0.3 Turbine inlet valve

Inlet valve type	Butterfly valve		
Inlet valve diameter	D_{IV}	= 4500	mm
Volume of inlet valve cylinders (2x 300/180x1500)	V_{SMI}	= 106 +106	dm^3
Volume of by-pass valve servomotor	V_{SMI}	= 2	dm^3
Valve opening time	T_{Vo}	**= 120**	**sec**
Valve closing time	T_{Vc}	**= 180**	**sec**

1 DIGITAL GOVERNOR

Central controller Siemens Simatic **S5-135**	**6ES5-135-6KA31**
Power supply - voltage	24 VDC
Power supply output	at 5V => 18 A
	at 15V => 0,5 A
	at 24V => 1 A
Power supply unit No.	6ES5 955-3NC41
Number of slots	21 free slots
Dimensions	482 x 432 x 310 mm
Manual S5-135U PLC manual	6ES5 998-2UL21

CPU module	**6ES5 928-3OB12**
Microprocessor (16 bits)	80186,80188
Internal RAM (for data blocks)	46 Kbytes
Memory submodule (EPROM 64 Kbytes)	6ES5 376-0AA31
Execution time for 1 K word statements	1,5 ms
Execution time for 1 K binary statements	0,6 ms
Dimensions ($2^2/_3$ SEP-2 slot)	233,4 x 160 x 40 mm
Manual S5-135U PLC manual	6ES5 998-2UL21

Counter module IP 242	**6ES5 242-1AA13**
Supply voltage - via basic plug 1	5 V
Power consumption	0,9 A
Number of counters	5
Input signal level	13 to 33 V
Input current	12 mA
Interrupt line	IRA
Potential isolation between Input and S5 bus	Yes
Potential isolation between two inputs	Yes
Dimensions ($1^1/_3$ SEP-1 slot)	233,4 x 160 x 20 mm
Manual IP 242	6ES5 998-OK21

Digital input module	**6ES5 430-4UA12**
Supply voltage - external L	24 VDC / 100 mA
Supply voltage - via basic plug 1	5 VDC / 100 mA
Number of inputs	32
Galvanic isolation	Yes - in 1 group
Input voltage	13 ÷ 33 VDC

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Frequency of input signal	max. 10 Hz
Dimensions ($1^{1}/_{3}$ SEP-1 slot)	233,4 x 160 x 20 mm
Manual U range manual Periphery	6ES5 998-OPC12

Digital output module	**6ES5 451-4UA13**
Supply voltage - external L	24 VDC / 150 mA
Supply voltage - via basic plug 1	5 VDC / 120 mA
Number of outputs	32
Galvanic isolation	Yes - in 1 group
Supply voltage	20÷30 VDC
Switching frequency	max. 10 Hz
Short-circuit (Red LED)	for groups of 8
Dimensions ($1^{1}/_{3}$ SEP-1 slot)	233,4 x 160 x 20 mm
Manual U range manual - Periphery	6ES5 998-OPC12

Analog input module	**6ES5 466-3LA11**
Supply voltage - via basic plug	5 VDC / 0,7 A
Number of inputs	8 differential
Galvanic isolation	Yes
Input signal range	0 ÷ 10V; 0 ÷ 20 mA; 4 ÷ 20mA
Cycle time for 8 inputs	2 ms
Measuring principle	Instantaneous encoding
Digital representation of inp. signal	12 bits binary
Permissible voltage between input and ground	± 30V
Dimensions ($1^{1}/_{3}$ SEP-1 slot)	233,4 x 160 x 20 mm
Manual U range manual - Periphery	6ES5 998-OPC12

Analog output module	**6ES5 470-3UA12**
Supply voltage - external L	24 VDC / 0,3 A
Supply voltage - via basic plug	5 VDC / 0,25 A
Number of outputs	8
Galvanic isolation	Yes-Not between outputs
Input signal range	0 ÷ 10V; 0 ÷ 20 mA; 4 ÷ 20 mA
Conversion time	1 ms
Digital representation of outp. signal	12 bits two's compl.
Load resistance for voltage outputs	min. 3,3 kΩ
Short circuit protection	Yes
Dimensions ($1^{1}/_{3}$ SEP-1 slot)	233,4 x 160 x 20 mm
Manual U range manual - Periphery	6ES5 998-OPC12

POSITIONER	6ES5 095-8MC21
OPERATOR PANEL	OP15-C

More detailed data can be found in producer's manuals.

valve Y404 and hydraulic overspeed protecting valve N504 perform direct servomotor closure through the hydraulic valves N408 and N409.

1. ELECTRONIC DIGITAL GOVERNOR T2000s

The governor consists of a digital processing unit, analog circuits and hydraulic amplifiers for wicket gates control. The digital programmable control part (SIMATIC S5) consists of Central Controller with power supply unit (S5-135), Central Processing unit (CPU), Counter intelligent module (IP 242) and discrete input (S5-430), discrete output (S5-451), analog input (S5-466) and analog output (S5-470) modules. Most of the calculation are made in floating point mathematics. Analog circuits are used to drive actuators-proportional valves and to transform the position measuring signals into a current signal.

Small digital unit Simatic S5-95 is used for separate manual control. This unit consists of CPU S5-95 which includes digital inputs and outputs and also the analog inputs and output and of added analog module for additional analog inputs.

Speed monitoring device for speed indication with speed relays, pressure switches, level switches and *temperature switches used for control functions are* also included in the governor. Separate speed switches are added (made in s5-95) for overspeed protection and brakes control. Governor internal operation control of electronic and hydraulic part and turbine protection at particular operating conditions are included in governor. The governor is provided for operation in following modes: net parallel operation, isolated operation and idle run operation.

Block diagram of governor system of ÇATALAN HPP is shown on **drawing No.100634**. For speed and power control loop the error signal (difference between reference and actual value) is transformed to output signal through parallel three term regulator with proportional, integrative and derivative action. The basic control dynamics is established by sum of those three actions to error signal. The water hammer compensating function is operating as compensating feedback to PID regulator taking the signal from opening reference output.

1.1 *OPERATING MODES*

The units can operate in following operating modes:

- **operation in isolated system- speed control**
- **operation in parallel with the other units, connected to national grid in load control or in openingl control**
- **idle run of the unit**

1.1.1 Operation in an isolated system

When the unit operates in an isolated system, the governor maintains the system frequency on the level determined by speed reference signal "c". In steady conditions the system frequency does not change if the speed regulation is set to e_P=0% else it does follow the speed droop characteristic.

Speed reference signal can be adjusted by push buttons "LOWER" and "RISE" or on the operator panel. For better stability and better transients the water hammer compensation feedback signal is added to PID function of speed control. The governor settings with **index 3** are active in isolated run speed control. When only one unit is running in an isolated system, it is convenient to set e_P=0%. The same setting is recommended for one of the units, when few units are running together. The other units should be set to e_P>0% (e_P=2÷3%).

Frequency at certain load of isolated system (when only one unit is running in the system) can be calculated by the following formula:

$$f = 50 - \frac{P_{ACT} - P_{REF}}{2P_{MAX}} \cdot e_P \rightarrow [Hz]$$

P_{ACT} - Actual unit power equal to isolated system load
P_{REF} - Power reference
P_{MAX} - Maximum power
e_P - Speed regulation-speed droop in [%]

1.1.2 Operation in parallel network

When the unit is connected to the rigid grid, the unit rotating speed is determined by system frequency. Changing the power reference signal, the wicket gate opening will be changed proportionally to reference change. If the reference signal is constant and the system frequency is changing, the unit power will change following the speed droop characteristic. It means that the governor is active in primary frequency regulation with intensity determined by speed droop setting. The governor settings with **index 2** are active in parallel run mode. Governor operating modes are switching automatically from parallel to isolated mode and back to parallel mode by internal automatics. Automatics is checking the stability of system frequency (unit speed) and operates to change the mode.

1.1.3 Unit idle run

The unit will run in no load condition after unit start up to the synchronization and after certain protection are activated and the generator breaker is opened again up to the synchronization. In no load run speed control is active and separate governor parameter's settings with **index 1** are active. Those parameters are adjusted to have optimum gains for load rejections and for no load run. Some additional actions are provided for transient time after the load rejection.

1.2 *UNIT SPEED MEASUREMENT*

Speed signal generator (SSG), consisting of toothed disc rotating with the turbine shaft and proximity switches (pick-up), is used as speed sensing device. Block diagram of frequency measurement is shown in **Fig .1** with data memory locations (data blocks - DB and data register DD). Speed measuring module **(counter IP242)** uses separate micro processor to calculate the speed signal in the range 0-300%. Speed is measured three times using one counter channel for each channel.

1.2.1 Speed signal calculation

Internally in counter module generated high frequency (**2 MHz**) signals controlled by quartz are counted in a time of one signal given by SSG and converted into a digital signal proportional to unit speed. Counters count in 16 bit registers. Signal coming from SSG is used as a gate for a counter. At each rising gate signal the counter value is saved and counter is loaded with 0 value and it starts to count again. Counted value is transferred to CPU and rotating speed is calculated for each channel separately.

The frequency signal is taken twice and the output is calculated twice, than the resulting signal is obtained as mean value of both signals. Nominal frequency of SSG is **50 Hz.** The third speed measurement is not that accurate as first two and is used only to check the operation of first two to determine the fault of speed measurement.

1.2.2 Speed reference

Speed reference signal can be increased or decreased through the rise or lower contact on governor discrete input module or writing the set point on operator panel. The "RISE" or "LOWER" request can be set manually from control location or automatically by synchronizer. At the unit start and *in parallel operation the reference signal is set* to speed of 100% or to frequency 50 Hz and the inputs for "RISE" and "LOWER" are disabled. Speed reference is used only for no load run and isolated operation else it is fixed and the unit is loaded through the power reference.

Speed reference can also be set on operator panel OP15 in the screen for references. To enter the new value the screen shall be selected by key sequence **K1-F1**.

1.2.3 Speed signal filter

After the speed signal is calculated, it is filtered by *digital second order filter.* The filter frequency and damping factor are finally determined at commissioning and used later permanently. Filter cycle time is determined by timed interrupt and is calculated each 10 ms.

$$f_f = \frac{1}{(1 + 2.\zeta.T_f.s + T subf^2.s^2)} \cdot f$$

f_f	-	Filtered frequency signal	[rel]
T_f	-	Filter time constant	[sec]
z	-	Damping factor	[rel]
f	-	Measured frequency signal	[rel]

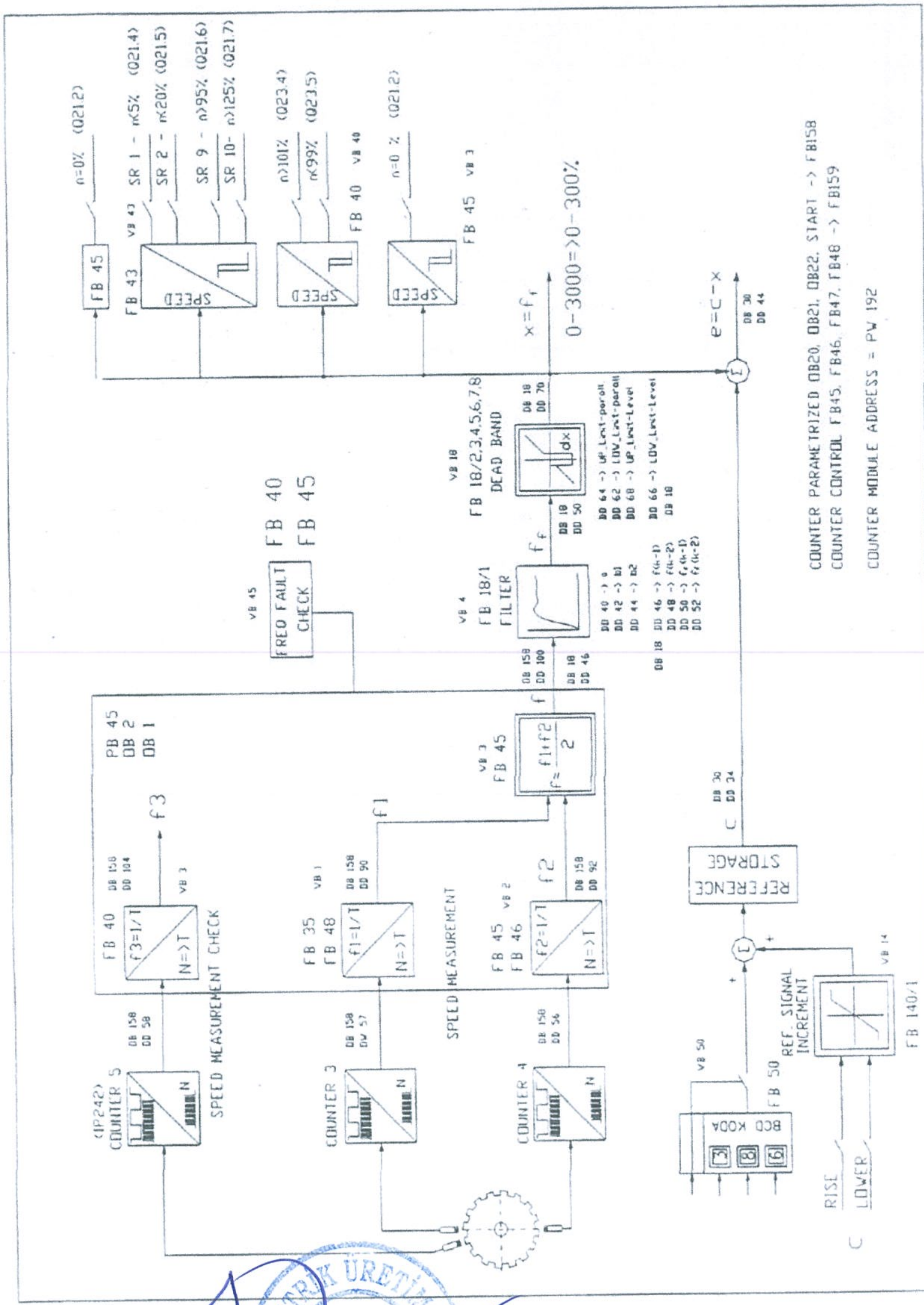

Fig 1: Block diagram of governor speed measuring and speed relays

Speed dead band

Adjustable frequency dead band is used to make the governor insensitive to certain frequency changes minor of dead band. Dead band is applied to filtered speed signal. Dead band is adjustable and become active in parallel operation only. If the frequency come out of set dead band it is disabled and become active again if the frequency become stable within narrower frequency band for certain time (5 min). This function is practical for all movable parts of wicket gate mechanism, because in time when the dead band is active there will be no movements of the gates unless the operate changes the power or opening setpoint.

1.2.4 Internal speed measurement check

Governor diagnostic circuits are determining the fault of each of three speed measurements and the warning diode will be lighting on discrete output module DO2. If one of the main measuring channels becomes faulty the unit proceeds to run normally taking the speed signal from correct measured channel, signal for governor fault 1 is activated and also the diode warning is indicated. If both measuring channels become faulty when the turbine is running it will cause the unit shut down (governor fault 2) but the signal for speed relays and for indication will be taken from third speed measurement channel and the unit will be stopped normally.

1.2.5 Speed monitoring

Speed signal for indication on analog indicating instrument is taken from governor speed measurement after the filter and converted to analog current signal through the analog output module AO1. The second speed indication can be on digital display (in Hz) if selected by selector push button. The indication on display is more accurate (2 decimal places) but it is refreshed each 0,5 seconds. Third indication of the speed signals is on the operator panel OP15 when selected (K6).

In the CPU the following speed switches for unit automation are formed:

n = 0 % - Unit is in stand still for more than 30 s
n < 20 % - Signal used for mechanical brakes
n > 60 % -Signal used for switching ON and OFF the bearing starting pumps
n > 95 % - Signal used to switch the excitation on and off
n >160 %- Signal for unit shut down - overspeed protection
n >110% - Signal for unit shut down when the governor is in manual control

Those signals are formed on filtered speed signal with adjustable hysterezis. The signal for n=0% is made in a different way based on counter input from SSG. It will indicate speed n=0% when for more than 20 sec there is no change in state of SSG input signal. If the SSG signal would change from 0 to 24V or opposite the signal (n=0%) will disappear.

Separate speed supervision is made out of main digital part in small redundant digital unit S5-95 with the outputs used to double the most important speed switches. This digital module is fed by separate inductive switch on SSG. The speed switches coming from this module are:

n <20 % - Signal used for mechanical brakes
n >160% - Signal for unit shut down - overspeed protection

Speed relays switching points for same speed level are calculated separately also in digital governor. Resulting switching output is taken as "OR" function for overspeed protection and as "AND" function for signal to start mechanical braking to give more safety to those functions.

1.3 *PID REGULATOR WITH COMPENSATION FUNCTION*

PID regulator is programmed to operate with adaptable functions for different modes of operation. Output - opening reference signal is calculated as a sum of proportional, derivative and integrative action. All three functions are acting in parallel. PI function operates on error signal obtained as difference between speed reference signal, filtered speed signal, power error signal multiplied by speed regulation factor e_P and feedback signal calculated by water hammer compensating function. Governor structure of PID regulator together with waterhammer compensating function is shown in **Fig. 2**.

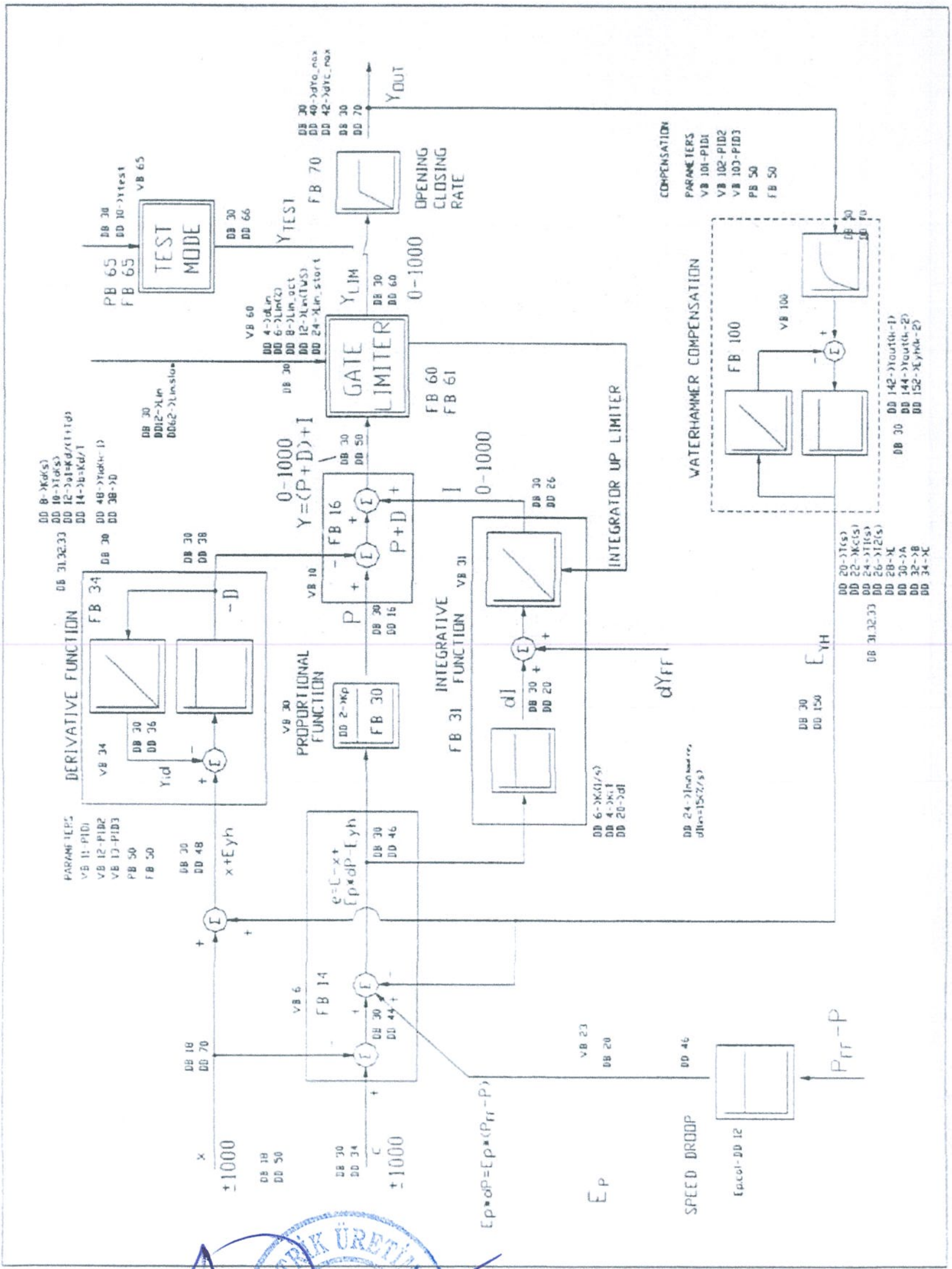

Fig 2: Block diagram of PID regulator with compensating function

1.3.1 Error signal of PID regulator

Error signals for **PI** regulator and **D** regulator are calculated separately in function block FB 14 called by organization block OB 10 controlled by timed interrupt each 10 ms.
Error signal for **PI** regulator function is obtained as sum of:

$$e_{PI} = c - x + e_P . dP - e_{yh}$$

Error signal for D regulator function is obtained as sum of:

$$e_D = x + e_{yh}$$

e_{PI}	-	Error signal for PI regulator functions	[rel]
e_D	-	Error signal for D regulator function	[rel]
c	-	Unit speed reference	[rel]
x	-	Unit speed or sys. frequency deviation	
e_P	-	Governor speed droop or speed regulation factor	[rel]
dP	-	P_{ref}-P -> Power control loop error	[rel]
e_{yh}	-	Water hammer compensating function signal	[rel]

All signals in calculation of governor functions are relative values represented as floating point numbers in range **0,0 ÷1000,0**.

1.3.2 PID regulator

PID actions are calculated in fixed times controlled by timed interrupts each 10 ms. All regulator changes are calculated in floating point mathematics with 24 bit mantissa. **P** function is the simplest and is active all the time. **I** function has many limitations when the opening is limited by gate limiter, in test mode, at load rejections and is limited down to 0% and up to 100%. All those limitations are made to provide the bump less changing between operating modes and to prevent overshoots at load rejections. The integrator change in one step (**dI**) is also limited and is adjustable. When frequency dead band is active the input to **PI** regulator is 0 and the output is unchanged. **D** function is made as real derivative function with adjustable damping time constant. **D** function output is disabled when frequency dead band is active but the D output is calculated all the time to prevent jumps when coming out of dead band. The block diagram of governor linearized mathematical model is shown in **Fig .3**. Output reference is calculated as sum of **P, I and D**action:

$$Y = K_P \cdot e_{PI} + K_I \cdot \int e_{PI} \cdot dt + \frac{K_D}{T_D} \cdot \frac{de_D}{dt} - T_D \cdot \frac{dY_D}{dt}$$

or represented with Laplace transform:

$$Y = K_P \cdot e_{PI} + K_I \cdot e_{PI} \cdot \frac{1}{s} + e_D \cdot \frac{K_D \cdot s}{1 + T_D \cdot s}$$

e_{PI}	-	Error signal for PI regulator	[rel]
e_D	-	Error signal for D regulator	[rel]
K_P	-	Proportional action gain	[rel]
K_I	-	Integrative action gain	[1/sec]
K_D	-	*Derivative action gain*	[sec]
T_D	-	Damping time const. of derivative term	[sec]
y_D	-	Derivative term output	[rel]
y	-	Calculated opening reference	[rel]

The act[rel] of regulator function is to reduce the error signal to zero. The result is that speed is back on reference level after each load change transient if the speed droop is set to zero and in power control the unit power will be equalized to reference power if system frequency is unchanged (100%). Final servomotor position corresponds to turbine power required of the unit.

Each regulator function is programmed in separate functional block FB30, FB31, FB34 and are called by organization block OB 10 and OB11 executed in fixed time basis, each called at a different time interval (10 ms and 20 ms). When at fixed time interval the interrupt is triggered the corresponding function is called and cycle program is interrupted.

Gains for PID function are adjustable in three sets for speed control (isolated operation), for power control (parallel operation) and for no load operation. Gains are also changing with error signal and opening to assure the stable operation and to get optimal response to small or big changes of load in isolated operation and optimal response at sudden load rejections. **PI** function is also used to correct the power control loop. **PID** function parameters gain can be set as numbers on operator panel (K13-K16) on the front governor panel *separately for different operating modes.*
The safety circuit is checking stability of governor system in power control and switches over automatically to frequency control if unstable operation occurs. The signal is given for signalization

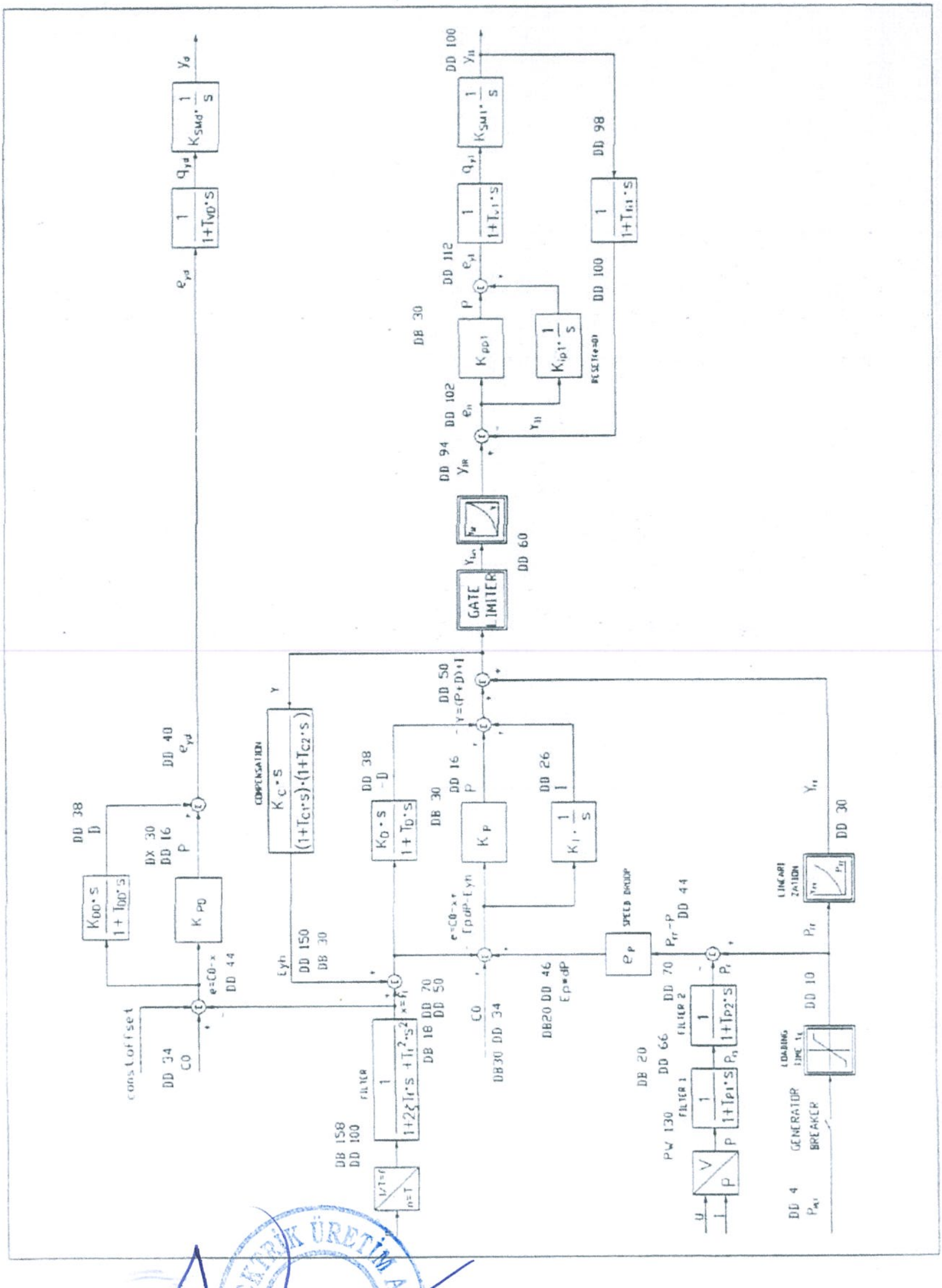

Fig 3: Governor samplified linear block diagram represented with Lapalace transform

as free contact when the governor mode is switched to isolated. When the governor operation become stable and frequency is within limits (small deviation) for long time (5 min) the governor is switched automatically back to parallel mode. If the unstable operation occurs in frequency control the turbine will be shut down.

1.3.3 Waterhammer compensating function

Derivative function in feedback to PID regulator compensates the water hammer's negative influence on speed and power control. Compensating function is made of D function with two first order elements to break the water hammer oscillations acting in opposite to pressure surges. Three parameters of compensating function (compensation function gain K_C and time constants of first order elements - T_1, T_2) are adjustable separately for isolated, parallel and no load run of the unit. Compensating function output is disabled at first part of load rejection transient to get greater governor response of the wicket gates.

Compensating function is programmed in separate function block FB100, which is executed when called from organization block OB11 (each 20 ms). Program is obtained by z transform of following transfer function:

$$e_{yh} = \frac{K_C \cdot s}{(1 + T_1 \cdot s) \cdot (1 + T_2 \cdot s)} \cdot y_{out}$$

e_{yh}	-	Correction signal of compensation func.	[rel]
K_C	-	Compensating function gain	
T_1	-	First time const. of comp. function	[sec]
T_2	-	Sec. time const. of comp. function	[sec]
y_{out}	-	Output calculated by PID governor	[rel]

1.4 *POWER CONTROL*

Power control become active always after the generator breaker goes on if the power control or level control is selected. Up to synchronization the frequency control is active. As reference power, for loading after start it is used minimum operating power (base power). The unit is than loaded to minimum or maximum power. After the unit is loaded to selected load the signal is given to unit controller that starting procedure is finished (base power reached). After that the unit can be loaded to different loads, setting the power reference from governor control board or from plant control location if the unit is switched to automatic mode.

Structure of power control loop with memory locations of loop parameters is shown in block diagram in **Figure 4**.

1.4.1 Power feed forward signal

After the power control loop become active it starts to load the unit up to the set load. The reference signal is changing according to the adjustable loading rate T_l up to the reference value. Obtained signal is then transformed to the feed forward signal through the load linearization curve. Feed forward signal is added to integrator of PID regulator. Feed forward signal together with the output of PID action is making the opening reference signal.

1.4.2 Loading time

Loading time T_l can be set as parameter on governor operator panel in seconds (5 ÷ 2.000 sec). The same change rate is used for loading and unloading when the unit is connected to the system. If the generator breaker is switched of due to unit protection the reference signal will be changing down faster with unloading time T_{l0}. Fast unloading time is set in commissioning time to get optimum [sec] load rejection transient.

1.4.3 Power linearization curve

The power linearization curve is provided to get as linear as possible the relation between power reference signal and actual unit power. This is useful due to the fact that the unit power is not linear to wicket gate opening. Feed-forward signal is operating directly to opening reference signal. Linearization function is applied to reduce power overshoot or slow

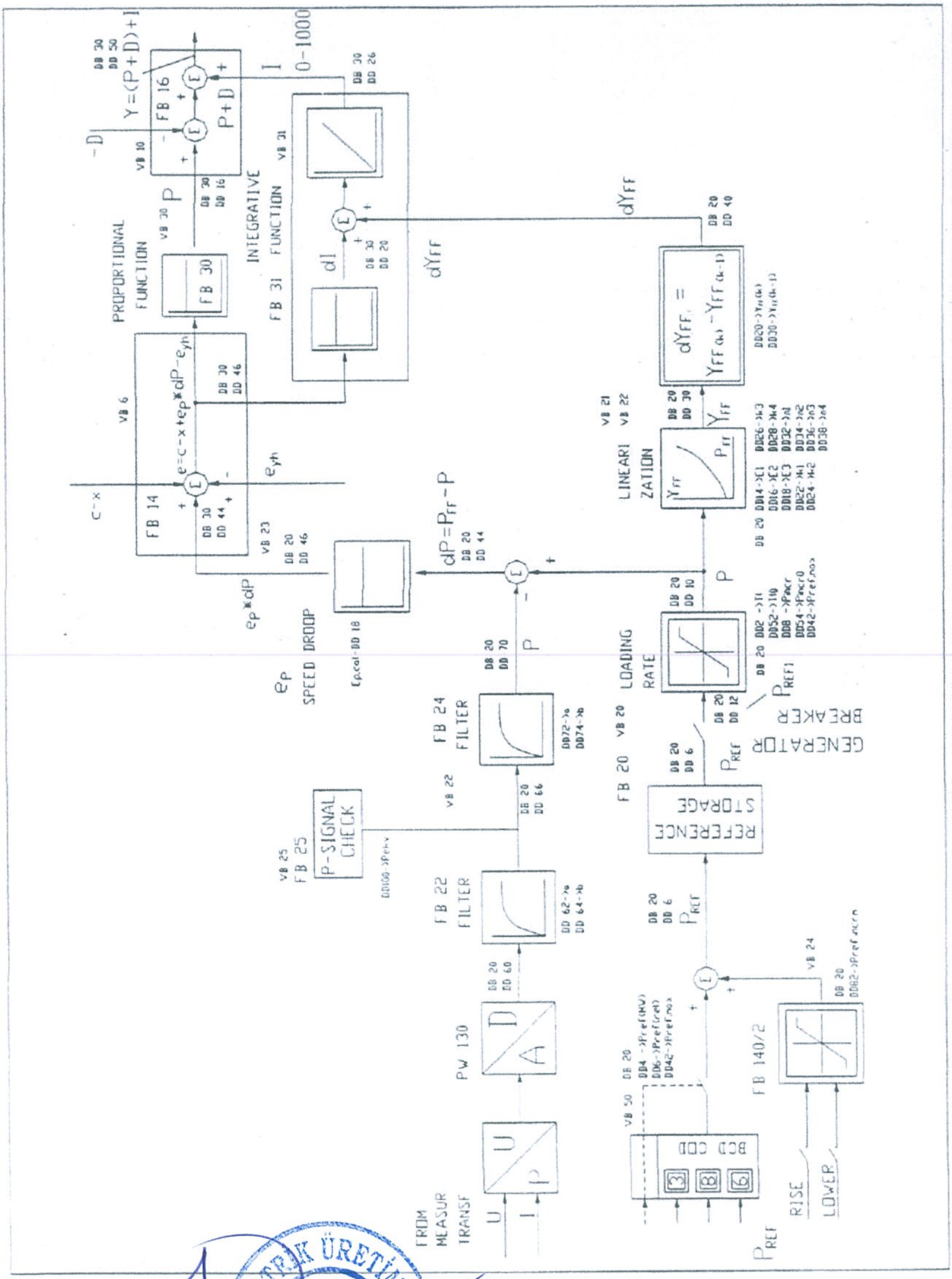

Fig 4: Power control loop block diagram

aperiodic approaching the final load at loading or unloading the unit. The **PI** function is affected only to correct deviation between programmed power curve and actual curve. The linearization is determined by three curves using the measured water head as a parameter. The curves are programmed as third order polynoms after measuring the static curve $P=f(P_{REF})$. Linearization curve should fit the reverse of obtained curve. The principle of lines with coefficients is shown in **Fig. 5b** and **Fig. 5a**

1.4.4 Power reference adjustment

Reference power can be set on operator panel ON governor front panel or remotely through input for "P-rise" and "P-lower". The reference could be entered on operator panel in Megawats (MW) as decimal number with two decimal digits. Discrete input for rising and lowering is changing the reference signal with an adjustable rate according to level controller requirements. The rate is determined at commissioning time and is memorized after to be used permanently. The rate is not parameter adjustable on front governor panel. Step of those changes can be very small. For a 100% change of reference signal in 50 seconds the step would be 0,1% of full signal. The reference signal can be displayed on digital four digits display installed on front governor panel.

"P-rise" and "P-lower" inputs are active when the unit control is in automatic mode. Reference input conversion, when using operator panel is made through function block **FB55**. Reference evaluation for "P-rise" and "P-lower" input is made in function block **FB140/2**.

1.4.5 Power loop feedback signal - Actual power

Power feedback signal is obtained from generator power measuring as current signal and enters through the A/D module to digital part with address **PW 142**. Signal is converted to floating point number and than filtered twice with two first order filters to prevent noise entering to **PID** regulator.

Time constant of first filter is $T_{P1}=0{,}1s$ and the time constant of second filter is $T_{P1}=2{,}0s$. First filter is programmed in function block **FB22** called by organization block **OB11** each **20ms** and the second filter is programmed in function block **FB24** called by organization block **OB 14** each **0,2sec**.

1.4.6 Check of power measurement

Governor diagnostic circuits are determining the fault of power measuring and the alarm is initiated on operator panel OP15. Power signal is compared to calculated power from actual opening of wicket gates (**Fig 5a**). If the measured signal differs more than 10% from power which should be obtained at actual opening longer than 30 seconds the power measurement fault will be initiated. After the fault is detected, governor fault 1 is activated, signal for speed droop is taken from opening and power control loop will operate normally as position controller.

1.4.7 Speed droop - speed regulation

In parallel operation the speed droop feedback signal is used by power control loop to keep the unit power constant and equal to reference. In speed control it is used to determine the load which the unit is taking in the isolated system. Power control loop keeps constant the unit power output when the system frequency is unchanged otherwise it does change proportionally to the speed droop gain and to the frequency deviation. When the speed droop is set different of zero the regulator is not any more astatical with free integrator and the speed deviation in isolated system will be equal to power error multiplied by speed droop at steady state condition:

$$x = e_P \cdot (P_{ref} - P)$$

In parallel operation of the unit with the other units the speed droop will determine the power change of the unit when the system frequency is changed.

$$P = P_{ref} - \frac{x}{e_P}$$

P_{ref} -	Power reference signal	[rel]
P -	Generator Power signal	[rel]
x -	Speed signal deviation	[rel]
e_P -	Speed Droop	[rel]

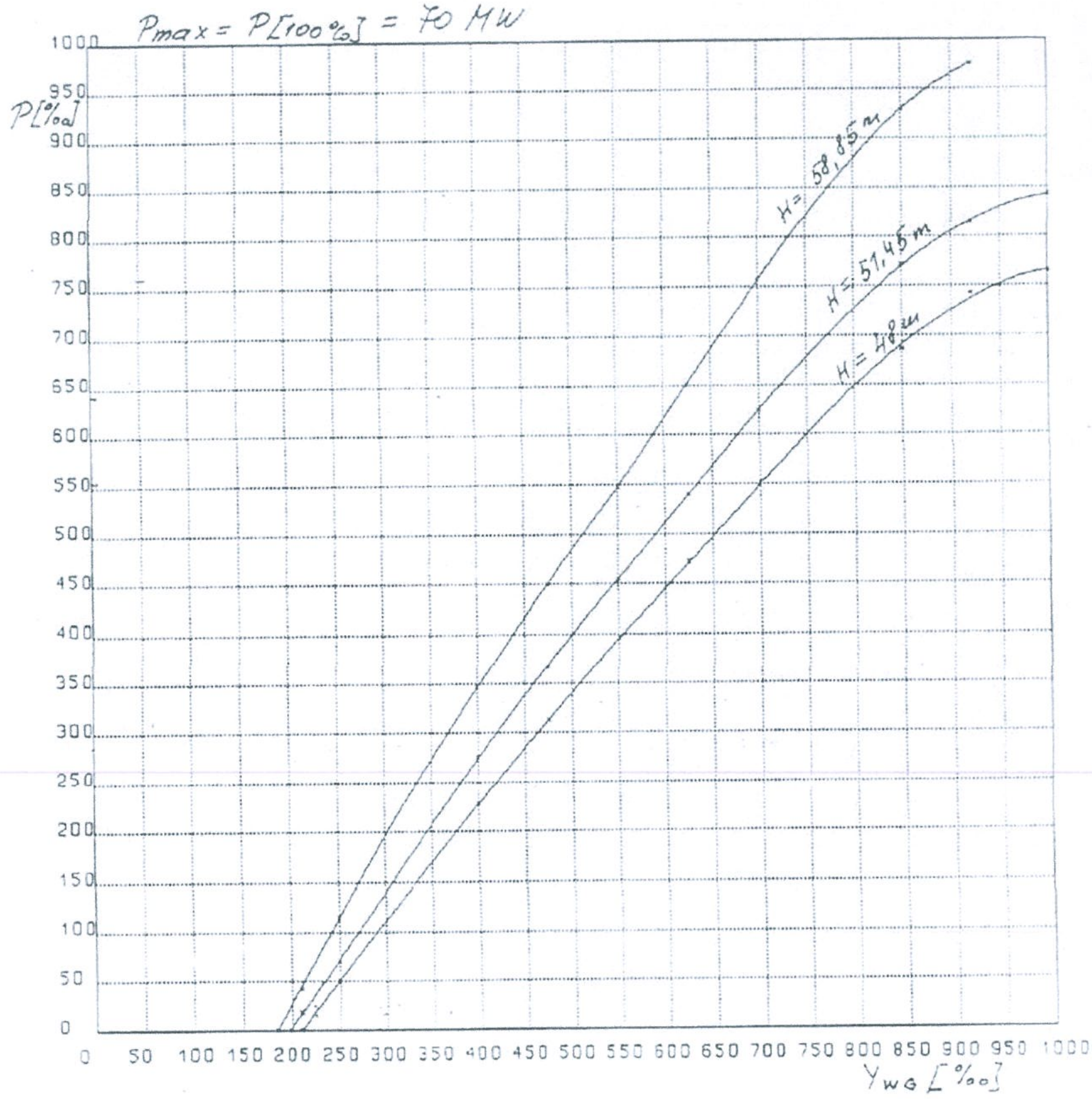

Figure 5a: Catalan Francis turbine power characteristic - $P=P(Y_{WG},H)$ CATALAN HPP

Coeficients for P calculation
Curves number N = 6

Head = 48.0 550 - Lim
A0 (1) = -2.963406e+02 A0 (2) = 5.991947e+02
A1 (1) = 1.561476e+00 A1 (2) = -2.489959e+00
A2 (1) = -8.213604e-04 A2 (2) = 5.320348e-03
A3 (1) = 4.922509e-07 A3 (2) = -2.663950e-06

Head = 58.9 550 - Lim
A0 (5) = -3.915378e+02 A0 (6) = 7.825532e+02
A1 (5) = 2.403000e+00 A1 (6) = -3.388700e+00
A2 (5) = -1.734480e-03 A2 (6) = 7.576601e-03
A3 (5) = 8.552024e-07 A3 (6) = -3.984816e-06

Head = 51.5 550 - Lim
A0 (3) = -2.579045e+02 A0 (4) = 3.753993e+02
A1 (3) = 1.191511e+00 A1 (4) = -1.526378e+00
A2 (3) = 7.696139e-04 A2 (4) = [illegible]315066e-03
A3 (3) = -1.053784e-06 A3 (4) = [illegible]21788e-06

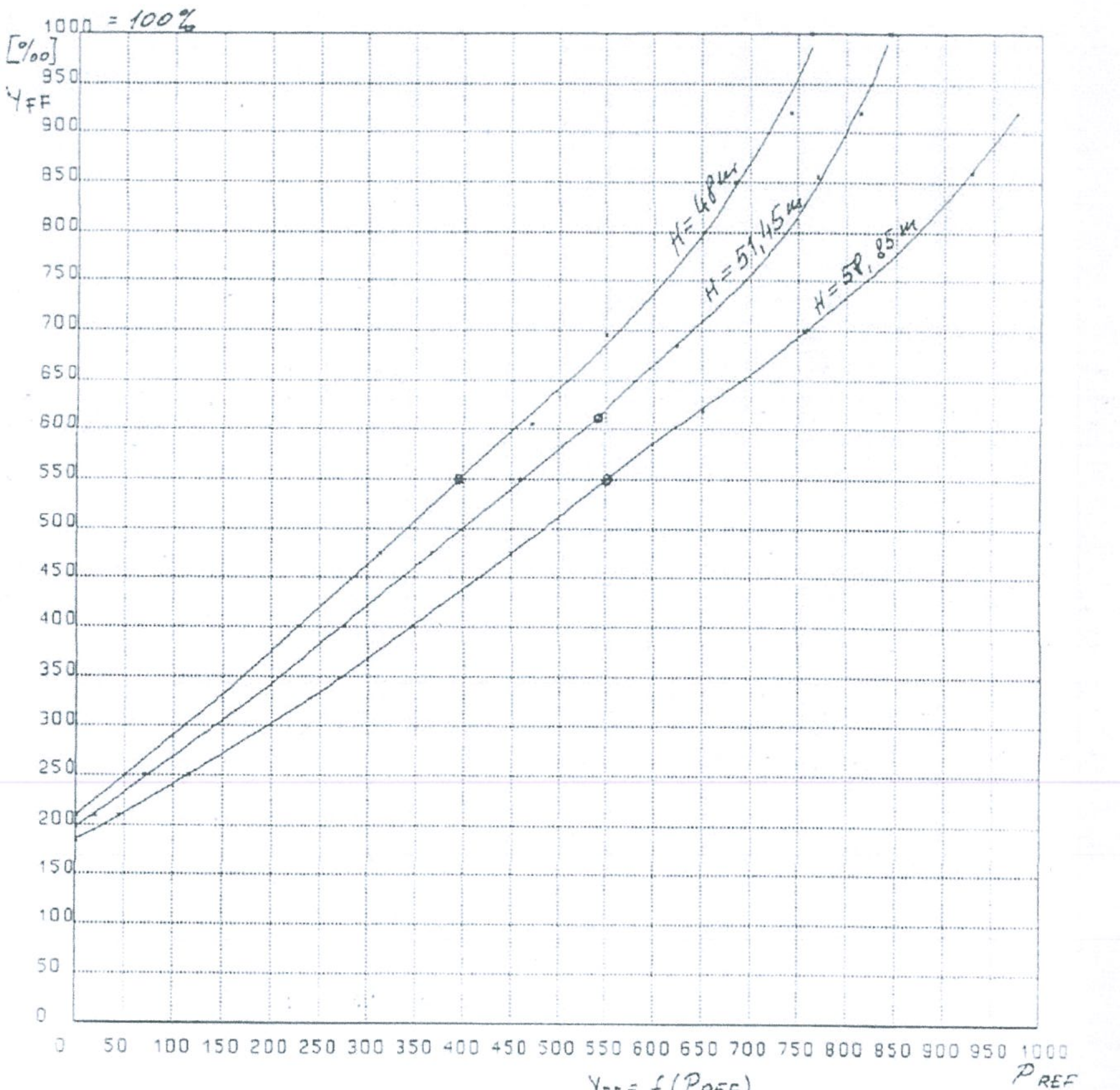

Figure 5b: Catalan Francis turbine power linearization curves $Y_{WG} = Y_{WG}(P)$ CATALAN HPP
Curves number N= 6

Head = 48.0 395-Lim
A0 (1) = 2.100963e+02 A0 (2) = -2.727119e+02
A1 (1) = 7.778599e-01 A1 (2) = 3.939069e+00
A2 (1) = 2.823857e-04 A2 (2) = -6.537898e-03
A3 (1) = -2.105045e-07 A3 (2) = 4.628632e-06

Head = 51.5 540-Lim
A0 (3) = 1.990316e+02 A0 (4) = -2.539009e+03
A1 (3) = 6.644341e-01 A1 (4) = 1.390700e+01
A2 (3) = 3.506130e-04 A2 (4) = -2.107613e-02
A3 (3) = -3.193315e-07 A3 (4) = 1.133379e-05

Head = 58.9 550-Lim
A0 (5) = 1.856600e+02 A0 (6) = -3.280580e+02
A1 (5) = 5.312582e-01 A1 (6) = 3.012961e+00
A2 (5) = 2.815229e-04 A2 (6) = -3.612140e-03
A3 (5) = -8.202065e-08 A3 (6) = 1.881200e-06

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Since the speed droop signal is taken from power error signal the power deviation is linear to speed deviation as shown in **Figure 6**.

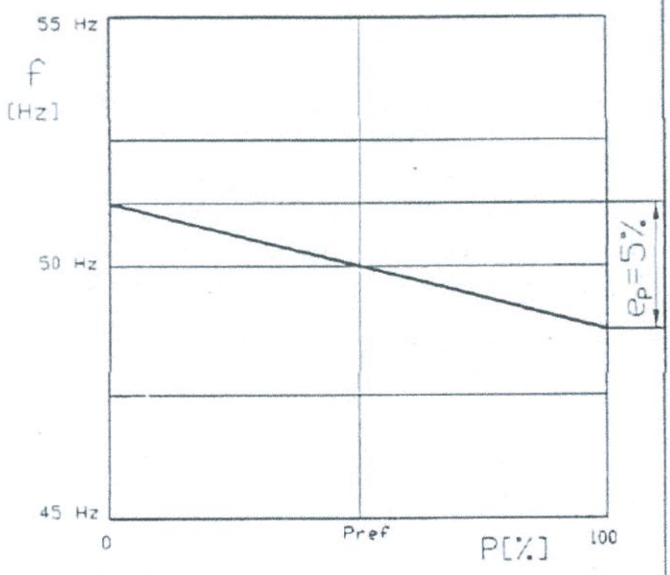

Fig 6: Speed droop curve

1.5 GATE LIMITER, TEST, OPENING AND CLOSING RATE

The gate limiter is provided to limit the maximum opening. The limiter can be set at any time on operator panel OP15 on front governor panel. The gate limiter changing rate is adjustable as governor parameter. The range of adjustments is 1÷999s. The gate limiter is also used for turbine start opening. At turbine start the unit speed is low, PID regulator tends to open the gates and gate limiter is limiting the maximum opening to assure the unit start with constant acceleration up to the nominal speed when the PID governor takes over the opening control.

Separately adjustable no load maximum opening limit is always applied when the generator breaker is off. Gate limiter is also used to close the turbine at unit stop. When the gate limiter is applied (active) the event message is shown on operator panel. Block diagram of gate limiter and test function is shown in **Figure 7**.

1.5.1 Gate limiter adjustment

Gate limiter reference can be set on operator panel from governor front panel. The reference should be entered in percents as decimal number with two decimal digits. The limiter changing rate is adjustable as a parameter from governor panel. The limiter setting can be displayed on digital four digits display installed on front governor panel. When the gate limiter is applied, the I regulator is disabled in opening direction to insure smooth transient when the limiter setting is changed to higher opening. Gate limiter function is programmed in function block **FB60** called by **OB10** and selection of actual limiter is made in function block **FB61**.

1.5.2 Test mode

Governor test mode is intended for testing of governor equipment. In this mode it is possible to open the wicket gate to any position and keep it in this position - speed and power control is disabled.

It is allowed to use this mode only by qualified personnel for testing and for maintenance but not for operation. To use this mode it shall be selected on operator panel (Shift + K3). To prevent non autorized use of test mode the selection on operator panel is protected by the password. This mode can be used when the turbine inlet valve is closed. When selected it is possible to open the wicket gate on any opening. The opening can be set on operator panel. The opening changing rate is a half of the gate limiter rate. When the test is switched on the opening remains the same as it was before. If the test mode is selected, the governor start cannot be activated. Test function is programmed in function block **FB65** called by OB10.

1.5.3 Opening and closing rate

The calculated gate position coming out after the gate limiter and test function is limited in velocity. The timing is set separately for opening and closing as fixed value determined at commissioning. This is programmed in function block **FB70** called by organization block **OB10**.

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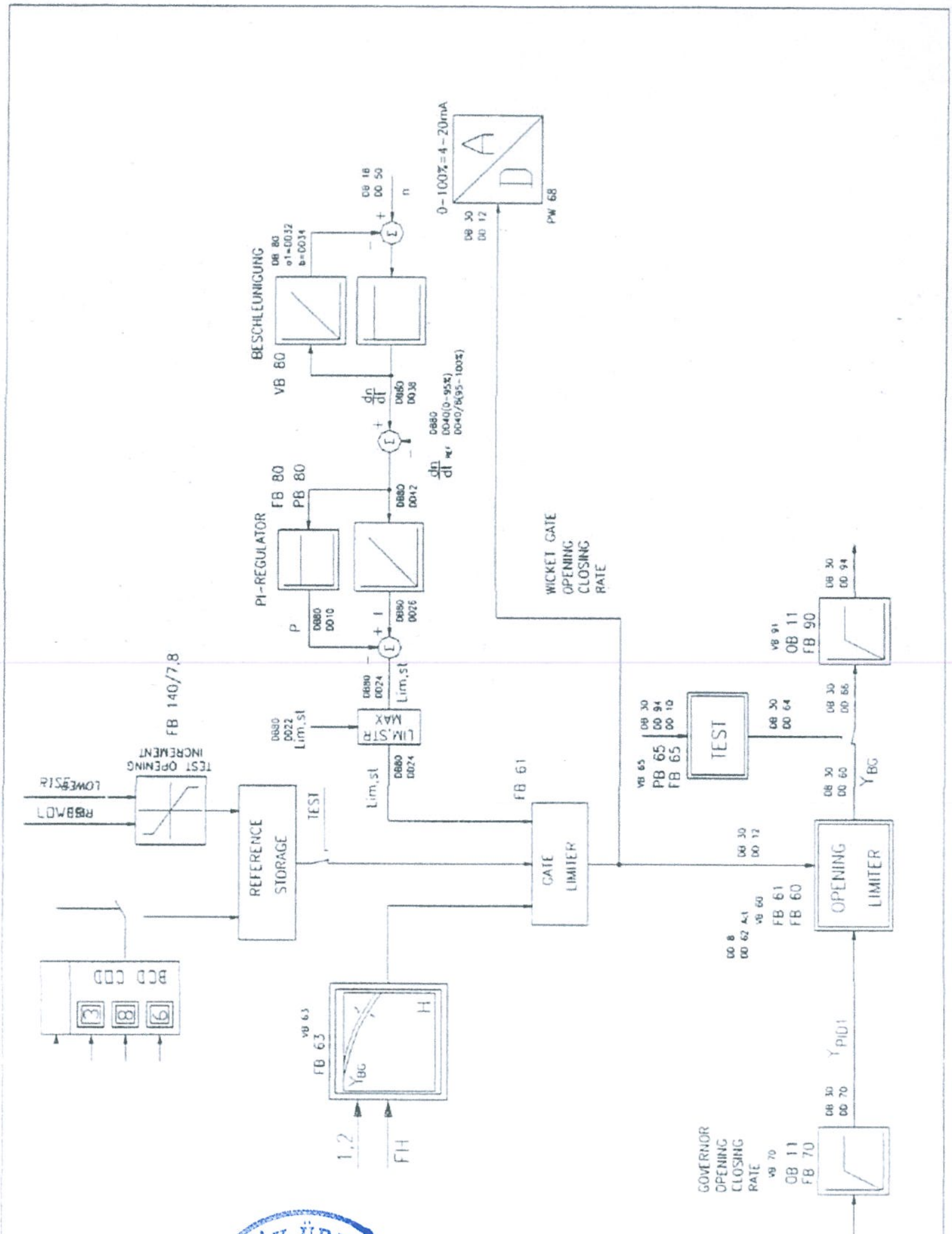

Fig 7: Block diagram of Gate Limiter and Test functions

1.6 *POSITIONING OF WICKET GATES*

Gate position output is used as opening reference for wicket gate servomotor and wicket gate positioning control loop is following this signal. The positioning functions are shown in block diagram in **Figure 8**.

1.6.1 Wicket gate opening and closing rate

The calculated wicket gate reference signal is limited in velocity. The timing is set separately for opening and closing as fixed value determined at commissioning. Timing have to be set on little lower values as wicket gate timing set by throttling valves on servomotor. This is programmed in function block **FB90** called by organization block **OB10**.

1.6.2. Wicket gate servomotor position control

Positioning control is also performed in digital part. Wicket gate opening reference is compared to actual wicket gate opening and the difference between this two signals is making the positioning error. To this error the **PI** regulator is applied. Calculated output after PI regulator is transformed to analog voltage signal (± 10V) and transferred to power amplifier integrated in wicket gate proportional valve. Proportional valve output is oil flow proportional to voltage signal.

1.6.3 Opening signal and positioning error signal

Wicket gate servomotor position is measured twice by the transducer integrated in each cylinder with current output 20÷4mA and 4÷20 mA corresponding to opening of 0˛100%. The first signal is used for main positioning loop and is oriented like that to ensure wicket gate closure in case of position measurement fault. This signals is transformed to digital signal through analog input module DA1 (S5-466) with address **PW 128** and for first servomotor and **PW 130** for second servomotor. Opening signal is than filtered by second order filter with time constant T_{tf}=0,05 sec. The filter is calculated by z transform of following transfer function:

$$Y_{wg,f} = \frac{1}{(1 + 2.\zeta.T_{wg}.s + T_{wg}^{2}.s^{2})}.Y_{wg}$$

$Y_{wg,f}$-	Filtered opening signal	[rel]
T_{wg}	- Filter time constant	[sec]
Y_{wg}	- Measured opening signal	[rel]

Positioning error is calculated as difference between wicket gate opening reference after opening-closing rate is applied and actual filtered opening signal.

1.6.4 Positioning PI regulator

PI regulator calculates output signal for proportional valve control. **P** action provides fast response on error signal. The gain of P function is set as high as possible to have fast response and to reduce the valve insensitivity to minimum but to have stable positioning with sufficient margin. The **I** action is provided to reduce the positioning error to zero (to the measurement resolution limit), which remains after **P** action. The gain of **I** term is set very low in order to prevent oscillating positioning. The **I** term output magnitude is limited (1-3 percents). It is also set to zero when the positioning error becomes zero. Output signal for proportional valve is obtained as sum of P and I action. Output signal is than transformed to analog voltage signal (± 10V) with address **PW 78**.

1.6.5 Supervision of positioning loop

Governor diagnostic circuits are determining the fault of wicket gate positioning. The position feedback signal conversion in D/A module is checked for error at each reading. The two position measuring signals are compared between them and if the difference comes out of tolerance the alarm is initiated on operator panel and as governor fault 1 forwarded to unit signalization. The positioning error is also checked and if the error is bigger than 4% for more than 20 seconds the positioning fault is initiated and the alarm will be initiated on operator panel. If the

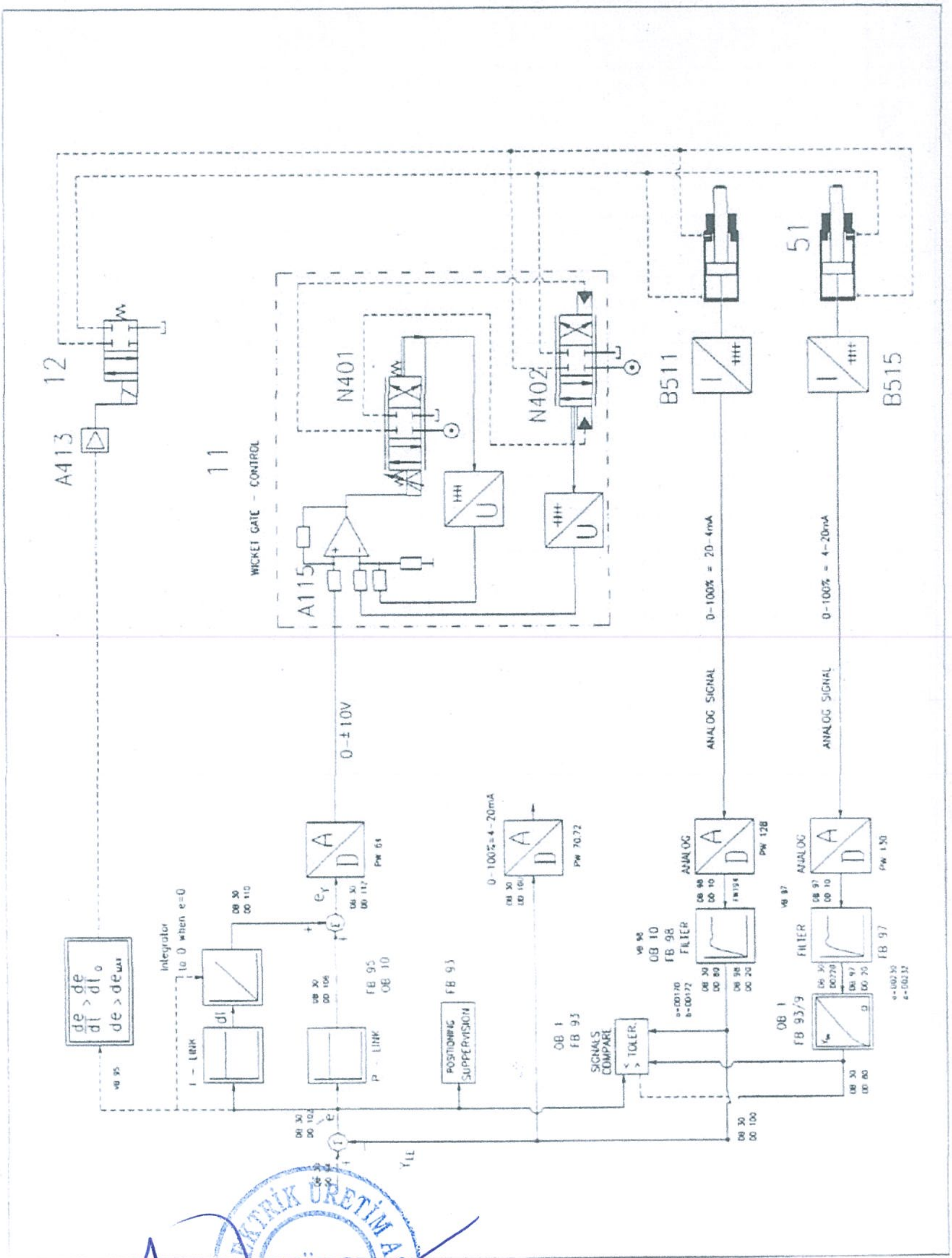

Fig 8: Block diagram of Wicket Gate positioning

second position measuring feedback signal is ok. the second feedback will be switched as a main signal and the unit would run further. If the positioning error remains further for long time (90 seconds) the governor fault 2 and unit shut down will be activated.

1.6.6 Manual control of wicket gate position

Manual positioning of the wicket gates can be selected by selector key switch on local terminal box at hydraulic pressure unit. When selected it is possible to position the wicket gates by reference set using push buttons "Rise" and "Lower" on terminal box on hydraulic power unit or operated directly using the same push buttons. This two modes are different. The first mode is called **"Positioning"** and the second **"Manual"**. In positioning mode the small digital unit S5-95 build the opening reference from impulses coming to **"Rise"** and **"Lower"** and through the programmed positioning loop with feedback taken from the servomotor position measurement operates the gates with impulses to the solenoid valve (Y431, Y432) and keeps the opening all the time. In manual mode the position is not controlled by feedback signal but by the oil trapped in the servomotor and the signal is proceeded through digital unit directly to the solenoid valve (Y431, Y432). Position is mostly kept due to the fact that the servomotor is sealed well and the solenoid valve has the leakage prevented with seat valve 43. Manual positioning can be used in testing time and at maintenance works and also to operate the unit in the case when the main digital unit is inoperative..

1.7 *STARTING AND STOPPING OPERATIONS*

The part of unit starting and stopping sequence is made in governor. It is controlling the operation of wicket agte servomotor. The governor is also providing the speed switches for unit controller.

1.7.1 Governor start

Before the unit start the governor is giving the signal "Governor ready for start". This signal is giving the information that there is no fault in governor and the starting conditions are normal. After the unit sequence controller prepares all the auxiliaries it provides signal "Governor start". If the governor is still ready for start the following is made: the wicket gate opens to starting position determined by limiter starting position. Special starting control of unit acceleration is than reducing the limited opening to keep the unit acceleration constant up to 95% of speed. At this speed the reference for unit acceleration is reduced to make unit come smoothly to nominal speed when the governor speed control is taking over control of wicket gate opening.

After the 98% of speed is attained, the starting acceleration control is disabled and governor is keeping constant the speed level set by speed reference. The unit synchronizer is operating the speed reference through digital inputs "c-rise" and "c-lower" to equalize the generator frequency to system frequency and after the voltage and angle is equalized, the unit generator breaker is closed. After that governor is loading the turbine up to the minimum load. After the required power is attained, the unit load can be changed to any other load. The starting limiter regulator is programmed in function block **FB80** and the start and stop sequence in program block **PB80.**

1.7.2 Governor stop

If the unit is running on the load when the governor gets the signal "Governor stop" the governor starts unloading the unit closing the gates up to the position for 0MW power and gives the signal "Unit power = 0MW" to sequence controller. After the generator breaker is opened, the gate limiter is set to zero and turbine is closed completely. If the unit is running in no load run and the governor gets the signal "Governor stop" the gate limiter is immediately closing to zero. Rate of limiter change at stop operation is the same as in normal operation.

1.8 *GOVERNOR DIAGNOSTIC CIRCUITS*

Governor diagnostic circuits are checking the governor operation conditions switching automatically between the operating modes if necessary and are determining the faults of signals coming from periphery and the internal processing faults. If the faults are detected, the signals "Governor fault 1" or "Governor fault 2" are transmitted to unit controller and corresponding alarms and event messages are transmited to the operator panel.

1.8.1 ISOLATED - PARALLEL switching

It is automatically switched from "Isolated" to "Parallel" governor mode when the conditions in energy system are changed. After the unit synchronization to the network the governor is switched always to "Parallel". It remains in this mode until the unit speed comes out of allowed band limits (±3%) for time t_1 (3 sec) when it is automatically switched over to "Isolated" mode. Governor mode is switched automatically back to "Parallel" mode if the regulator control becomes stable and speed (frequency) enters the narrow band limit (±0,5%) and remains in those limits for time t_2 (5 min). When the governor is switching from one to other mode, the parameters of regulator functions (PID and compensation) are switched to corresponding gains. Mechanism of switching from "Parallel" to "Isolated" and back is shown in **Figure 9**.

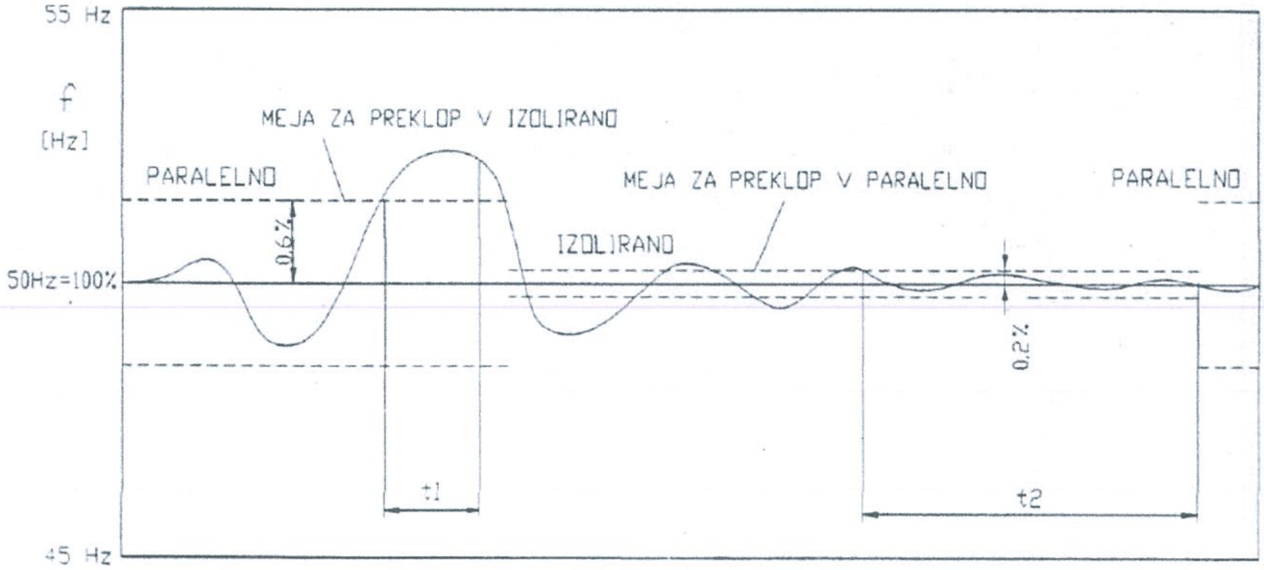

Fig 9: Parallel <-> Isolated switching

It is possible to select different governor mode by pressing the push button on governor panel if conditions are fulfilled. If selected manually, it would remain in this mode until the conditions are not changed the same way as described before.

If the governor is in "Isolated" mode it will change to "Parallel" if the speed is in range when the unit control is switched to level control. The switching function is programmed in function block **FB85** and program block **PB85**. Switching of parameters is programmed in function block **FB53**.

1.8.2 Governor faults diagnostic

The governor is checking the speed signal detecting and indicating the fault of each of three speed measurements separately. The fault is determined by comparing the measured values between them. The alarm is initiated on operator panel for corresponding speed measuring channel. If both main measuring channels become faulty when the turbine is running it will cause the unit shut down (governor fault 2) and the alarm will be initiated on operator panel.

Wicket gate positioning fault is also determined. The position feedback signal conversion in D/A module is checked for error at each reading. The positioning error is also checked and if the error is bigger than 2% for more than 90 seconds the *positioning fault is initiated and the alarm on* operator panel is initiated too.

Power signal feedback is checked and the alarm on operator panel will be initiated if the signal is incorrect. Power signal is compared to actual opening of wicket gate. If the measured signal differs more than 10% from power which should be obtained at actual opening longer than 30 seconds the power measurement fault will be initiated. - Governor fault 1.

Counter module is checked when the module is parameterized which is done at S5-135 unit restart and at each turbine start and at each reading of counter value. There are several possible errors which are checked and if there is an error the counter module fault is initiated and indicated on operator panel and transmitted to unit protection circuits as Governor fault 2.

Live zero check of all analog input signalsl. If the signal is smaller than or 2 mA the fault is detected and signalized on operator panel. Signal for Governor fault 1 will be also initiated.

CPU - Processor operation is checked for exceeded cycle time and for double call of timed interrupt programs. Exceeded cycle time means that whole program in one cycle is taking more time than expected (with some margin). Double call of timed interrupt means that part of program called by timed interrupt (each 10ms, 20 ms, . . .) cannot be *executed in this time interval* and is called again before first call is finished. Those errors are checked and counted and if the error happens more than 10 times the fault is initiated and diode is lit. If the error is repeated more than 20 times the shut down and alarms on operator panel are initiated.

1.9 *Second digital unit S5-95*

Second digital unit of smaller capacity is used as redundant unit to main governor digital unit. It can be used to operate the wicket gates also in case when the main unit is not operative. Beside that the digital unit S5-95 is used to perform automatic *control of pumps loading/unloading according to the* oil pressure in pressure vessel. It operates also the air replenishing valve following the oil level in pressure vessel.

1.9.1 *Control of unloading valve*

One oil pump is running continuously and the unloading valve is controlling the pressure in the system. Oil pressure transducer generates the current signal 4÷20 mA corresponding to the oil pressure in pressure vessel in range 0÷100 bar. Pressure analog signal enters the digital unit through analog input module. The signal is normalized and the switches are build to be used for different functions.

When the pressure is raised to 59 bar the pump is unloaded and when the pressure drops below 57 bar the pump is loaded again (pumps the oil to the system).

1.9.2 Air replenishing valve

Air replenishing system is used to replace the oil lost through the leakage and mostly through penetration into the oil. Indication when air shall be added comes from oil level in pressure vessel signal which is measured by level transducer based on level operated read switches. Resulting signal is an analog signal 4÷20 mA for range of level indication 0 ÷ 100%. When the oil level is raised over the upper limit of operating range the air replenishing valve is opened and is closed back when the level is pushed down below lower operating limit. To prevent the pressure rise in time of air filling the pressure is also considered and the valve is closed when the pressure raises over 59,5 bar. Valve is again opened when the pressure drops below 58,9 bar.

1.9.3 Temperature and level in oil sump

The analog signals for oil sump level and temperature as analog current signal 4÷20 mA for range of level indication 0 ÷ 100% and temperature range 0 ÷ 100°C is checked and switches for too low, too high value are build to shut down the unit. Beside the cooling water valve is operated on temperature - opens when the temperature is higher 45 °C and closes when the temperature drops below 43°C.