates repeatable patterns of data sets for benchmark purposes.

Coordinator data generator (**CORDGEN**) generates repeatable patterns of data sets with hidden faults for benchmark purposes.

Performance indexes calculator (**PICALC**) automatically calculates performance indexes for benchmark purposes.

The **PROCESS COMPONENTS** block group contains components that are used only in case of process simulating. The main benchmark blocks mentioned above are not useful in this case.

The **DABLIB UTILITIES** block group contains the set of components that are used by other DABlib blocks. This **UTILITIES** are not intended to be used directly for benchmark purposes. The main utility blocks are:

- Actuator (**COREACT**) block is a core of a library. This block is a model of final control element consisting of positioner, pneumatic motor and control valve.

- Actuator (**COREACT+BYPASSVALVE**) block is a model of final control element together with bypass valve.

4. Assumptions and remarks

- Blocks inputs and outputs are divided into two classes: measurements and physicals. All the measurement signals are normalised in the range of `<0,1>` referring to the real measurement spans. Such a variables are denoted by the apostrophe. The physical signals are sized in physical units.
- The measurement signals are additionally limited to the range `<0,1>` what reflects the real conditions.
- All measurement signals are disturbed by artificial generated noise on demand (see Figure 4).

5. Description of blocks

5.1. 'ACT' block

This block is a model of final control element consisting of positioner, pneumatic motor, control valve and bypass valve.

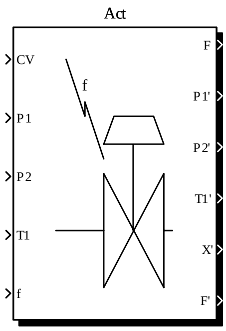

*Figure 3. **ACT** block symbol*

This block reflects the virtual actuator however the parameters of the model were tuned using experimental data achieved during the laboratory tests as well as data from real process (Actuator 3 from Lublin Sugar Factory, see DAMADICS Information Website in the **Benchmark** section). The sub-elements of the actuator are corresponding to the industrial devices: positioner A785, servo-motor type 37 and equalpercentage control valve (see references on DAMADICS Information Website in the **Benchmark** section).

'ACT' inputs and outputs

The description of block inputs and outputs are given in Table 1 and Table 2.

*Table 1. **ACT** inputs*

Input	Range	Physical units	Description
CV	<0,1>	100%	Control variable is the output signal from the controller.
P1	-	Pa	The value of the pressure on the control valve inlet.
P2	-	Pa	The value of the pressure on the control valve outlet.
T1	-	^{0}C	The temperature of medium
f	each element of vector f is in the range <-1,1> or <0,1>	see Table 3	The vector of faults. The size of the vector equals to the number of 19 faults.

*Table 2. **ACT** outputs*

Output	Range	Physical units	Transducer range	Description
F	-	t/h	-	The medium flow.
P1'	<0,1>	-	<0, 4[1)]> [MPa]	The disturbed value of the pressure on the control valve inlet.[2)]
P2'	<0,1>	-	<0, 4[1)]> [MPa]	The disturbed value of the pressure on the control valve outlet.[2)]
T1'	<0,1>	-	<0, 200[1)]> [^{0}C]	The disturbed medium temperature. [2)]
X'	<0,1>	-	<0, 100[1)]> [%]	The disturbed value of the rod displacement.[2)]
F'	<0,1>	-	<0, 40[1)]> [t/h]	The disturbed medium flow.[2)]

1) Equal to the measuring range of corresponding transducer installed on Actuator 3. see DAMADICS Information Website in the **Benchmark / Real Data Benchmark** section.

2) The values are not disturbed in a case if Disable Disturbance option of the block is ticked.

Simulation of signal disturbances

Figure 4 shows scheme of noise entries in **ACT** block. According to proposed notation, the disturbed variables are denoted by apostrophes. Please pay attention that the CV value is disturbed when entering **ACT** block. Use exclusively not disturbed CV value for diagnostics purposes (see Figure 6).

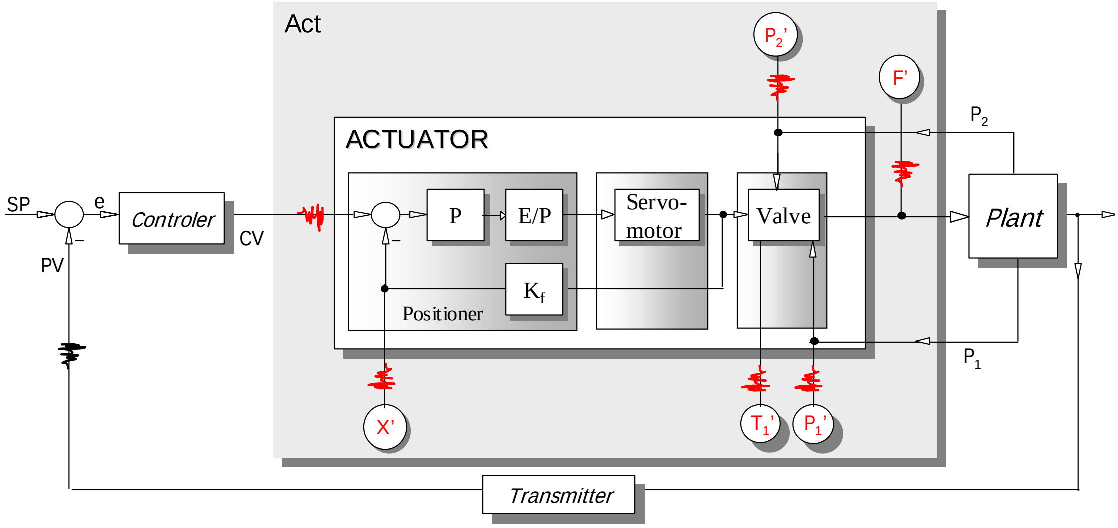

*Figure 4. Illustration of noise entries in **ACT** block*

Noise may be switched off by the ***Disable noise*** parameter.

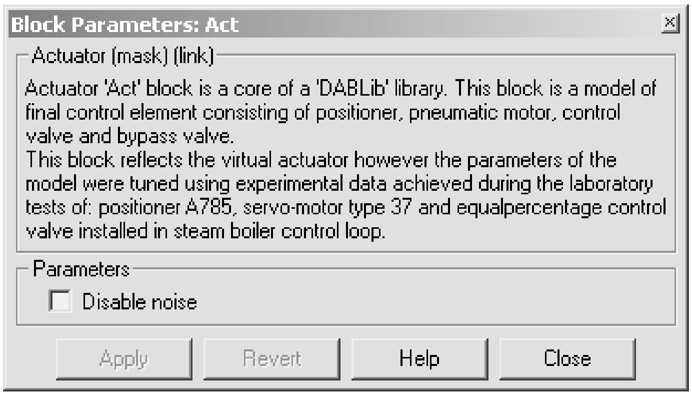

*Figure 5. '**ACT**' block parameters window*

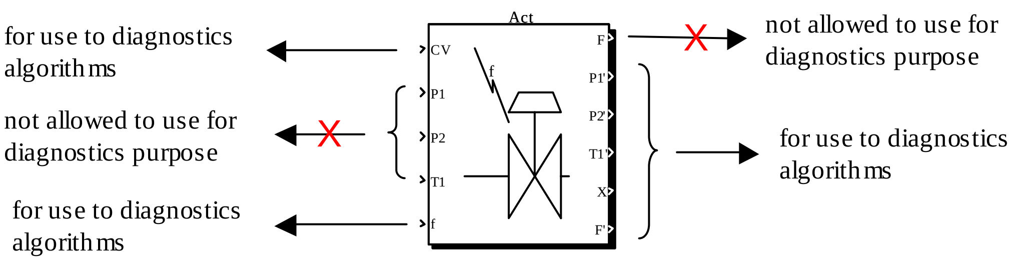

*Figure 6. Principles of using **ACT** block for diagnostics purpose*

An example of using **ACT** block are given in Section 5.7.

Simulation of faults

The model was designed to be able to simulate 19-th distinguished faults. Faults notation and descriptions are presented in table "Fault specification".

Table 3. Fault specification

Fault	Description	Limits of i^{th} element of f	Details
	Control valve faults		
f1	Valve clogging	<0, 1>	Table 4
f2	Valve plug or valve seat sedimentation	<0, 1>	Table 5
f3	Valve plug or valve seat erosion	<0, 1>	Table 6
f4	Increased of valve or bushing friction	<-1, 1>	Table 7
f5	External leakage (leaky bushing, covers, terminals)	<0, 1>	Table 8
f6	Internal leakage (valve tightness)	<0, 1>	Table 9
f7	Medium evaporation or critical flow	<0, 1>	Table 10
	Pneumatic servo-motor faults		
f8	Twisted servo-motor's piston rod	<0, 1>	Table 11
f9	Servo-motor's housing or terminals tightness	<0, 1>	Table 12
f10	Servo-motor's diaphragm perforation	<0, 1>	Table 13
f11	Servo-motor's spring fault	<0, 1>	Table 14
	Positioner faults		
f12	Electro-pneumatic transducer fault	<-1, 1>	Table 15
f13	Rod displacement sensor fault	<-1, 1>	Table 16
f14	Pressure sensor fault	<-1, 1>	Table 17
f15	Positioner feedback fault	<0, 1>	Table 18
	General faults / external faults		
f16	Positioner supply pressure drop	<0, 1>	Table 19
f17	Unexpected pressure change across the valve	<-1, 1>	Table 20
f18	Fully or partly opened bypass valves	<0, 1>	Table 21
f19	Flow rate sensor fault	<-1, 1>	Table 22

The ***fault strength*** *(*`fs`*)* elements of vector f are standardised to the range <0,1>. The limiting values "0" and "1" corresponds to some pre-defined states or physical values (fs_{min}, fs_{max}). Sometimes, the fault may cause bi-directional consequences, *e.g. sensor faults*. To distinguish between fault consequence directions the ***fault direction*** parameter ($fd \in \{-1;1\}$) is defined. The fault vector **f** = $fd \cdot$ **fs**.

Table 4. Simulation technique of f1 **Return to** *Table 3*

Fault	f1
Group	Control valve
Description	valve clogging
Physical interpretation	blocking servomotor rod displacement by external mechanical nature event
Fault primary nature	abrupt
Simulated action	unilateral rod displacement limitation
Limits of 1st element of fault vector f	{0..1}
Fault strength interpretation	0 – no fault; 1- no movement
Fault simulation technique equation	$H_f = H_0(1 - f_s)$ *H_f – higher rod travel bound* *H_0 – nominal higher rod travel bound* *f_s – fault strength*

Table 5. Simulation technique of f2 **Return to** *Table 3*

Fault	f2
Group	Control valve
Description	valve plug or valve seat sedimentation
Physical interpretation	sedimentation of solid particles on the surfaces of valve seat and plug
Fault primary nature	slowly developing
Simulated action	decreasing of plug travel and lowering the diameter of valve seat (lowering the relative valve K_{vr} factor)
Limits of 2nd element of fault vector f	{0..1}
Fault strength interpretation	0 – no sedimentation; 1- advanced sedimentation
Fault simulation technique equation	$H_f = H_0(1 - 0.2 f_s)$ $X_f = \min\{1, (X_0 + 0.2 f_s)\}$ $K_{vrf} = \min\{1, [K_{vr0}(1 - 0.2 f_s)]\}$ *H_f – higher rod travel bound* *H_0 – nominal higher rod travel bound* *f_s – fault strength* *X_f – relative plug travel* *X_0 – nominal plug travel* *K_{vrf} – relative valve flow factor* *K_{vr0} – nominal relative valve flow factor*

Table 6. Simulation technique of f3 **Return to** *Table 3*

Fault	f3
Group	Control valve
Description	valve plug or valve seat erosion
Physical interpretation	mechanical wear (friction, cavity, aging, fatigue) or chemical treatment (corrosion) of valve seat and plug
Fault primary nature	slowly developing
Simulated action	increasing of plug travel and valve seat diameter (increasing the relative valve K_{vr} factor)
Limits of 3rd element of fault vector f	{0..1}
Fault strength interpretation	0 – no erosion; 1- advanced erosion
Fault simulation technique equation	$H_b = H_0(1 + 0.1 f_s)$ $X_f = X_0 - 0.1 f_s$ $K_{vrf} = K_{vr0}(1 + 0.1 f_s)$ *H_f – higher rod travel bound* *H_0 – nominal higher rod travel bound* *f_s – fault strength* *X_f – relative plug travel* *X_0 – nominal plug travel* *K_{vrf} – relative valve flow factor* *K_{vr0} – nominal relative valve flow factor*

Table 7. Simulation technique of f4 **Return to** Table 3

Fault	**f4**
Group	Control valve
Description	increasing of valve or bushing friction
Physical interpretation	mechanical wear, air pollution, corrosion products, sedimentation
Fault primary nature	slowly developing
Simulated action	increasing or decreasing of hysteresis loop depending on fault strength
Limits of 4th element of fault vector f	{-1..1}
Fault strength interpretation	-1 – no friction 0 – unchanged friction; 1- advanced friction
Fault simulation technique equation	$D_{bf} = \max(0, X_0(D_{b0} + f_s))$ *D_{bf} – hysteresis loop width in [m]* *D_{b0} – relative nominal hysteresis loop width (1%)* *X_0 – nominal plug travel (0.0381m)* *f_s – fault strength*

Table 8. Simulation technique of f5 **Return to** Table 3

Fault	**f5**
Group	Control valve
Description	external leakage
Physical interpretation	mechanical wear, material or erosion fault or valve assembly mounting fault causing leakage from the control valve body by leaky bushing , valve covers or terminals
Fault primary nature	slowly developing
Simulated action	lowering the valve outflow (additive fault)
Limits of 5th element of fault vector f	{0..1}
Fault strength interpretation	0 – without leakage; 1- moderate leakage
Fault simulation technique equation	$F_f = \max[0, \ F_0(1 - 0.05 * f_s)]$ *F_f – valve outflow* *F_0 – valve outflow for f_s=0* *f_s – fault strength*

Table 9. Simulation technique of f6 **Return to** Table 3

Fault	**f6**
Group	Control valve
Description	internal leakage
Physical interpretation	valve seat – plug assembly tightness caused by mechanical wear, erosion, corrosion
Fault primary nature	slowly developing
Simulated action	increasing relative valve flow factor Kv (additive fault)
Limits of 6th element of fault vector f	{0..1}
Fault strength interpretation	0 – without leakage; 1- moderate leakage
Fault simulation technique equation	$K_{vrf} = K_{vr0}(1 + 0.1 f_s)$ *K_{vrf} – relative valve flow factor* *K_{vr0} – nominal relative valve flow factor* *f_s – fault strength*

Table 10. Simulation technique of f7 **Return to** Table 3

Fault	**f7**
Group	Control valve
Description	Medium evaporation or critical flow. IMPORTANT: Evaporation may appear even if not strictly simulated when necessary physical conditions are fulfilled due to other reasons (e.g., combination of P1, P2 and T1).
Physical interpretation	two phase flow (mixture of fluid and steam) caused when local fluid pressure drops down to steam evaporation pressure level. This manifests in flashing or cavity phenomenon.
Fault primary nature	abrupt
Simulated action	increasing fluid temperature
Limits of 7th element of fault vector f	{0..1}
Fault strength interpretation	0 – without fluid temperature change; 1- advanced evaporation
Fault simulation technique equation	$T1_f = T1_0 \quad if \ f_s = 0$ $T1_f = T1_0 + 200 + 100 * f_s \quad if \ f_s > 0$ *$T1_f$ – fluid temperature* *$T1_0$ – nominal fluid temperature* *f_s – fault strength*

Table 11. Simulation technique of f8 ***Return to** Table 3*

Fault	**f8**	
Group	Pneumatic servomotor	
Description	twisted servomotor's rod	
Physical interpretation	permanent bending of the servomotor's rod due to mechanical tensions caused by the internal or external forces acting on rod perpendicular to its axis	
Fault primary nature	abrupt	
Simulated action	simulated as a linear change of friction hysteresis loop width versus rod displacement	
Limits of 8th element of fault vector f	{0..1}	
Fault strength interpretation	0 – no twist; 1- advanced twist	
Fault simulation technique equation	$D_{bf} = \min\{X_0, \max[0, D_b(1+0.5 * f_s(1-X))]\}$	*D_{bf} – hysteresis loop width in [m]* *D_b – input hysteresis loop in [m]* *X_0 – nominal plug travel (0.0381m)* *f_s – fault strength* *X – relative rod displacement*

Table 12. Simulation technique of f9 ***Return to** Table 3*

Fault	**f9**	
Group	Pneumatic servomotor	
Description	servomotor's housing or terminals tightness	
Physical interpretation	due to actuator mechanical vibrations installed in harsh industrial environment the screws fastening the servomotor covers or air pipe terminals may loose involving unwilled tightness	
Fault primary nature	slowly developing	
Simulated action	simulated as an additional air mass outflow from servomotor's chamber	
Limits of 9th element of fault vector f	{0..1}	
Fault strength interpretation	0 – no tightness; 1- advanced tightness	
Fault simulation technique equation	$\dot{m}_f = \dot{m}_0(1-2f_s 10^{-6}\sqrt{Ps})$	*dm_f/dt – air mass flow* *dm_0/dt – nominal air mass flow* *f_s – fault strength* *Ps – pressure in servomotor's chamber*

Table 13. Simulation technique of f10 ***Return to** Table 3*

Fault	**f10**	
Group	Pneumatic servomotor	
Description	servomotor's diaphragm perforation	
Physical interpretation	caused by fatigue of diaphragm material	
Fault primary nature	abrupt	
Simulated action	simulated as an additional air mass outflow from servomotor's chamber and as a change of effective diaphragm area	
Limits of 10th element of fault vector f	{0..1}	
Fault strength interpretation	0 – no tightness; 1- advanced tightness	
Fault simulation technique equation	$\dot{m}_f = \dot{m}_0(1-2f_s 10^{-6}\sqrt{Ps})$ $Aef = Ae(1-fs)$	*dm_f/dt – air mass flow* *dm_0/dt – nominal air mass flow* *f_s – fault strength* *Ps – pressure in servomotor's chamber* *Ae – nominal diaphragm area* *Aef – diaphragm area*

Table 14. Simulation technique of f11 ***Return to** Table 3*

Fault	**f11**	
Group	Pneumatic servomotor	
Description	servomotor's spring fault	
Physical interpretation	caused by fatigue or corrosion of spring material	
Fault primary nature	abrupt	
Simulated action	simulated as lowering of spring constant	
Limits of 11th element of fault vector f	{0..1}	
Fault strength interpretation	0 – no spring fault; 1- advanced fault	
Fault simulation technique equation	$k_{sf} = k_{s0}(1-f_s)$	*k_{sf} – spring constant* *k_{s0} – nominal spring constant* *f_s – fault strength*

Table 15. Simulation technique of f12 ***Return to** [Table 3]*

Fault	**f12**	
Group	Positioner	
Description	electro-pneumatic transducer fault	
Physical interpretation	change of electro-pneumatic transducer characteristics or coil damage or mechanical transducer part fault (broken springs, obstacles in nozzles, e.t.c.)	
Fault primary nature	abrupt	
Simulated action	simulated as change of current supplying the transducer	
Limits of 12th element of fault vector f	{-1..1}	
Fault strength interpretation	-1 - cancelling of the left half of transducer characteristics; advanced fault 0 – no fault; 1 - cancelling of the right half of transducer characteristics; advanced fault if *sgn*(f_s) = *1* then transducer characteristics is shifted right if *sgn*(f_s) = *-1* then transducer characteristics is shifted left	
Fault simulation technique equation	$i_f = i_0(1 - f_s)$	i_f – *transducer current* i_0 – *nominal transducer current* f_s – *fault strength*

Table 16. Simulation technique of f13 ***Return to** [Table 3]*

Fault	**f13**	
Group	Positioner	
Description	rod displacement sensor fault	
Physical interpretation	wear of the potentiometer conductive plastic layer or wear of potentiometer wiper or fatigue wiring break or displacement electronics failure	
Fault primary nature	slowly developing	
Simulated action	simulated as a change in rod displacement measurement	
Limits of 13th element of fault vector f	{-1..1}	
Fault strength interpretation	-1 – relative rod displacement measurement = 0 independent on real displacement 0 – no fault; 1 - relative rod displacement measurement = 1 independent on real displacement	
Fault simulation technique equation	$X_f = X_0(1 + 1.25 f_s)$	X_f – *relative displacement measurement* X_0 – *relative rod displacement* f_s – *fault strength*

Table 17. Simulation technique of f14 ***Return to** [Table 3]*

Fault	**f14**	
Group	Positioner	
Description	electro-pneumatic transducer pressure sensor fault	
Physical interpretation	fatigue wear of the pressure sensor membrane, pressure transducer electronics part failure	
Fault primary nature	abrupt	
Simulated action	simulated as a change in electro-pneumatic transducer pressure measurement	
Limits of 14th element of fault vector f	{-1..1}	
Fault strength interpretation	-1 – relative pressure measurement = 0 independent on real pressure 0 – no fault; 1 - relative pressure measurement = 1 independent on real pressure	
Fault simulation technique equation	$\begin{cases} P'_{sf} = P'_s(1 + f_s) \\ if\ P'_s < 0\ then\ P'_{sf} = 0 \\ if\ P'_s > 1\ then\ P'_{sf} = 1 \end{cases}$	P'_{sf} – *relative pressure measurement* P'_s – *relative pressure* f_s – *fault strength*

Table 18. Simulation technique of f15 ***Return to** Table 3*

Fault	**f15**	
Group	Positioner	
Description	positioner feedback fault	
Physical interpretation	caused by fault of spring cancelling the clearance in the positioner mechanical lever feedback system	
Fault primary nature	abrupt	
Simulated action	simulated as a backlash in the positioner feedback	
Limits of 15th element of fault vector f	{-1..1}	
Fault strength interpretation	-1 – relative pressure measurement = 0 independent on real pressure 0 – no backlash; 1 - relative pressure measurement = 1 independent on real pressure	
Fault simulation technique equation	$D_{sf} = f_s X_n$	*D_{sf} – dead band width* *f_s – fault strength* *X_n – nominal valve plug displacement*

Table 19. Simulation technique of f16 ***Return to** Table 3*

Fault	**f16**	
Group	General faults/external faults	
Description	positioner supply pressure drop	
Physical interpretation	caused by pressure supply station fault or by throttling the air flow due to obliteration effect or system oversized air consumption or air leading pipes breaks, etc	
Fault primary nature	rapidly developing	
Simulated action	simulated as decreased positioner air supply pressure	
Limits of 16th element of fault vector f	{0..1}	
Fault strength interpretation	0 – no fault; 1 – positioner supply pressure drop to 0 Pa (relative)	
Fault simulation technique equation	$P_{zf} = P_{z0}(1 - f_s)$	*P_{zf} – positioner supply pressure* *P_{zo} – nominal air pressure* *f_s – fault strength*

Table 20. Simulation technique of f17 ***Return to** Table 3*

Fault	**f17**	
Group	General faults/external faults	
Description	unexpected pressure change across the valve	
Physical interpretation	caused by media pump station failure or process disturbance (increased flow output) or increased pipes resistance or change of fluid viscosity or external media leakage, etc	
Fault primary nature	rapidly developing	
Simulated action	simulated as a change of pressure difference P1-P2 across the valve	
Limits of 17th element of fault vector f	{-1..1}	
Fault strength interpretation	-1 – P1 = 0 0 – no fault; 1 – P2 = 0	
Fault simulation technique equation	$P1_f = P1(1 - \lvert f_s \rvert) \quad for\ f_s < 0$ $P2_f = P2(1 - \lvert f_s \rvert) \quad for\ f_s > 0$	*$P1_f$ – media pressure entering model* *P1 – media pressure (valve inlet)* *$P2_f$ – media pressure entering model* *P2 – media pressure (valve outlet)* *f_s – fault strength*

Table 21. Simulation technique of f18 ***Return to** Table 3*

Fault	**f18**	
Group	General faults/external faults	
Description	fully or partly opened bypass valves	
Physical interpretation	caused by operator fault when not closing the valve during valve manual operation or valve corrosion or seat sealing wear etc	
Fault primary nature	abrupt	
Simulated action	simulated as partly opening the bypass valve	
Limits of 18th element of fault vector f	{0..1}	
Fault strength interpretation	0 – no fault; 1 – fully opened bypass valve	
Fault simulation technique equation	$X_{bf} = 1 - f_s$	*X_{bf} – relative bypass valve closing* *f_s – fault strength*

Table 22. Simulation technique of f19

***Return to** Table 3*

Fault	**f19**
Group	General faults/external faults
Description	flow rate sensor fault
Physical interpretation	caused by electronics or wiring failure
Fault primary nature	abrupt
Simulated action	simulated by modifying sensor output characteristics
Limits of 19th element of fault vector f	{-1..1}
Fault strength interpretation	-1 - flow measurement =0 independent on real flow 0 – no fault; 1 – flow measurement =1 independent on real flow
Fault simulation technique equation	$\begin{cases} F_f^{'} = F'(1+f_s) \\ if\ F_f^{'} < 0\ then\ F_f^{'} = 0 \\ if\ F_f^{'} > 1\ then\ F_f^{'} = 1 \end{cases}$ *F'_f – relative flow measurement* *F' – relative flow* *f_s – fault strength*

5.2. 'EXTACT' **block**

This block is an extension of **'ACT'** block. This block is not foreseen for main benchmark purpose. It can be used for evaluation and testing the quality of FDI algorithms with extended set of measurements. The only difference between 'Act" block are additional three outputs, realistic to be measured.

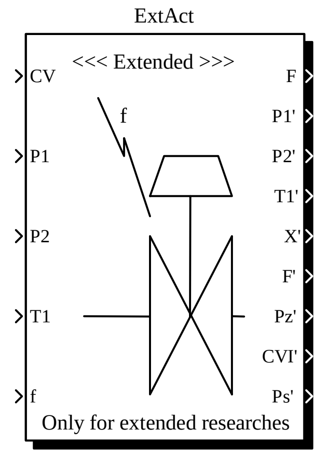

*Figure 7. **EXTACT** block symbol*

*Table 23. Additional '**EXTACT**' outputs*

Output	Range	Physical units	Transducer range	Description
Pz'	<0,1>	-	<0, 0.6> [MPa]	The value of the positioner supply pressure.[1)]
CVI'	<0,1>	-	<-1, 1>	The output of internal positioner P controller.[1)]
Ps'	<0,1>	-	<0, 0.6> [MPa]	The value of pressure in servo motor chamber. [1)]

[1)] The values are not disturbed by default. It corresponds to the case of digital transmission which is necessary in the case of multi output actuator.

5.3. 'FGEN' functional block

Fault generator **'FGEN'** is a fault strength setting device in time domain. It has 5 parameters shown on Figure 9 and explained on Figure 10. Abrupt fault can be generated setting ***Fault Development Time*** to '`0`'. Fault time horizon can be unlimited setting the ***To*** parameter equal '`inf`'.

*Figure 8. **'FGEN'** block symbol*

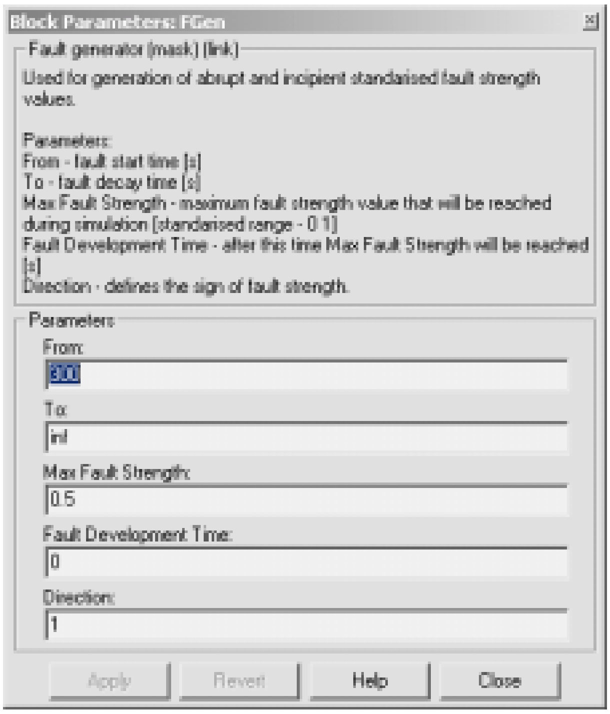

*Figure 9. **'FGEN'** block parameters window*

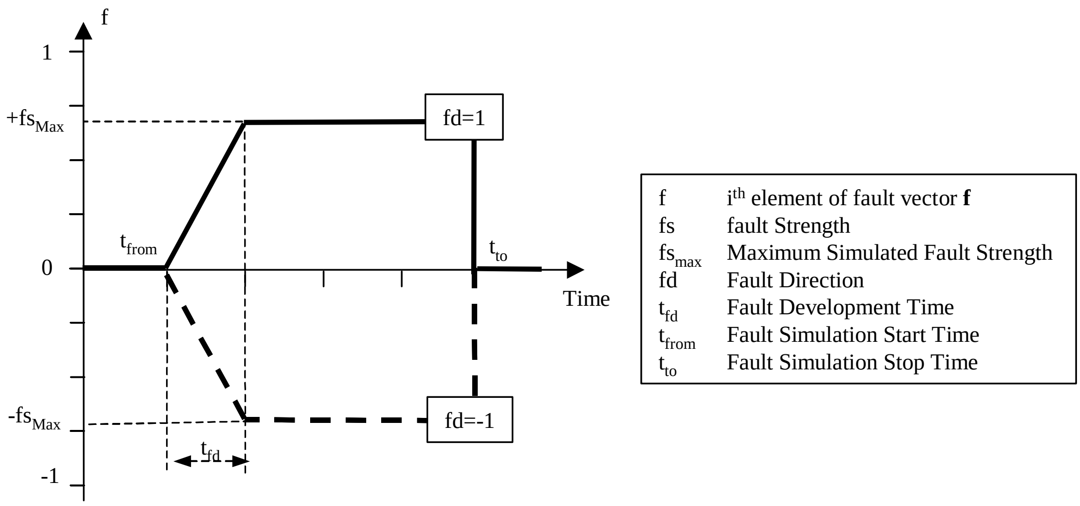

*Figure 10. **'FGEN'** block symbol*

*Table 24. **FGEN** outputs*

Output	Range	Description
f_i	<-1, 1>	i^{th} element of fault vector

5.4. 'FSEL' functional block

Fault selector **'FSEL'** generates fault vector **f** with selected single fault. The selected fault strength is transferred from block input. Fault selection is done by ***Fault selector*** block parameter. '`NO FAULT`' selection is also possible.

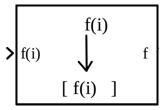

*Figure 11. '**FSEL**' block symbol*

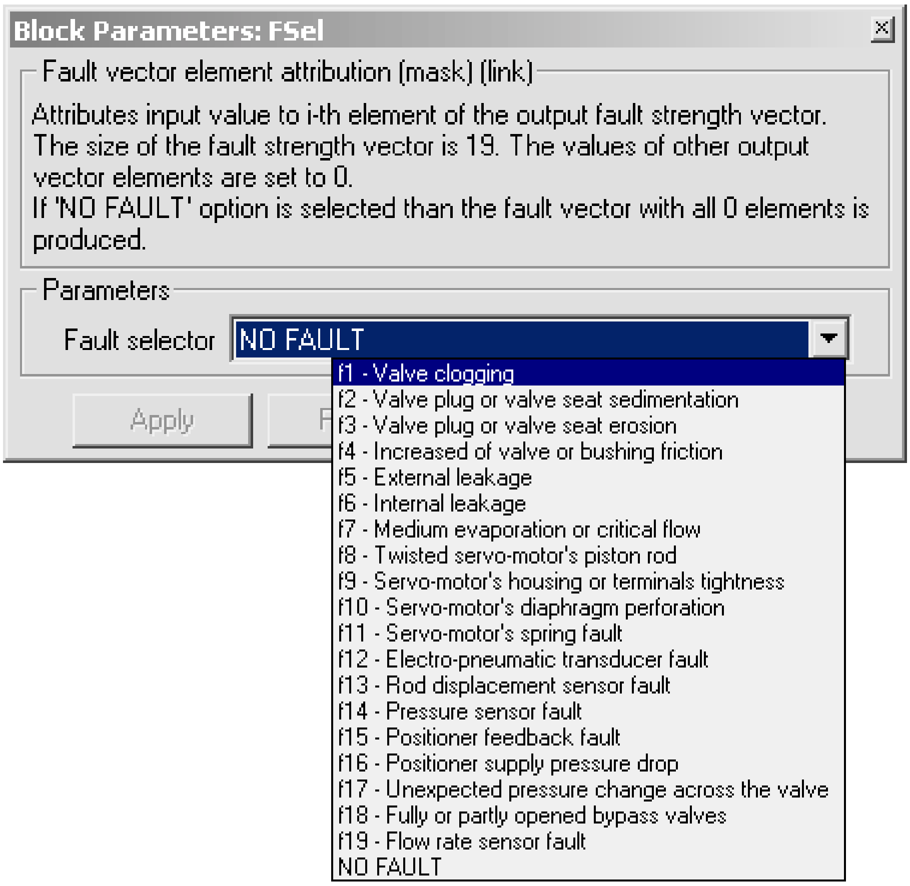

*Figure 12. '**FSEL**' block parameters window*

*Table 25. **FSEL** inputs*

Input	Range	Description
f(i)	<-inf, inf>	i^{th} element of fault vector

*Table 26. **FSEL** outputs*

Output	Range	Physical units	Description
f	<-inf, inf>	see Table 3	The vector of faults. The size of the vector equals to the number of 19 faults.

5.5. 'DGEN' functional block

Data generator (**DGEN**) generates repeatable patterns of data sets for benchmark purposes. Block allows simulating single fault scenarios. The data generated by the block can be easily used for diagnosis purposes.

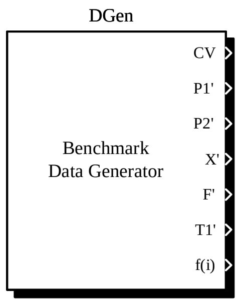

*Figure 13. **'DGEN'** block symbol*

The block structure is given in Figure 14. Block is design around **'ACT'** block (circle 1). The actuator is driven by low-frequency sine wave with a mean value of 50% (***CV*** value, circle 2). Water temperature passing the valve is fixed to a constant value. Pressure signals ***P1*** and ***P2*** are driven by the sine functions with appropriate amplitudes and frequencies (circle 3).

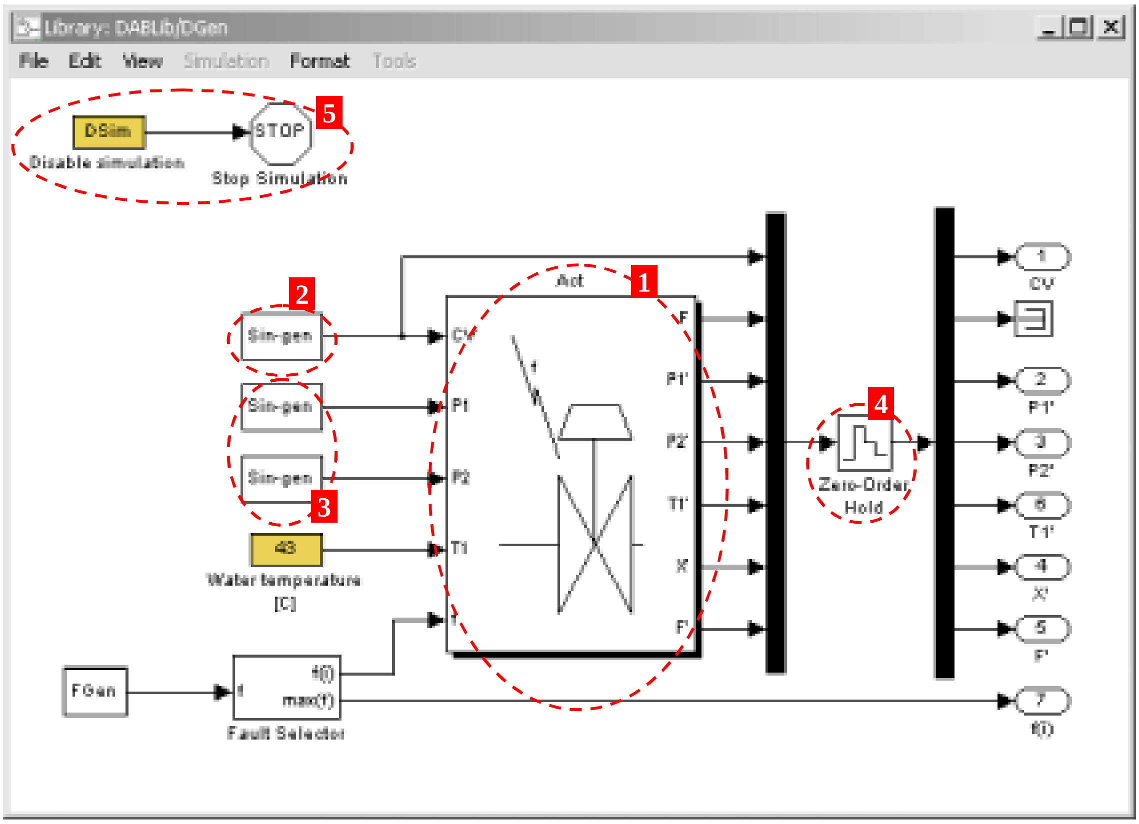

*Figure 14. **'DGEN'** internal structure*

Block outputs are updated every 1 second (circle 4) in respect to sampling time of SCADA system in Lublin Sugar Factory. Running the simulation is not possible (circle 5) in the case of improper settings of block parameters (see Table 29). In the case of choosing improper combination an error message is issued by Matlab.

The block has 2 parameters shown on Figure 15. Setting ***Fault selector*** and ***Failure mode*** determines fault scenario. See Sections 'Failure modes' and 'Fault scenarios' for more details.

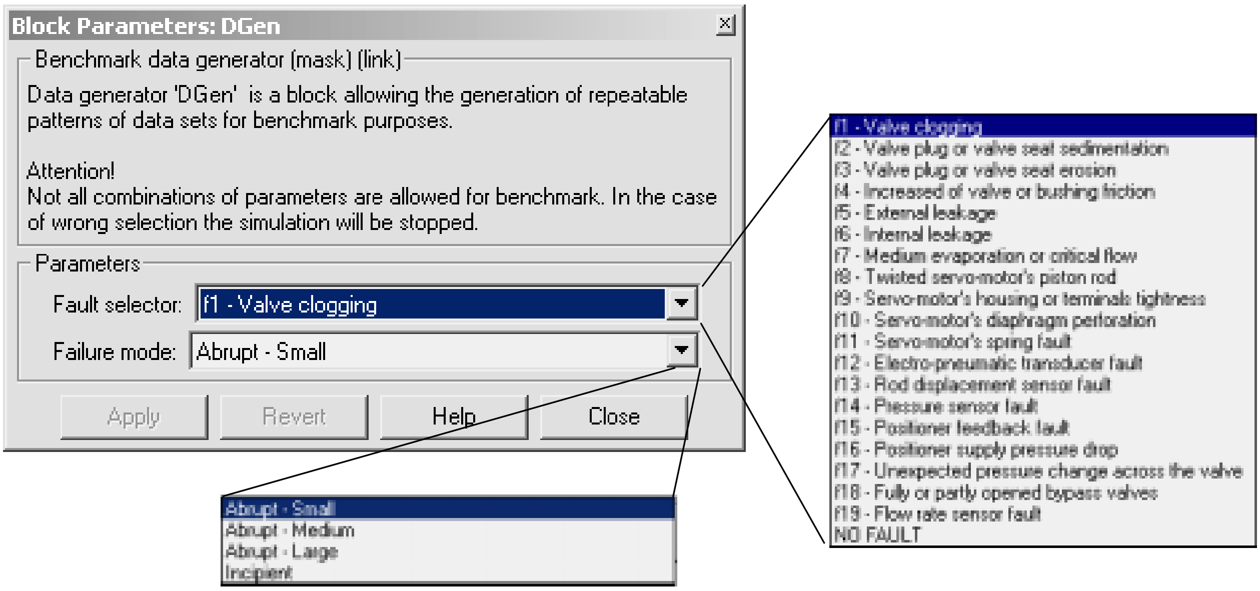

*Figure 15. '**DGEN**' block parameters window*

*Table 27. **DGEN** outputs*

Output	Range	Physical units	Transducer range	Description
CV	<-inf,+inf>	-	-	Control variable is the output signal from the controller.
P1'	<0,1>	-	<0, 4[1)]> [MPa]	The disturbed value of the pressure on the control valve inlet.
P2'	<0,1>	-	<0, 4[1)]> [MPa]	The disturbed value of the pressure on the control valve outlet.
X'	<0,1>	-	<0, 100[1)]> [%]	The disturbed value of the rod displacement.
F'	<0,1>	-	<0, 40[1)]> [t/h]	The disturbed medium flow.
T1'	<0,1>	-	<0, 200[1)]> [^{0}C]	The disturbed medium temperature.
f(i)	<-1,1> or <0,1>	see Table 3	-	simulated fault i^{th} element of fault vector.

[1)] Equal to the measuring range of corresponding transducer installed on Actuator 3. see DAMADICS Information Website in the **Benchmark** section.

Failure modes

Three standard values of fault strength were defined for the benchmark purpose. They are named as follows: `small-long`, `medium` and `big-short`. They correspond to the 0.25, 0.5 and 0.75 normalised values. Two fault strength time development are considered: ***abrupt*** and ***incipient*** (see Figure 16). The parameters of failure modes are described in Table 28.

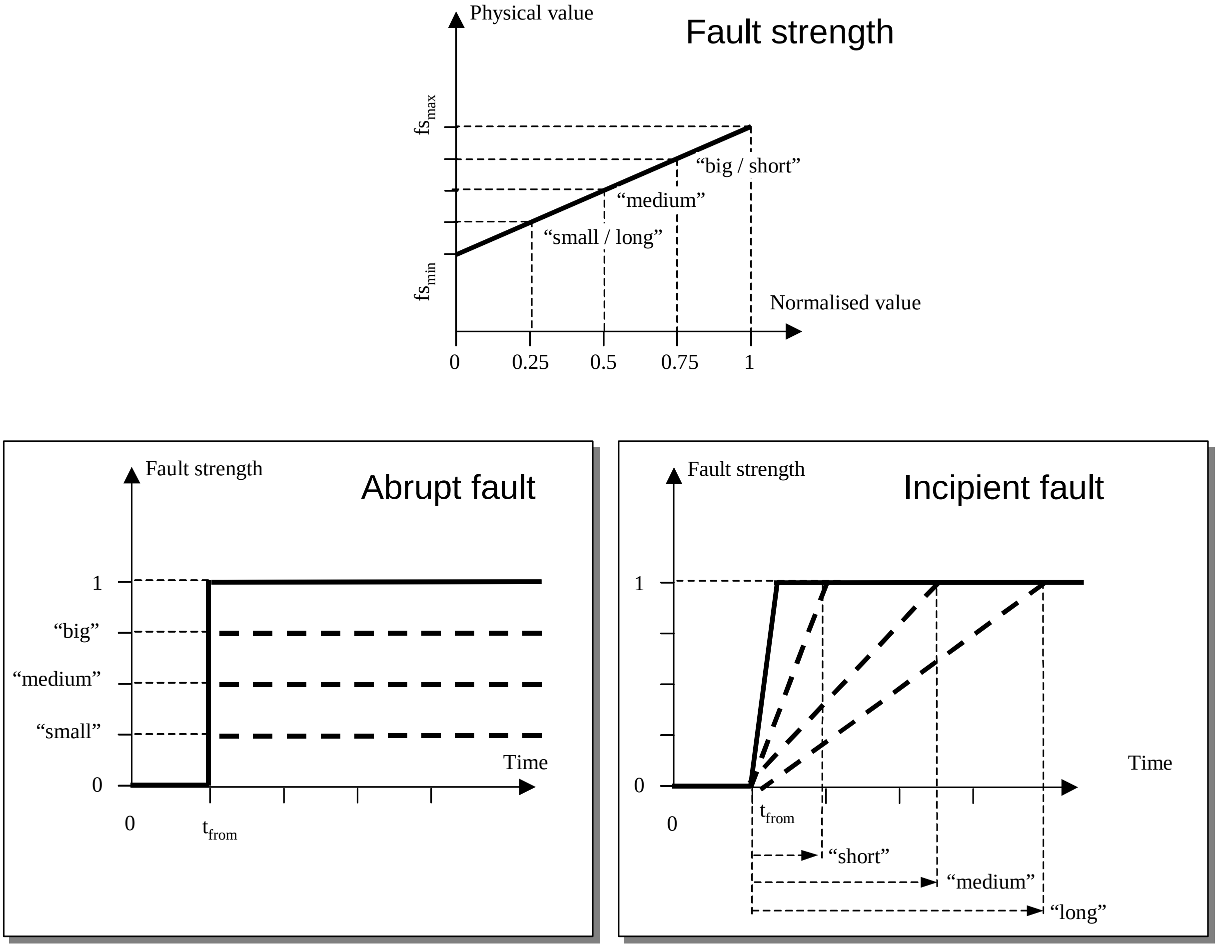

Figure 16. Fault time development of fault strength.

Table 28. Parameters of failure modes

Parameter		Failure mode: Abrupt `small`	Failure mode: Abrupt `medium`	Failure mode: Abrupt `big`	Failure mode: Incipient	Description
fs_{min}		to be defined in fault scenario, see Table 3				
fs_{max}						
t_{ffrom}		900 s	900 s	900 s	900 s	
fs(0)		0	0	0	0	At the beginning of simulation.
fs(inf)		0.25	0.5	0.75	1	At the end of simulation.
t_{fd}	`short`	0	0	0	600 s	Set automatically in respect to ***fault selection***
	`medium`				3600 s	
	`long`				84000 s	

In the case of abrupt fault, the user can select one of three pre-defined fault strength: `'small'`, `'medium'` and `'big'`. In the case of incipient fault, the fault development time is set automatically in respect to fault selection (see Table 29).

Fault scenarios

Table below shows allowed combinations of ***Fault selection*** – ***Failure mode*** and fixed fault directions.

Table 29. Set of faults specified for benchmark

Fault	Description	Abrupt S	Abrupt M	Abrupt B	Incipient	Fault Direction	Examples of explanation
				Control valve faults			
f1	Valve clogging	x	x	x		+	-
f2	Valve plug or valve seat sedimentation			x	$x^{1)}$	+	Abrupt fault reflects the situation when strange solid body is throttling the flow and limits plug travel, *e.g. a stone got stuck in the valve seat.*
f3	Valve plug or valve seat erosion				$x^{1)}$	+	-
f4	Increased of valve or bushing friction				$x^{2)}$	+	-
f5	External leakage (leaky bushing, covers, terminals)				$x^{1)}$	+	-
f6	Internal leakage (valve tightness)				$x^{1)}$	+	-
f7	Medium evaporation or critical flow	x	x	x		+	-
				Pneumatic servo-motor faults			
f8	Twisted servo-motor's piston rod	x	x	x		+	-
f9	Servo-motor's housing or terminals tightness				$x^{1)}$	+	-
f10	Servo-motor's diaphragm perforation	x	x	x		+	-
f11	Servo-motor's spring fault			x	$x^{1)}$	+	Abrupt fault reflects the situation of spring breaking. Incipient fault reflects the situation of spring corrosion.
				Positioner faults			
f12	Electro-pneumatic transducer fault	x	x	x		-	-
f13	Rod displacement sensor fault	x	x	x	$x^{3)}$	+	-
f14	Pressure sensor fault	x	x	x		-	-
f15	Positioner feedback fault			x		+	Abrupt fault reflects the situation of breaking the spring that cancels the clearance in feedback lever set.
				General faults / external faults			
f16	Positioner supply pressure drop	x	x	x		+	-
f17	Unexpected pressure change across the valve			x	$x^{2)}$	+	Abrupt fault reflects the situation of pump switch off. Incipient fault reflects the situation of pump efficiency factor drop.
f18	Fully or partly opened bypass valves	x	x	x	$x^{1)}$	+	Abrupt fault reflects the situation of bypass valve opening by the operator. Incipient fault reflects the situation of bypass valve leakage caused by corrosion.
f19	Flow rate sensor fault	x	x	x		-	-

1) Low fault development speed preset for simulation as (100% Fault Strength / 1 day).
2) Medium fault development speed preset for simulation as (100% Fault Strength / 1 hour).
3) High fault development speed preset for simulation as (100% Fault Strength / 15 minutes).

Legend: ■ - no physical background
x - specified for benchmark
□ - for connoisseurs (for research in free time)

5.6. 'CORDGEN' **functional block**

Coordinator data generator (**CORDGEN**) block is supposed to be used by the Project Coordinator to generates data sets with hidden faults for benchmark purposes. Block allows simulating of single fault scenarios. Simulated fault strength enters input `f(i)`.

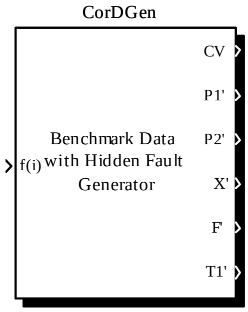

Figure 17. ***'CORDGEN'*** *block symbol*

Block internal structure and its functionality is the same as in **'DGEN'** block.

The block has 1 parameter shown on Figure 18. Setting ***Fault selector*** determines to which fault the fault strength form the input is assigned.

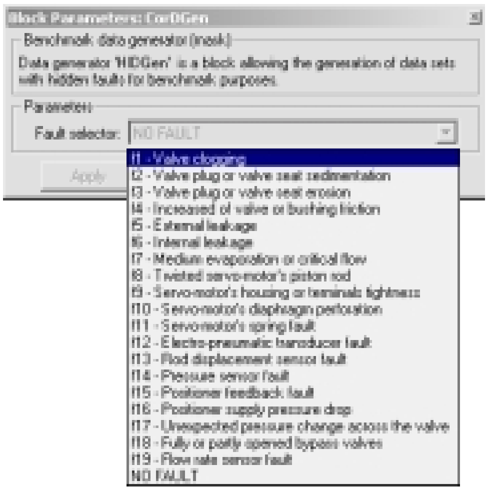

Figure 18. ***'DGEN'*** *block parameters window*

Table 30. ***ACT*** *inputs*

Input	Range	Physical units	Description
f(i)	corresponding to the choosen fault <0,1> or <-1,1>	see Table 3	The fault strength.

Table 31. ***CORDGEN*** *outputs*

Output	Range	Physical units	Transducer range	Description
CV	<-inf,+inf>	-	-	Control variable is the output signal from the controller.
P1'	<0,1>	-	<0, 4[1)]> [MPa]	The disturbed value of the pressure on the control valve inlet.
P2'	<0,1>	-	<0, 4[1)]> [MPa]	The disturbed value of the pressure on the control valve outlet.
X'	<0,1>	-	<0, 100[1)]> [%]	The disturbed value of the rod displacement.
F'	<0,1>	-	<0, 40[1)]> [t/h]	The disturbed medium flow.
T1'	<0,1>	-	<0, 200[1)]> [^{0}C]	The disturbed medium temperature.

1) Equal to the measuring range of corresponding transducer installed on Actuator 3. see DAMADICS Information Website in the **Benchmark** section.

5.7. 'PROCESS COMPONENTS' **block group**

The **'PROCESS COMPONENTS'** block group includes special blocks intended to be used in process control simulations. Basic benchmark blocks are not suitable for this purpose because they are including external fault (f16-f19). In the case of process control simulation this faults are inherited from the process.

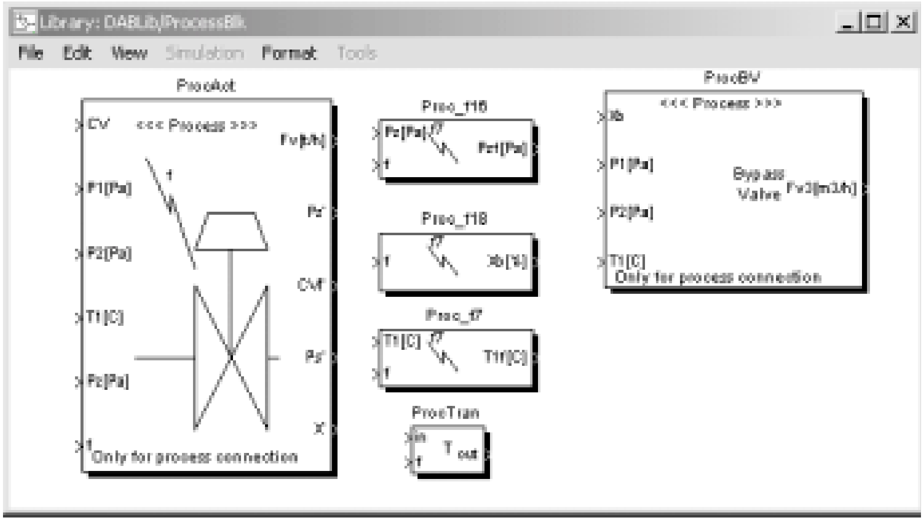

*Figure 19. **'PROCESS COMPONENTS'** block group*

The **'PROCACT'** and **'PROCBV'** blocks represents real industrial process devices, designed to be used as basic components in the process block diagram. They have only those outputs that are in real life, *e.g. the flow measurement is not an output of 'ProcAct', it must be realised by another basic component.*

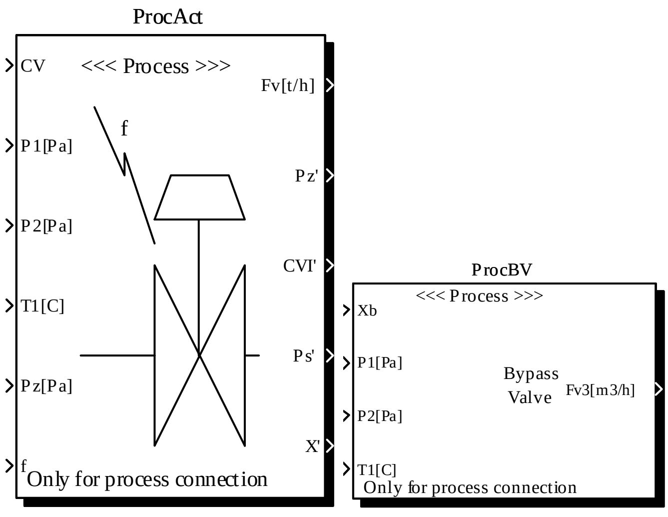

*Figure 20. **'PROCACT'** and **'PROCBV'** block symbols*

The blocks for external faults generation are added to allow simulation of the same fault scenarios as in the benchmark steps.

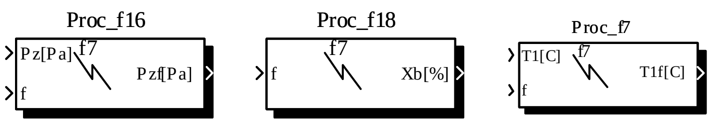

*Figure 21. **'PROC_F16', 'PROC_F18'** and **'PROC_F7'** block symbols*

The **'PROCTRAN'** block allows sensor fault simulation and noise generation. This block can be used for f19 simulation and disturbances for all the measurements.

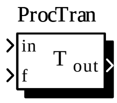

*Figure 22. **'PROCTRAN'** block symbol*

*Table 32. **PROCTRAN** inputs*

Input	Range	Physical units	Description
in	Physical	Corresponding to input signal	-
f	each element of vector f is in the range <-1,1> or <0,1>	see Table 3	The vector of faults. The size of the vector equals to the number of 19 faults.

*Table 33. **PROCTRAN** outputs*

Output	Range	Physical units	Transducer range	Description
out	<0, 1>	-	-	Limited to range <0,1>

The block has 4 parameters shown on Figure 23:

- ***Scaling Factor*** represents in physical units the range of sensor. it is assumed that the lower bound of the sensor is always 0.
- ***Seed*** is used to ensure the noise uniqueness. By setting the same seed as in the basic benchmark blocks it is possible to generate the same noise time series.
- Setting ***Fault selector*** determines which element on the input fault vector is passed into sensor fault simulation process.

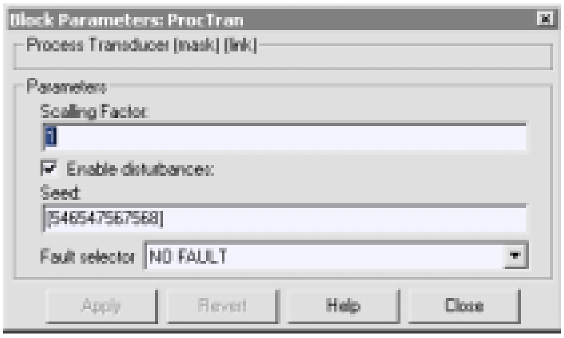

Figure 23. 'PROCTRAN' block parameters window

All the blocks from **'PROCESS COMPONENT'** are designed to accept the whole fault vector.

5.8. 'PICALC' functional block

The **'PICALC'** block can be used for automatic performance indexes calculation. A set of 12 indexes is generated on-line according to the definitions given in the ***Performance Indexes Appendix*** of Benchmark definition. This document can be downloaded from DAMADICS Information Website, section ***Benchmark*** / ***Definition***.

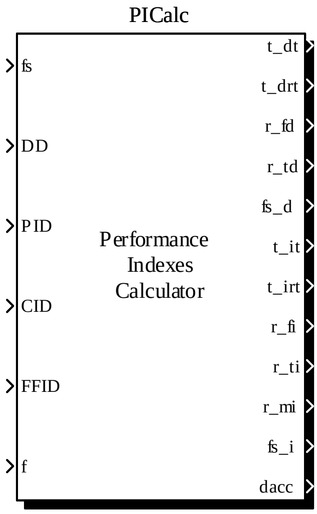

*Figure 24. **'PICALC'** block symbol*

*Table 34. **PICALC** inputs*

Input	Range	Physical units	Description
fs	<0,1>	see Table 3	The strength of simulated fault.
DD	binary	-	FDI decision signals. For definitions see the ***Glossary Appendix*** of Benchmark definition. This document can be downloaded from DAMADICS Information Website, section ***Benchmark*** / ***Definition***.
PID	binary	-	
CID	integer 0...20	-	
FFID	binary	-	
f	each element of vector f is in the range <-1,1> or <0,1>	see Table 3	The vector of faults indexes generated by the FDI algorithms.

*Table 35. **PICALC** outputs*

Output	Range[1)]	Physical units	Transducer range	Description
t_dt	-1 or <0,t_{hor}-t_{on}>[2)]	-	-	Performance indexes. For definitions see the ***Performance Indexes Appendix*** of Benchmark definition. This document can be downloaded from DAMADICS Information Website, section ***Benchmark*** / ***Definition***.
t_drt	-1 or <0,t_{hor}-t_{to}>[2)]	-	-	
r_fd	- 1 or <0,1>	-	-	
r_td	- 1or <0,1>	-	-	
fs_d	- 1or <0,1>	-	-	
t_it	-1 or <0,t_{hor}-t_{on}>[2)]	-	-	
t_irt	-1 or <0,t_{hor}-t_{to}>[2)]	-	-	
r_fi	- 1 or <0,1>	-	-	
r_ti	- 1 or <0,1>	-	-	
r_mi	- 1 or <0,20>	-	-	
fs_i	- 1 or <0,1>	-	-	
dacc	- 1 or <0,1>	-	-	

1) (-1) denotes an error or impossibility of index determining.
2) For definitions see ***Benchmark definition***. This document can be downloaded from DAMADICS Information Website, section ***Benchmark*** / ***Definition***.

Before using this block please check and eventually set the following block parameters: Benchmark Step, Fault selection, failure mode. Start of benchmark parameters are active only in the case of choosing Other benchmark parameter.

The block has 5 parameters shown on Figure 25:

- ***Benchmark*** selects benchmark step. Needed for automatic selection of the beginning and the end of benchmark time zone. For benchmark zone definition see ***Benchmark Definition Document***.

- ***Fault Selection*** and ***Failure Mode*** determine fault scenario in Benchmark / Step1. According to this parameters automatic selection of the beginning and the end of benchmark time zone is proceed. For benchmark zone definition see ***Benchmark Definition Document***. Important only in the case of selection: *Benchmark – Step I*.

- ***Start of Benchmark Zone*** and ***End of Benchmark Zone*** are used exclusively in the case of selection: *Benchmark – Other.* For benchmark zone definition see ***Benchmark Definition Document***. Important only in the case of selection: *Benchmark – Step I*.

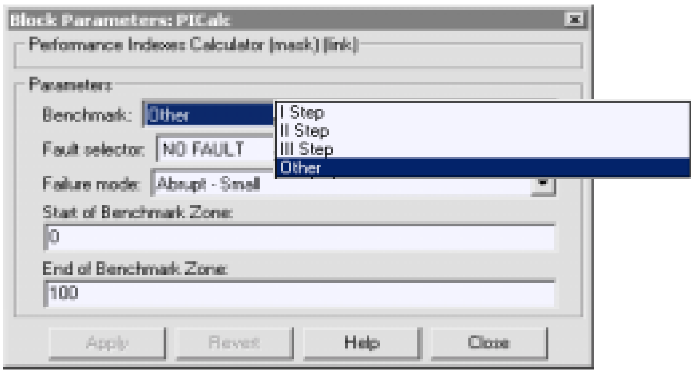

*Figure 25. '**PICALC'** block parameters window*

The following examples show how the performance indexes are calculated in different FDI decision scenarios.

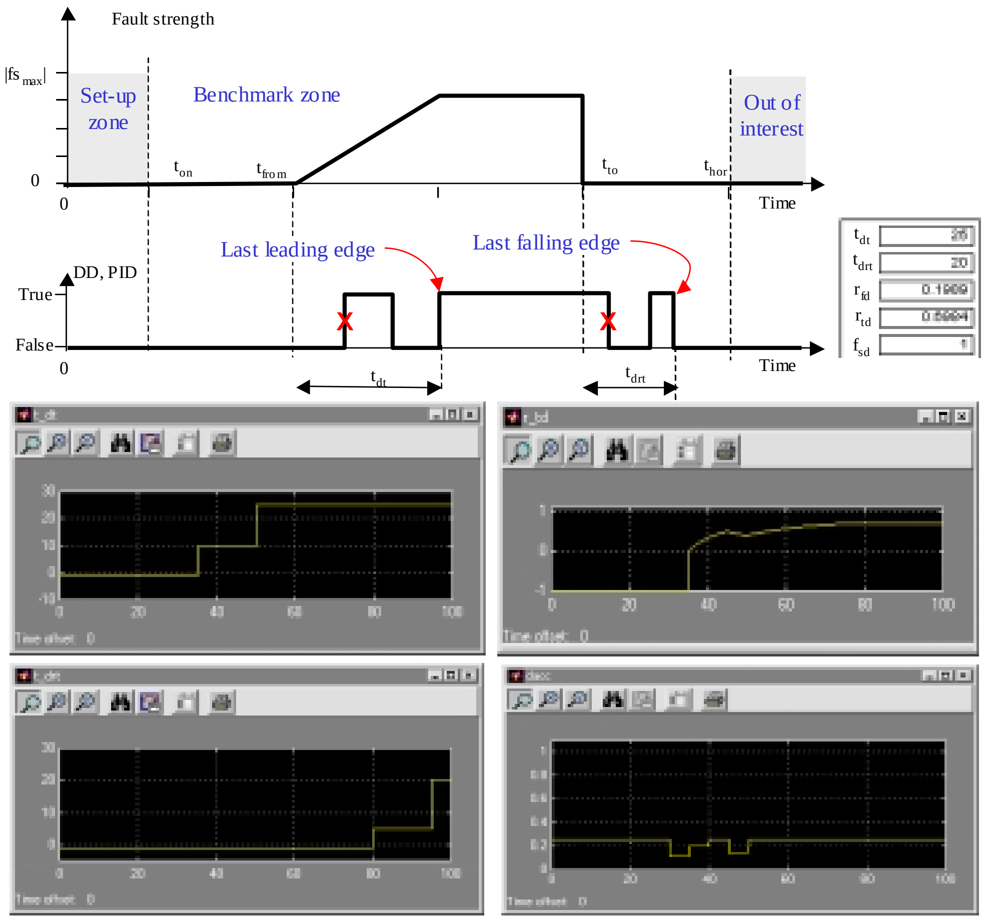

Figure 26. PI calculation example I

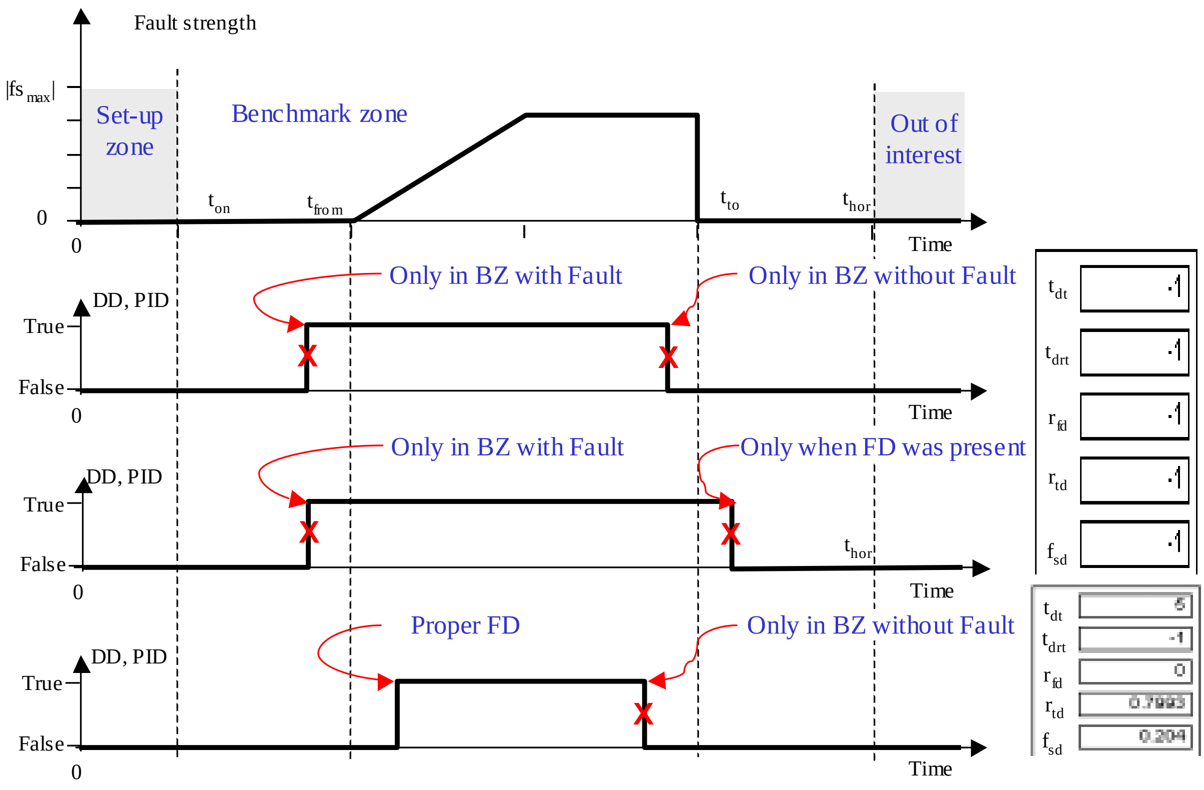

Figure 27. PI calculation example II

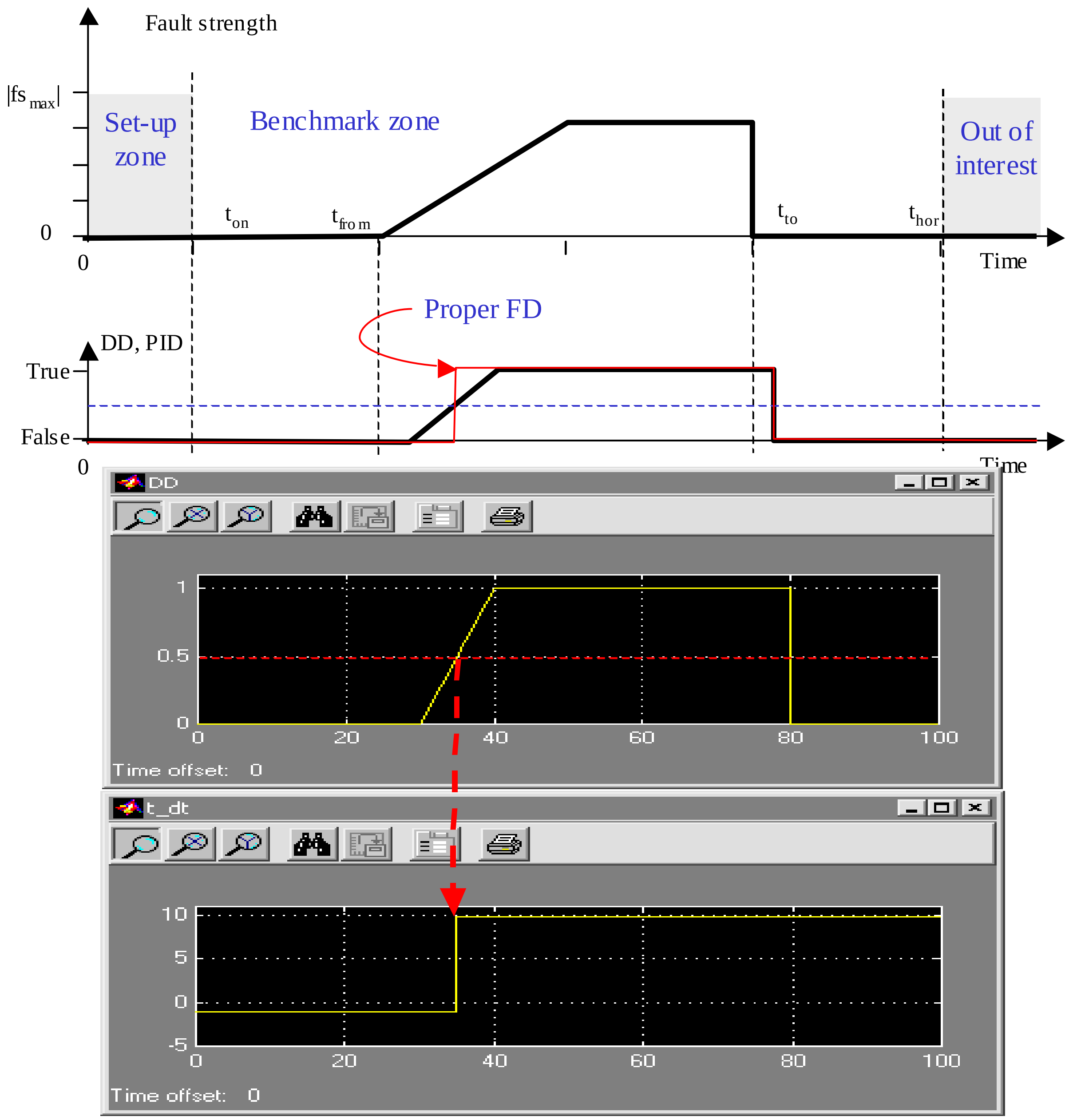

Figure 28. PI calculation example III

6. Examples of DABLib components application

Example I

An example of using **'ACT'** block.

The f2 abrupt fault is simulated. In 15th second a stone get stuck in the valve seat. One can see immediate flow decrease. Full valve closing become not possible.

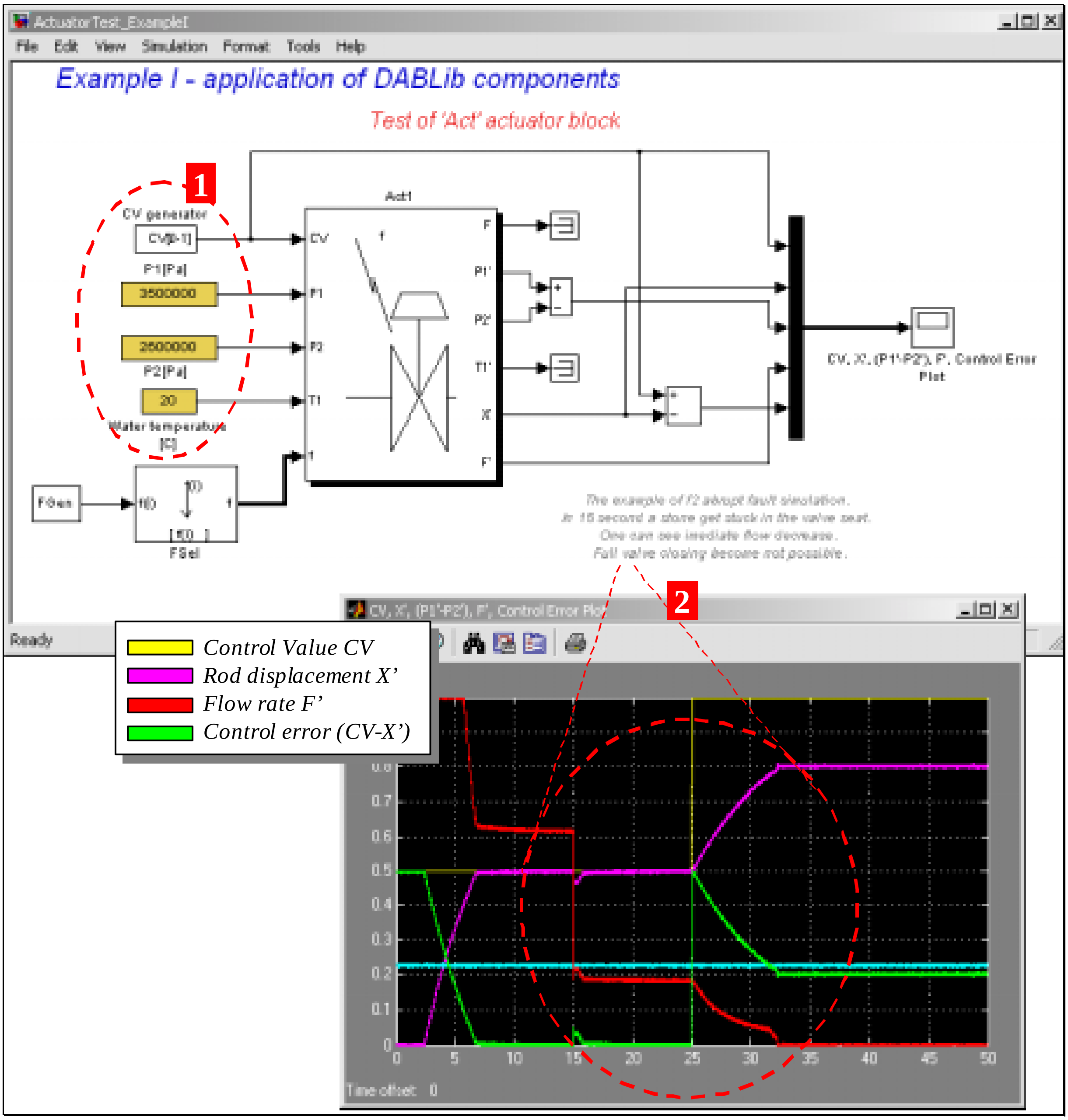

Figure 29. Example I – test of 'ACT' actuator block.

Ad 1. Input values are fixed except of step changes of CV. Inputs corresponds to typical process values for Actuator 3.

Ad 2. Fault effects are visible in the red circle.

Example II

An example of model validation.

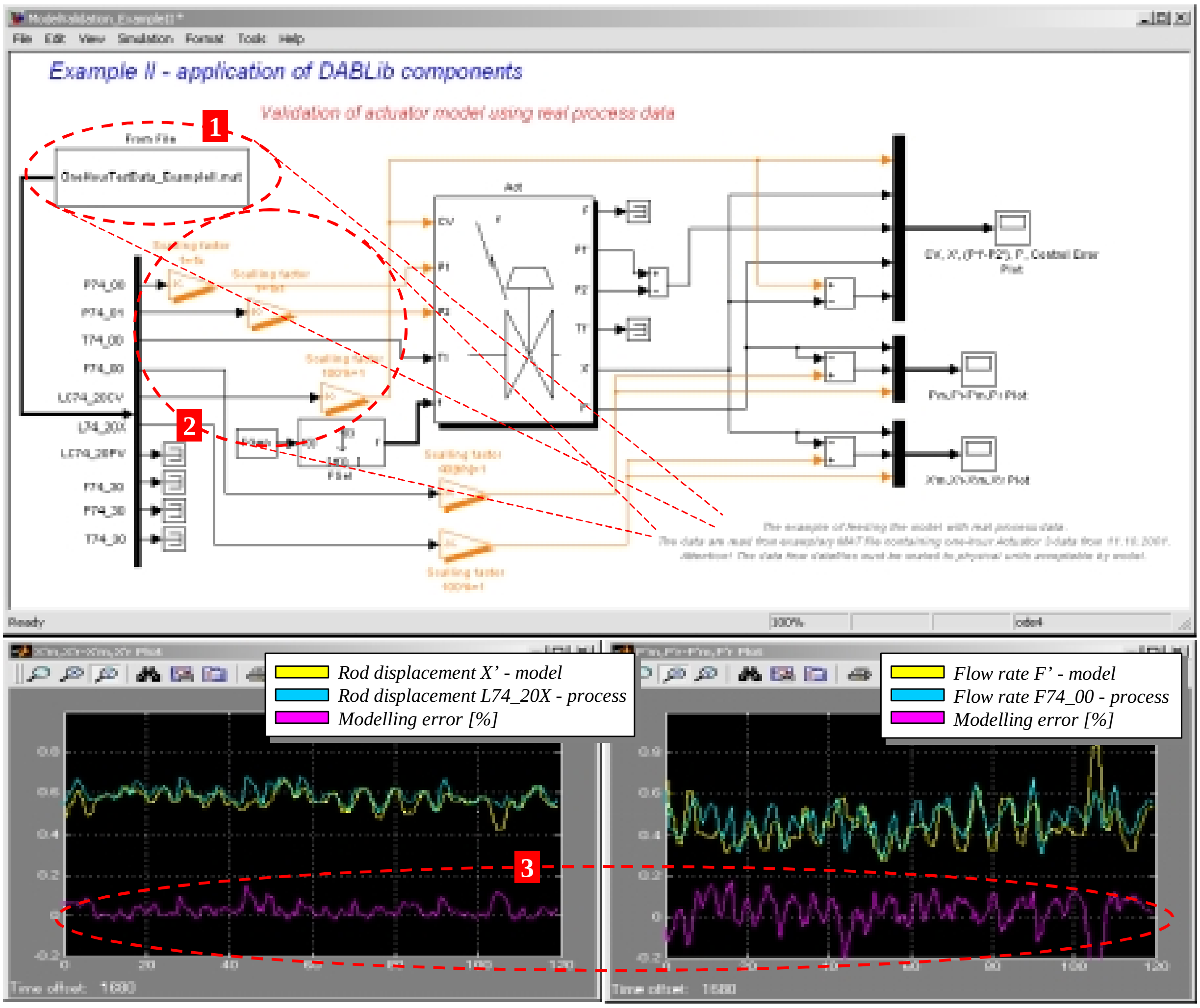

Figure 30. Example II – actuator model validation

Ad 1. The model is fed with real process data. The data are read from exemplary MAT file containing one-hour Actuator 3 data from 11.10.2001.

Ad 2. The data from data files must be scaled to physical units acceptable by model.

Ad 3. Modelling error seems to be acceptable.

Example III

An example of using '**DGEN**' block.

The example of data generation with f13 incipient sensor fault simulation. In 300th second a f13 strength starts to grow up from 0. The fault reaches full strength in 1200th second. One can see change in the relationship of X' and F'. Due to sensor fault, X' does not represent real X value.

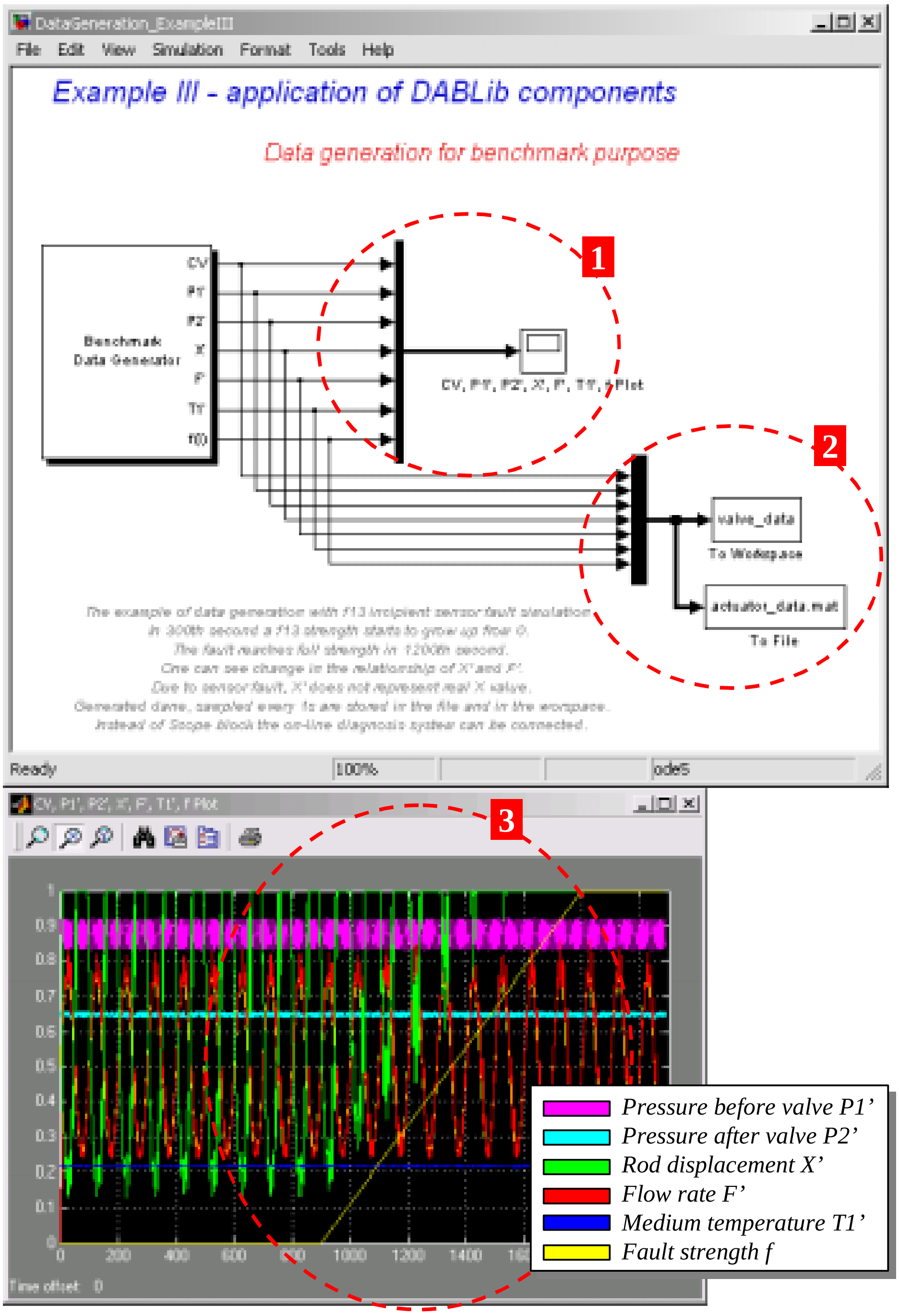

Figure 31. Example III – data generation for benchmark purpose.

Ad 1. Instead of Scope block the on-line diagnosis system can be connected.

Ad 2. Generated data, sampled every 1s, are stored in the file and in the workspace.

Ad 3. Fault strength and its effects are visible in the red circle.

Example IV

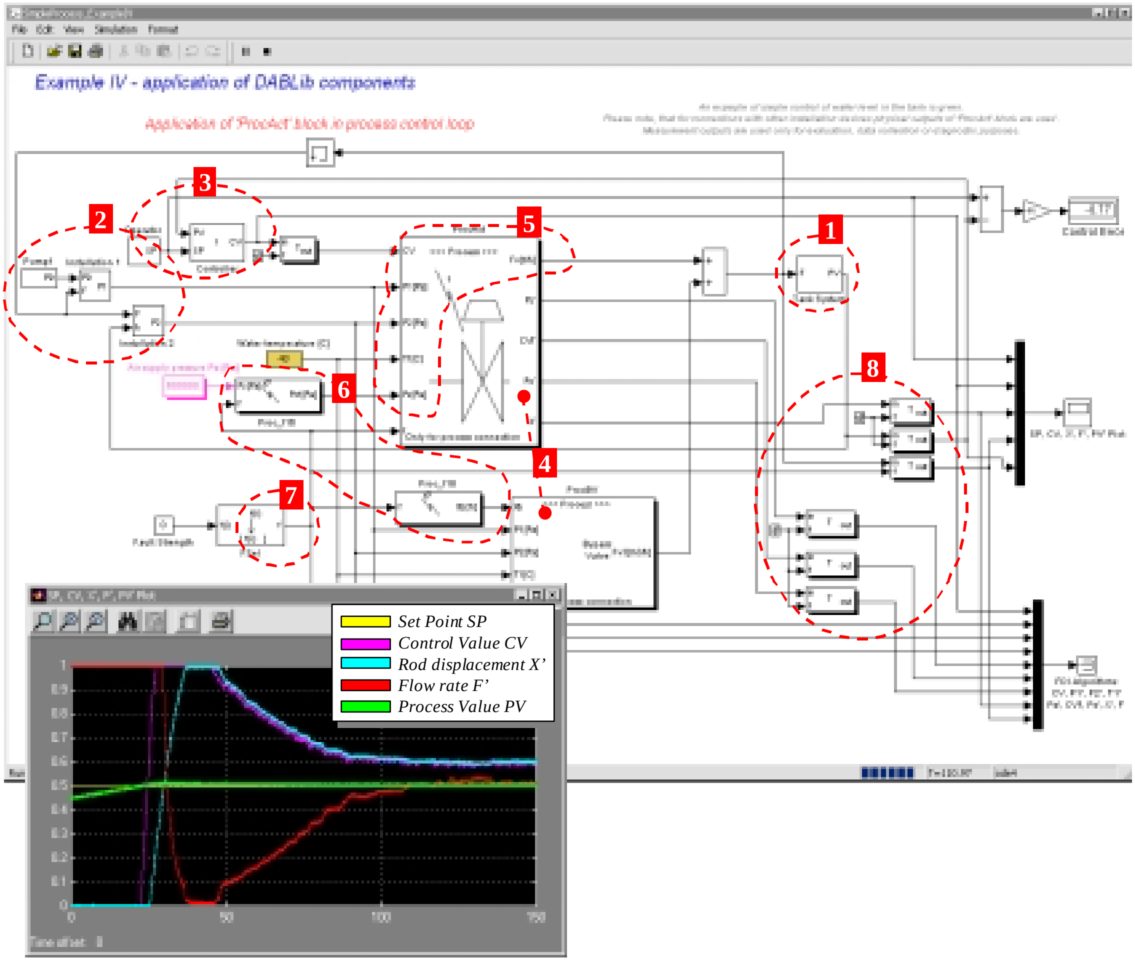

Figure 32. Example IV – **'PROACT'** block in level control loop

An example of using **'PROCACT'** block in a simple water level control loop. A noise is simulated as a superposition of sine wave and white noise.

Ad 1. Simple model of a tank with gravitational outflow.

Ad 2. Simple constant pressure pump and constant pipe resistances are simulated.

Ad 3. P controller is applied.

Ad 4. In case of process simulation the block representing real industrial devices must be used.

Ad 5. Please note, that for connections with other installation devices physical outputs of **'PROACT'** and **'PROCBV'** blocks are used. Measurement outputs are used only for evaluation, data collection or diagnostic purposes.

Ad 6. Simulation of external faults acting on air pressure supply **'PROC_F16'** or by-pass valve **'PROC_F18'** are applied

Ad 7. All the blocks from 'Process Component' are designed to accept the whole fault vector.

Ad 8. One must apply noise to all the process measurements that are used in FDI. This can be done by the **'PROCTRAN'** block.

Example V

An example of using **'PICALC'** block for automatic performance indexes calculation. An example shows the application of Performance Index Calculator for evaluation of FDI decision. A set of 12 indexes is generated on line. Please note that -1 index value refers either to situation when the index has none physical meaning or its value can not be determined. Before using this block please check and eventually set following block parameters: ***Benchmark Step***, ***Fault selection***, ***Failure mode***. ***Start of the benchmark*** and ***End of the benchmark*** parameters are active only in the case of choosing `'Other'` for ***Benchmark*** parameter. A grid of displays allows to follow the time evolution of performance indexes. **'PICALC'** must be supplied properly by the set of 6 input signals generated from FDI system. The responsibility of creating the block interfacing '**PICALC**' lies on the FDI evaluator. For further details please refer to appropriate section in Benchmark Definition description.

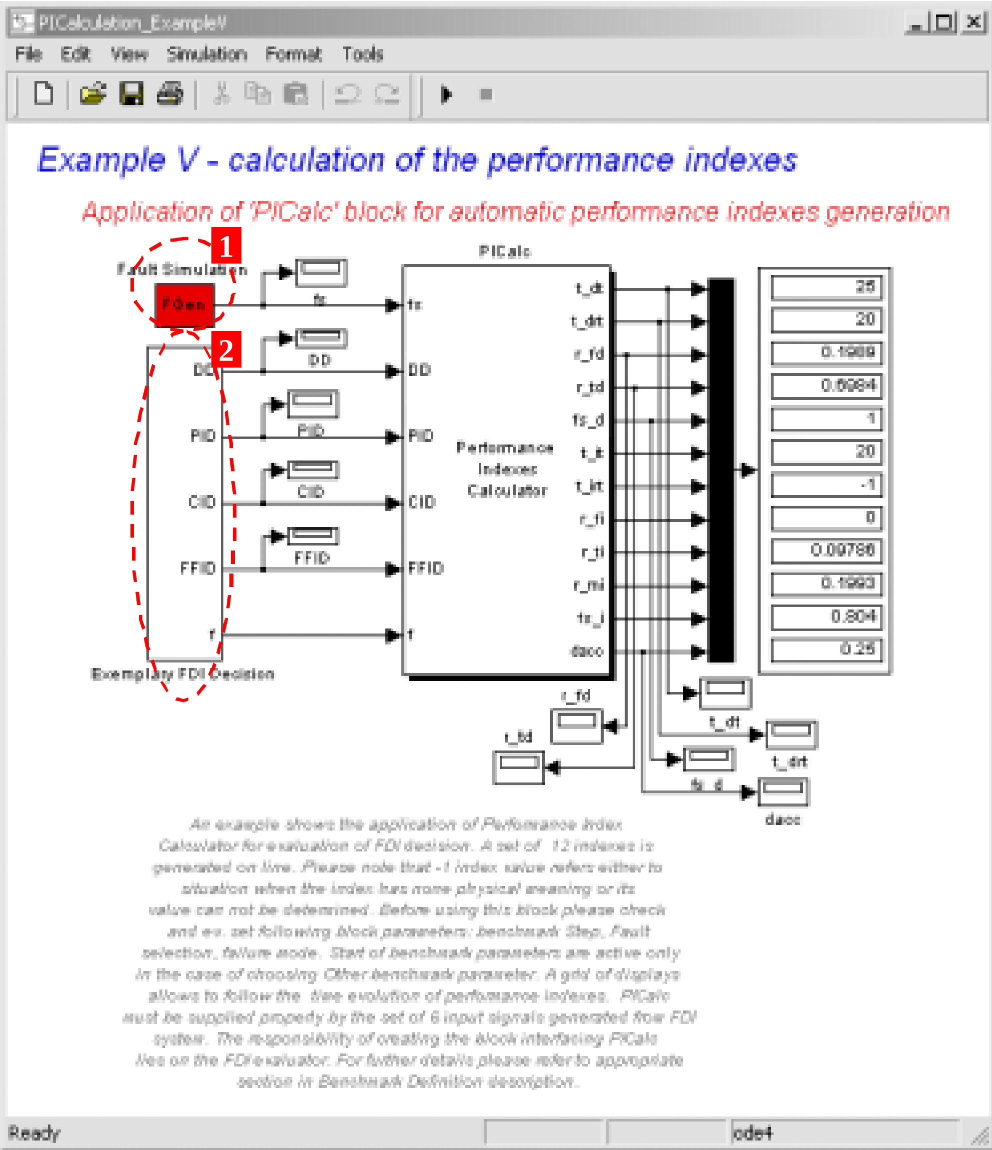

*Figure 33. Example V – '**PICALC**' block for performance indexes calculation.*

Ad 1. reference Fault strength signal introduction.

Ad 2. Symbolise the interface from FDI algorithms.