OPTIMAL POWER SHARING BEETWEEN STEAM POWER BLOCKS

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Abstract: This paper is analysing aspects regarding the control of the power and frequency of a synchronous generator coupled to an automatic power grid by a steam or hydraulic turbine. The mathematical modelling of the system allows choosing the adequate control structures function of the inter-influence that appears between the power grid and the steam power-blocks reported to the variables that allow the energy transfer: frequency and active power.

Keywords: Power system, modelling, optimisation, power control**.**
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1. INTRODUCTION

Through the liberalisation of the energy market, the pressure on public energy utilities grows enormously and gets essential for economic and commercial success. The planning of short and medium term operation of power plant is an important method to provide power and heat cost-efficiently.

In any modern electric utility system, cost reduction of the energy generated in fossil fuel or hydroelectric power plants is a major goal. This can be achieved through an optimal power sharing between the steam power-blocks in order to get minimal specific costs. Since the demand power in the system changes permanently, the set points of the power control loops shall be changed permanently for all power-blocks, thus leading to oscillations in the grid allocated to the generators or even in the entire power grid (Kamei T., 2003, Vinatoru M., 2001).

In this contest it is important to run own plants at minimal costs as a function of all available possibilities (fuel cost or energy and relevant boundary conditions). It is necessary to implement on-line optimisation programs for planning and sharing the loads in an optimal manner over the steam power-blocks of the plant. This problem is an optimisation problem with restrictions.

2. THE STRUCTURE OF STEAM POWER PLANT

In figure 1 is presented a block diagram of a steam power plant. A power plant consists of several power groups, usually between 4 and 8, having an installed power of 100 to 330MW each. The thermal structure of the plant allows either the connection of the steam boiler directly to the turbine-generator group (independent feed) or the connection to a steam manifold, which is feeding each group. The later is rarely used, since requires a strict control of steam parameters for each steam boiler. Synchronous generators send the electric power into the grid through step-up transformers and electric switches.

The plant, based on the available power, receives a power demand from the regional or national electrical dispatcher for a certain time interval (usually days or weeks). Moreover, sudden power demands can occur due to unexpected consumer demand or unavailability of other power plants connected to the grid.

The plant dispatcher shall distribute the demand to the power groups, based on combined criteria: specific costs and availability. The group loading planning may be modified due to unexpected demand therefore the group load (the power setpoint for each group controller) will be modified at certain times.

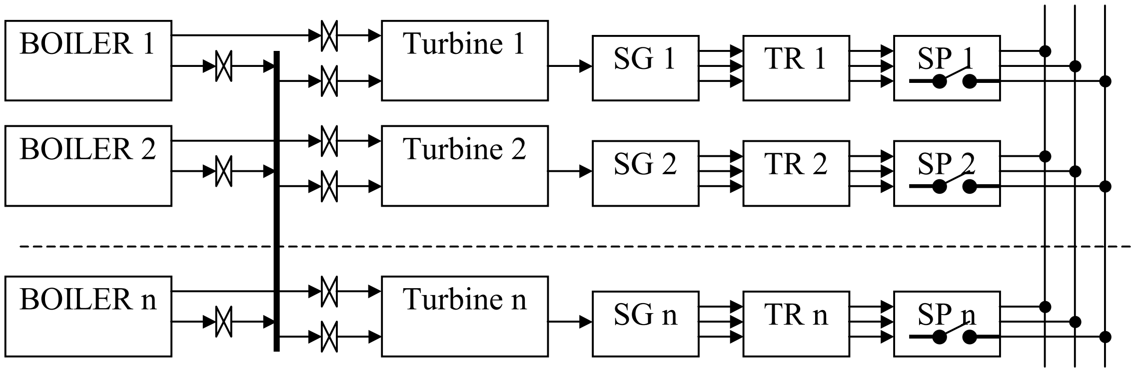


Fig. 1. The structure of the steam power plant

Legend: SGi – sincron generator, TRi – Transformer, SPi - Swich

Two main problems may arise in this case:

- the setpoints for the power controllers shall be based on optimization criteria, which shall assure the efficient operation of the power groups within the constraints imposed by the group or grid.
- due to the interconnection, both through the steam manifold and the connection to the grid, the time interval between two consecutive changes of the group power shall be greater than the transient regimes that can occur due to perturbations in the system. Therefore, is necessary to study the transient regimes of the turbine-generator group and to design the controller for the group accordingly, in order to get short transient regimes and to avoid or limit the oscillations that can occur due to variation of the group power.

These two problems will be further analyzed in this paper.

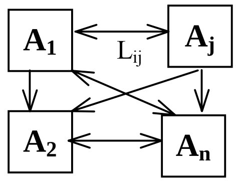
3. CONTROL SYSTEM FOR TURBINE-GENERATOR GROUP

The design of the control system for the turbine-generator group requires the generation of a mathematical model of the group, simple enough to reduce the computational time but accurate enough to reproduce the real operation of the group. This is necessary since the control structure that will be implemented shall allow periodic calculation of the control law's parameters based on the load of the power group and real time operational parameters.

During the previous research, the following mathematical models for the components of the power group were determined:

3.1. The mathematical model of the synchronous generator connected to the grid

A power grid is defined as a regional assembly of power generators and consumers, closed coupled together. The difference between the demand and supply is compensated through energy transfer between grids using transmission lines (see fig.2), where A_j are the power grids and L_{ij} is a transmission line.



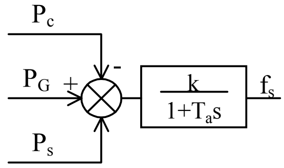


Fig. 2. Power system Fig.3. The power grid model

For the power grid will consider a simple mathematical model (Popovici D, V.P.Bhatkar, 1990, Vinatoru M., 2001) presented by the block diagram on figure 3, where P_c and P_G are the active powers consumed and generated inside the grid and P_s is the active power received from other grids.

The mathematical model of the synchronous generator shall be developed taking into consideration the followings:

a) Interaction with power grid

Using relations presented in (Vinatoru M., 2001) and (Câmpeanu A., 1998) we can obtain the linear relation (1):

$$\Delta P_G(s) = \frac{K_G}{s}[\Delta\omega_G - \Delta\omega_S] \qquad (1)$$

where P_G is the generated active power, $\omega_G=2\pi f_G$ is the angular frequency of the generator voltage and $\omega_s=2\pi f_s$ is the angular frequency corresponding to the frequency f_s of the power grid.

b). Internal power effects inside the generator

We can start from the equilibrium equation for the dynamic torques with respect to the generator shaft (Vinatoru M., 2001):

$$J_G \frac{d\omega_G^{(t)}}{dt} + \eta_G \omega_G^{(t)} + M_G(t) = M_T(t) \qquad (2)$$

where J_G is the momentum of inertia of the rotating elements with respect to the generator shaft, η_G-is the equivalent friction losses coefficient, M_G-is the back electromagnetic torque of the generator, M_T-is the active torque of the prime mover.

Through linearisation of the equation (2) around the steady state values we get:

$$(J_G s + \eta_G)\Delta\omega_G(s) + \Delta M_G(s) = \Delta M_T(s) \quad (3)$$

Considering the active power and frequency as variables and the relation $P_G(t) = \omega_G(t).M_G(t)$ and using relations developed in (Vinatoru M., Iancu E., C. Maican, 2004) for the $\Delta M_G(s)$ and $\Delta M_T(s)$, we can obtain the linear relation (4) for the generator frquence $\Delta\omega_G(s)$:

$$\Delta\omega_G(s) = \frac{1}{J_G s^2 + \left(\eta_G - P_{Go}/\omega_{Go}^2\right)s + K_G/\omega_{Go}} \left[\frac{1}{\omega_{To}}\left(s - \frac{N_T}{\omega_{To}T_t}\right)\Delta N_T + \frac{N_{To}}{\omega_{To}^2\eta_G T_t}\Delta P_G + \frac{K_G}{\omega_{Go}}\Delta\omega_S\right] \quad (4)$$

3.2. The mathematical model of the steam turbine

Using the power balance equations for the prime mover (steam or hydraulic turbine) we get:

$$T_t \frac{d(\Delta\omega_T)}{dt} = \Delta N_T - \Delta N_S \quad (5)$$

where $T_t = \omega_{T0} J_r$, ω_{T_o} is the steady rotational speed of the turbine, J_r is the momentum of inertia with respect to the turbine shaft, ΔN_T is the power generated by the turbine, ΔN_S - is the power consumed by the generator coupled to the turbine.

For the prime mover, the generated power is a function of the opening of the inlet valve X_{VR}, which is controlled by the control loop, and the pressure ΔP_t (the pressure of the superheated steam or pressure of the water at the turbine inlet) of the motor agent (steam or water).

$$\Delta N_T = H_{Ny}(s)\Delta X_{VR}(s) + H_{NP_t}(s)\Delta P_t(s) \quad (6)$$

The power consumed by the generator N_S can be expressed as a function of the generated power P_G using the generator efficiency η_G:

$$\Delta N_S(s) = 1/\eta_G.\Delta P_G(s) \quad (7)$$

The transfer functions $H_{Ny}(s)$ and $H_{NPt}(s)$ can be determined from the energy balance equations for the prime mover (steam or hydraulic turbine) and can be represented as follows (Vinatoru M., 2001) :

$$H_{Ny}(s) = B + \frac{b}{T_N s + 1}; \; H_{Np_t}(s) = C + \frac{c}{T_N S + 1} \quad (8)$$

where T_N is the time constant of the prime mover (thermal or hydraulic).

Eventually we can get the block diagram for the turbine-generator assembly, represented in figure 3, considering that generator speed is equal with the turbine speed (ω_T=ω_G).

From this block diagram results that, on the channel ΔN_T-ΔP_G, the system is at the limit of stability:

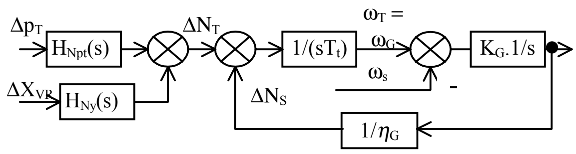


Fig. 4 Block diagram of the turbine-generator ensemble

$$H(s) = \frac{\Delta P_G(s)}{\Delta N_T(s)} = \frac{K_G/T_t}{s^2 + K_G/T_t/\eta_G} \quad (9)$$

which does not correspond to the real operation of this system. This anomaly is a result of neglecting the internal power effects inside the generator, in order to get a simplified model.

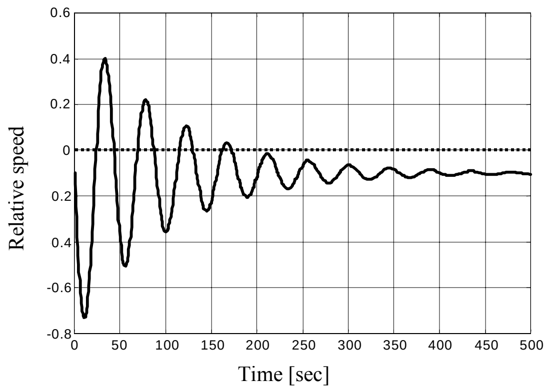


Fig. 5. The relative turbine speed variations

From (1), (4), and (8) we can get the block diagram of the turbine-generator assembly presented in figure 4, which is used for the simulation.

3.3. The simulator of the frequency and power control system of the steam power bloc

Analysing the relation (10) and the block diagram presented in figure 4, we observe that characteristic polynomial corresponding to the blocks for channels ΔN_T –$\Delta\omega_G$ and $\Delta\omega_s$ –$\Delta\omega_G$ can have the coefficient of *s* negative, thus the assembly turbine-generator can get unstable or at the limit of stability. This coefficient is a function of the resistant torque at the generator shaft (given by η_G) or of the generated power, both having significant variations during transitory regimes of the generator. It can be observed the strong oscillatory response of the power-block in the initial part of the transient regime, confirming our theoretical observations presented before (see fig.5).

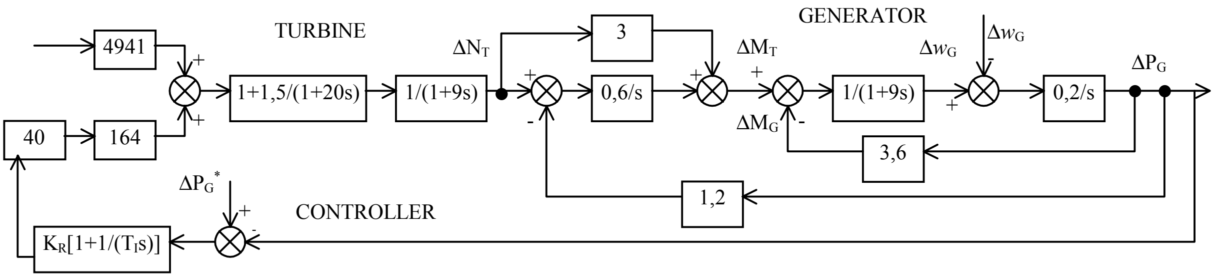


Fig. 6. Turbine-Generator block diagram and Power Control System

In practice, the operation manual of the steam power-block imposes a certain variation speed of the load, in order to avoid these oscillations.

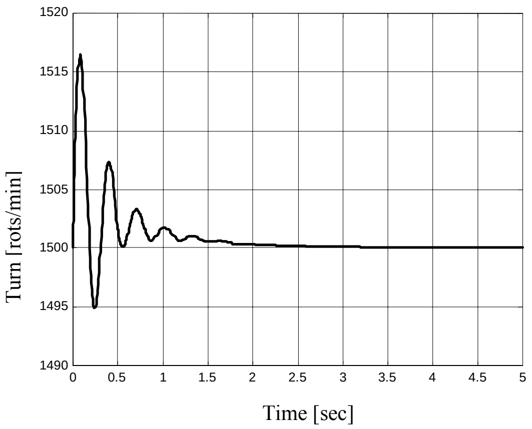


Fig. 7. The generator speed variations

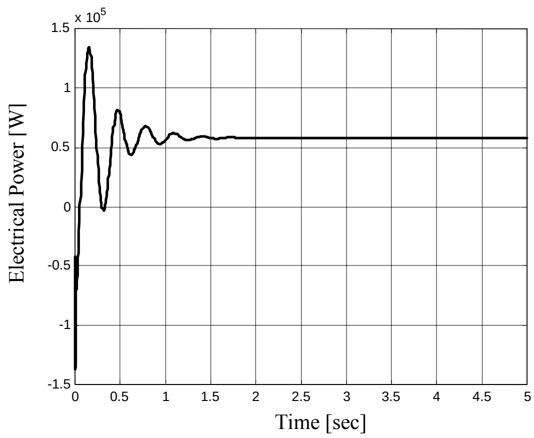


Fig. 8. The electrical power variations

Using the simulation software Matlab, we implemented the control structures presented in figure 6. The graphic results at the load variation are presented in figure 7 and 8. It can be observed the strong oscillatory response of the power-block in the initial part of the transient regime, confirming our theoretical observations presented before. Analysing these simulations, we can draw the following conclusions:

- digital control algorithms shall be implemented for the steam power-blocks;
- design algorithms that can impose limited variations of the control value shall be used;
- software or hardware blocks shall be used to limit the variation speed of the output from the numerical controller used to regulate the load and the frequency of the generator.

4. THE OPTIMAL POWER SHARING BETWEEN STEAM POWER-BLOCKS

The planning of short and medium term operation of power plant is an important method to provide power and heat cost-efficiently. In this contest it is important to run own plants at minimal costs as a function of all available possibilities (fuel cost or energy and relevant boundary conditions). It is necessary to implement on-line optimisation programs for planning and sharing the loads in an optimal manner over the steam power-blocks of the plant. This problem is an optimisation problem with restrictions, and using the basic relations (Calin S., s.a. 1979) we can develop an algorithm to compute the optimal load for each generator as a function of specific costs.

The algorithm is as follows:

- *Get the restrictions* imposed to the power-block operation:

1). The plant load (active power) P_c is imposed by the power dispatcher.

$$P_c = \sum_{i=1}^{n} P_{iG} \qquad (10)$$

where n is the number of power-blocks in the plant and P_{iG} is the power generated by each block.

*2).*The load limits for each block (function of operating conditions or availability)

$$P_{iG\min} \le P_{iG} \le P_{iG\max} \text{ .i=1....n} \qquad (11)$$

- *Generate the cost functions*, representing the total costs to produce electric energy

$$C_i(P_{G1}, P_{G2} ......P_{Gn}) = \sum_{i=1}^{n} C_i(P_{iG}) \qquad (12)$$

where $C_i(P_{Gi})$ is the cost function for power-block i, which is determined experimentally and can be approximated using a polynomial expression:

$$C_i(P_{iG}) = a_{oi} + a_{1i} P_{iG} + a_{2i} P_{iG}^2 \qquad (13)$$

-Define the Lagrange function

$$F(x,\lambda) = f(x) + \sum_{j=1}^{r} \lambda_j g_j(x) \qquad (14)$$

where x is the variables vector $\left(X^T = [P_{1G}, P_{2G} ....P_{nG}]\right)$ and f(x) is the criteria function, which equals the cost function for the plant $C_t(P_{1G}........P_{nG})$

$$C_t(P_{iG}) = \sum_{i=1}^{n} (a_{0i} + a_{1i}P_{iG} + a_{2i}P_{iG}^2) \qquad (15)$$

where λ_j-represent the components of the Lagrange vector, $g_j(x)$-are the components of the restriction vector, defined by (10) and (11) as per specifications of Kuhn-Tucker theorem (Vinatoru M., 2001).

$$\sum_{j=1}^{r} \lambda_j g_j(x) = \lambda_1 (P_t - \sum_{i=1}^{n} p_{iG} + \sum_{i=1}^{n} \lambda'_{2i} (P_{iG\max} - P_{iG}) + \sum_{i=1}^{n} \lambda''_{2i} (P_{iG} - P_{iG\min}.) \qquad (16)$$

- The solution of the problem:

From conditions Kuhn-Tucker, we get that, if there is a vector x=x* that satisfies the minimum of Lagrange function (14) then the following relations are satisfied:

$$\frac{\partial F(x,\lambda)}{\partial x} = f'(x) + \sum_{j=1}^{r} \lambda_i g'_j(x) = o \qquad (17)$$

$$\langle \lambda g \rangle = \sum_{j=1}^{r} \lambda_j g_j(x) = 0 \qquad (18)$$

The theorem Kuhn-Tucker imposes that $g_j(x) \geq 0$ and the components of the Lagrange vector shall be positive $\lambda_j \geq 0$, thus equation (16) can be satisfied if:

$$\lambda_j g_j(P_{iG}) = 0 \quad \text{j=1,r}$$

For the given problem, equations (15) and (16) generate the following relations that can be used to design a software algorithm, to implement on-line the strategy for optimal load sharing between the power-blocks of a power plant, and satisfying the relations (10) to (18):

$$a_{1i} + 2a_{2i}P_{iG} - \lambda_1 - \sum_{j=2}^{r} \left(\lambda'_{ji} - \lambda''_{ji}\right) = 0 \text{ ,i=1...n} \qquad (19)$$

$$P_t = \sum_{i=1}^{n} P_{iG} \qquad (20)$$

$$\sum_{i=1}^{n} \lambda'_{2i} \left(P_{iG\max} - P_{iG}\right) = 0 \qquad (21)$$

$$\sum_{i=1}^{n} \lambda''_{2i} \left(P_{iG} - P_{iG\min}\right) = 0 \qquad (22)$$

Analysing equations (19) to (22), we see that the number of unknown variables is greater than the number of equations. In order to get past this problem, we consider that all powers P_{iG} are inside the restriction domain $P_{iG\min} < P_{iG} < P_{iG\max}$, therefore relations (21) and (22) can be satisfied only if $\lambda'_{2i} = \lambda''_{2i} = 0$

In these conditions, from (19) we get:

$$P_{iG} = \frac{\lambda_1}{2a_{2i}} + \frac{a_{1i}}{2a_{2i}} \qquad (23)$$

Replacing (23) in (20):

$$\lambda_1 = \frac{P_t - \sum \frac{a_{1i}}{2a_{2i}}}{\sum \frac{1}{2a_{2i}}} \qquad (24)$$

From (23) and (24) the optimal values for the power-blocks' loads can be obtained, which assure the minimum production cost for the entire plant:

$$P_{iG} = \frac{1}{2a_{2i}} \left(\frac{P_t - \sum \frac{a_{1i}}{2a_{2i}}}{\sum \frac{1}{2a_{2i}}} + a_{1i} \right) \qquad (25)$$

From (17) and (19) we can get the strategy for load allocation for each power-block. This strategy can be expressed in graphical form and becomes a useful instrument for the plant personnel:

$$\frac{\partial C_1(P_{1G})}{\partial P_{1G}} = \frac{\partial C_2(P_{2G})}{\partial P_{2G}} = ... = \lambda_1 = ct; \qquad (26)$$

But:

$$C'_I(P_{iG}) = \frac{\partial C_i(P_{iG})}{\partial P_{iG}} = a_{1i} + a_{2i} \cdot P_{iG} = \lambda_1 \qquad (27)$$

represent lines in the plane $C'_i - P_{iG}$, which intersect the same horizontal line λ_1, (see figure 9). The intersection points give the optimal powers $P_1, P_2, . . . P_n$. If the working conditions are changed, a new value λ_1 is calculated and a new line is drawn.

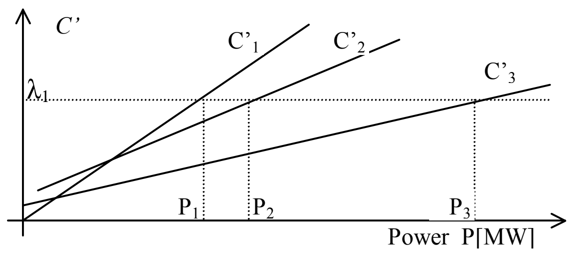


Fig. 9. Graph for Optimal Power

If one of the calculated powers P_{iG} is outside the restriction domain, the optimal value is chosen at the nearest domain margin (i.e. $P_{iG}=P_{iGmin}$ if $P_{iG}<P_{iGmin}$) and the optimisation algorithm is run again.

The logical diagram of the program is presented in figure 10.

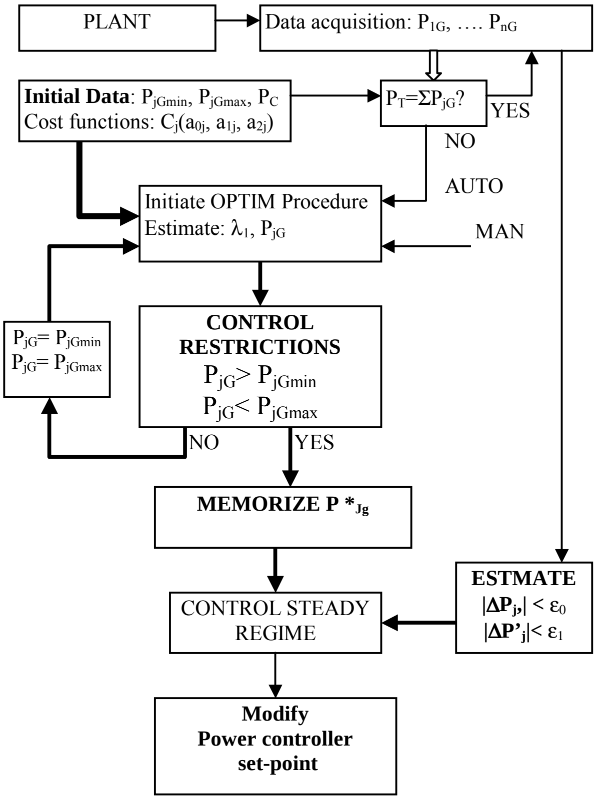


Fig. 10. The logical diagram for the optimal power sharing

Legend: P_C – Plant load, active power

ΔP_j, - power controller deviations

$\Delta P'_j$ – differentiations of power controller deviations

5. CONCLUSIONS

From the analysis of the real operational conditions of the power groups, result the economical advantages of the implementation of complex systems for monitoring and decision, in order to obtain an efficient control of the power groups.

Permanent supervision and analysis of the operational regimes provide the following advantages:
-avoiding or preventing fault conditions that can lead to group shut down and losses;
-implementing a system for optimal sharing of the load between power group will reduce the operational costs and will increase the profit;
-operation of the group without transient stresses and the avoidance of extreme regimes, which will reduce the wear and will increase the life of the equipment.

This paper presented a systematic study of control problems in the power plant control and the possibilities of the optimal power sharing.

For the implementation of the optimisation algorithm, the following rules shall be considered:

-The optimal powers are calculated in real time but the set point changes at the power controller of the power-blocks shall be done only at specific moments in time and only if the variations from previous values are greater than 5%. If the set point is changed continuously, the power-block will be permanently perturbed and oscillations can occur.

-The set point modification shall be done in steps ΔP imposed by the operation rules.

-The set point modifications shall be performed only during steady regimes of the power control loops.

For the real time implementation we can use data acquisition and control equipment designed for power plant applications.

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