APPLICATION OF ADAPTIVE REGULATOR IN POWER SYSTEM

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1. Introduction

In the recent years there has been a greet interest in the practical application of the results of modern control theory. The formation of the state space method and the optimal control theory radically changed the analysis and the synthesis of the control systems. These circumstances have led to the developement of design techniques which result significant improvement in the control. The realization of these control methods gives essentially a more complicated construction than the conventional PID compensation and at the same time it requires a lot of a priori information in order to design a regulator. So it requires the knowledge of the structure of the system to be controlled, its order, its parameters, the type and the statistical features of the disturbances acting on the process. These parameters often are unknown, and it is difficult to measure or change them in time. In this way the parameters of a regulator which are optimum under a given condition will be far from their optimum values under another condition.

From the control techniques developed during the past few years, the methods of the self-tuning regulators seem to be the best for practical applications. These methods were introduced by Peterka and by Aström and Wittenmark for the optimum control of systems with unknown parameters [1, 2]. A self-tuning control algorithm is based on the parameter estimation of the closed loop system and the estimated parameters are directly applied by the control law itself. The basic method was later improved [3, 4] and successfully applied for process control [5, 6].

The purpose of this paper is to direct the attention to the possibility of the application of the self-tuning minimum variance regulator for the load-frequency control of interconnected power systems on the basis of successful simulation investigations.

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2. Purpose of the load-frequency control

The basic task of a power system is to satisfy continuously the requirements of the consumers in respect of both quality and quantity. This means that the power plants of the power system have to ensure the real and reactive power required by the consumers in such a way that the voltage and the frequency have to be kept between given limits [8]. Since the electric power cannot be stored in relative big quantity, therefore power plants have to immediately and continuously fulfil the consumers' requirements.

A great number of regulators ensure the satisfaction of the requirements for the electric power system. In this paper an element of this hierarchical control system, namely the load-frequency control is considered.

The tasks of the load-frequency control (LFC) are the following:

- to maintain the frequency on a given value
- to follow the tie-line power schedule.

The export and the import of electrical energy is settled in the base of half hour accounting. The price of the extra energy obtained over the scheduled value depends on the average frequency in the current period. Therefore one of the tasks of the control system is to ensure that the required energy is equal to the scheduled values at the accounting time instants.

The operation of the load-frequency controller can be characterized by different quantities. For examples:

- the area frequency deviation from its set point (f)
- the deviation of the tie-line power from its set points (p_t)
- the *Area Control Error* (ACE)

$$ACE = p_t + B \cdot f,$$

where B is the frequency factor of the given area. The integrals of the above quantities are also important performance indices:

$$IF = \frac{1}{T} \int_0^T f \, \mathrm{d}t$$

$$IP = \frac{1}{T} \int_0^T p_t \, \mathrm{d}t$$

$$IACE = \frac{1}{T} \int_0^T ACE \, \mathrm{d}t .$$

It is desired to construct a regulator for load-frequency control which performs optimally the following objectives:

- It is desired to keep the area control error as small as possible. According to this the system should cover the load changes arising in the system itself. It is attempted to follow the permanently varying load fluctuation and to realize the minimum variance control of *ACE*.
- The minimization of the area control error does not ensure the desired value of the integral of the tie-line power at the accounting time by all means. Nevertheless this is the base in the international accounting system. It is wanted to ensure that the required energy be the scheduled one at the accounting time.
- The above two objectives have to be satisfied at a minimum of intervention in such a way that the control signals sent to the power plants be minimum with compromising other control objectives.

These purposes are contradictory. The minimum variance control requires frequent intervention. Scheduled values of the exchange energy can only be assured by increasing the variance. Hence it is evident that the synthesis of the optimum controller will be the result of a compromise.

3. The power system as a controlled plant

The method used to describe the power system consists of two generators interconnected by a loss-less network. The loads are modelled as real power sinks. The model is shown in Fig. 1. In our study it was assumed that

$$E_1 = E_2$$

and

$$\delta_1 - \delta_2 \ll 1 \qquad \text{(in radians).}$$

These assumptions are valid for the investigation of small changes in the process.

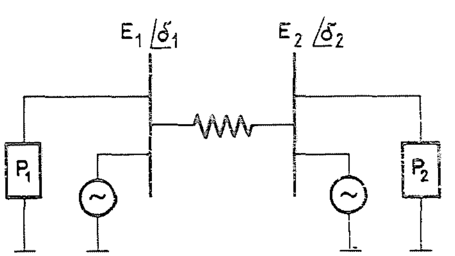

Fig. 1. Interconnected power systems

The reduced model of the process can be described be a differential equation system on the basis of physical considerations. Fig. 2 shows the block diagram of the turbine-generator-network system obtained from the equations.

p_t — deviation of the tie-line real power from its scheduled value
f — deviation of the frequency from its nominal value
p_c — change of the reference value of the tie-line power
p_m — mechanical power deviation
x_g — deviation in generator position
p_d — deviation in demand
T_t — turbine time constant
T_g — governer time constant
R — drop of the area
D — load damping coefficient
T — system constant
a — system constant.

In the co-operating power system the load-frequency controller is considered to be an integral type regulator. Taking into consideration that our purpose is to control the frequency and the tie-line power connecting to our

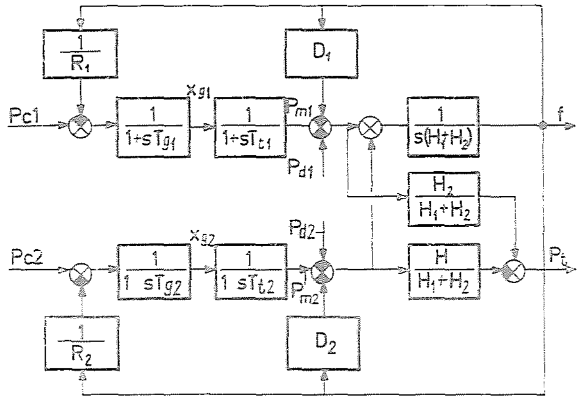

Fig. 2. Model of turbine-generator-network system

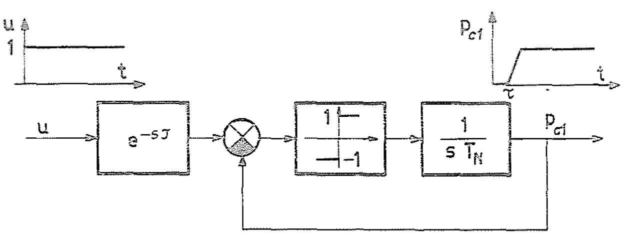

Fig. 3. Effect of the transfer system

area, the time delay between the command and the execution and the effect of the limiter in the governer of the turbine must be taken into account [9]. The step response of this part is illustrated in Fig. 3. Here τ is the time delay and T_N determines the maximal gradient of the response. Fig. 4 shows the block diagram of the model completed by the above influences.
This model is used for the investigation of the load-frequency control.

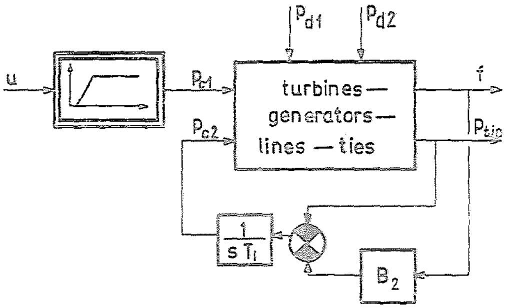

Fig. 4. Block diagram of the interconnected power systems

4. Optimum control strategy

The conventional load-frequency control is based on the tie-line bias control where each area tends to reduce the area control error to zero. The importance of ACE is shown by the fact that in steady-state the value $ACE=0$ means that production and consumption of the given area are balanced taking the reference values of the system frequency and tie-line power into consideration. The frequency factor (B) in Eq. (1) determines the rate of cooperation between the cooperating partners in case of disturbances. If the frequency characteristic of the area is nearly the same as that of the controller then the system itself is practically able to cover the load fluctuation arising in the system and in case of slow changes there is no co-operation between the co-operating systems.

The conventional proportional-integral type control action

$$u(t)=P^{*}ACE+\frac{1}{T_i}\int ACE\,\mathrm{d}t$$

takes care that the ACE becomes zero in steady-state. P and T_i determine the speed of the response.

For the suitable choice of the load-frequency regulator it is necessary to investigate the dynamic features of the cooperating power systems. A high speed LFC is not favourable because of the great control action. On the other hand a slow LFC gives great control error caused by the load fluctuation. The above reasons motivate the optimal setting of the controller.

With the known system parameters, optimum tuning of the regulator parameters is not easy, but not too difficult problem if an effective computer-aided design system is available. Much more complicated work is the investigation of the parameter sensitivity, the observation of changes in the parameters and in the features of the disturbances, and then the permanent tuning of the regulator. These problems can be solved by an adaptive regulator which is able to adjust itself according to the system parameters.

It was mentioned in the description of the load-frequency control that it is desired not only the minimization of the variance of the area control error which is the output signal, but also to ensure the scheduled value of the tie-line exchange energy during the accounting period.

The aim of this paper is not to give the theoretical background of the regulator which satisfies the above objectives. This can be found in [6, 8]. In this paper only the applied algorithm is presented.

The adaptive controller uses the discrete values of two measurable signals of the process:

- the area control error determined from the system frequency and the tie-line power, and
- the sampled values of the energy flowing through the international tie-line.

In the following it is supposed that the value of the energy counter is zero at the beginning of the periods of accounts and its value is reduced by its working point, so $e(t)$ is the integral of the difference between the tie-line power and its scheduled value

$$e(t)=\int_0^t p_t \, dt .$$

Using the first signal a minimum variance self-tuning control is realized. Applying the second signal permits to modify the structure of the regulator. The control strategy is shown in Fig. 5.

Since our investigation is based on the linearization of the system around a working point, the zero reference signal ($p_c=0$) can be chosen. In Fig. 5 p_{cm} is the modified reference value and u the output of the controller.

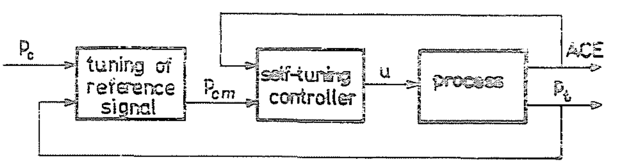

Fig. 5. Structure of the control system

Let us assume that N samples are obtained during a period. Our purpose is to minimize the loss function

$$V_a = \{e(N)\}$$

where $E\{.\}$ stands for mathematical expectation. At the k-th instant of the accounting period it is attempted to minimize the loss function

$$V_a(k) = E\{e(N|k)\} \qquad k = 1, 2, \ldots, N \tag{2}$$

where $e(N|k)$ can be estimated from:

$$\hat{e}(N|k) = e(k) + h \sum_{i=k-1}^{N} \hat{p}_t(i|k), \tag{3}$$

where h is the sampling time. At the k-th step $e(k)$ is known and the deviation of the tie-line power $\hat{p}_t(k+1|k), \ldots, \hat{p}_t(k+d-1|k)$ are determined by the control action $\ldots, u(k-2), u(k-1)$ in case of the known time delay d. In Eq. (3) a possible estimation of the values $\hat{p}_t(k+d|k), \ldots, \hat{p}_t(N|k)$ is

$$\hat{p}_t(j|k) = p_c(j)$$

where $p_c(j)$ is the scheduled value of the tie-line power. In order to determine the extremum of the loss let us change the reference value in every step in such a way as to meet:

$$\hat{e}(N|k) = 0.$$

If p_c is constant during the period, the value of the modified reference signal $p_{cm}(k+d)$ can be determined from the equation

$$p_{cm}(k+d) = -\frac{e(k) + \sum\limits_{i=k+1}^{k+d-1} \hat{p}_t(i|k)}{N-k-d+1}.$$

The minimum of the area control error can be reduced by a self-tuning controller. The optimum control law [8] is

$$u(k) = [ACE_r(k+d) - \hat{q}_1 u(k-1) - \hat{q}_2 u(k-2) - \ldots$$

$$- \hat{p}_0 ACE(k) - \hat{p}_1 ACE(k-1) - \ldots]/\hat{q}_0,$$

where

$$ACE_r(k+d) = p_{cm}(k+d).$$

The parameters to create the optimum control signal can be estimated in a recursive way, for example, by the recursive least squares method. In this case the parameters of the equation

$$ACE(k) = \hat{q}_0 u(k-d) + \hat{q}_1 u(k-d-1) + \ldots + \hat{p}_0 ACE(k-d) +$$

$$+ \hat{p}_1 ACE(k-d-1) + \ldots$$

are determined.

In practice the total control is a process consisting of N steps. Thus because of the time delay $u(N-d-1), \ldots, u(N)$ will already control the next period. In these steps the control relies on the original reference value again. The modification of the reference signal has especially great influence at the first part of a period, namely the average value may significantly deviate from the scheduled one, or at the last steps when $e(k)$ is far from zero.

5. Simulation results

Simulation results verify the effectiveness of the presented self-tuning algorithm. Here we would like to find such regulators where the pole $z=1$ of the controller is fixed. This means, if the number of parameters in the denominator of the regulator equals 0, 1 or 2, the wanted regulator corresponds to the conventional discrete *I*, *PI*, *PID* controllers, respectively. But, of course, it differs from them in several aspects:

- The parameters of the controller are automatically tuned in an optimal way.
- The parameters of the regulator adapt themself according to the variation of the process parameters.
- At the accounting time instants the scheduled value can be assured.

Fig. 6 shows the system response using adaptive integral type controller. The

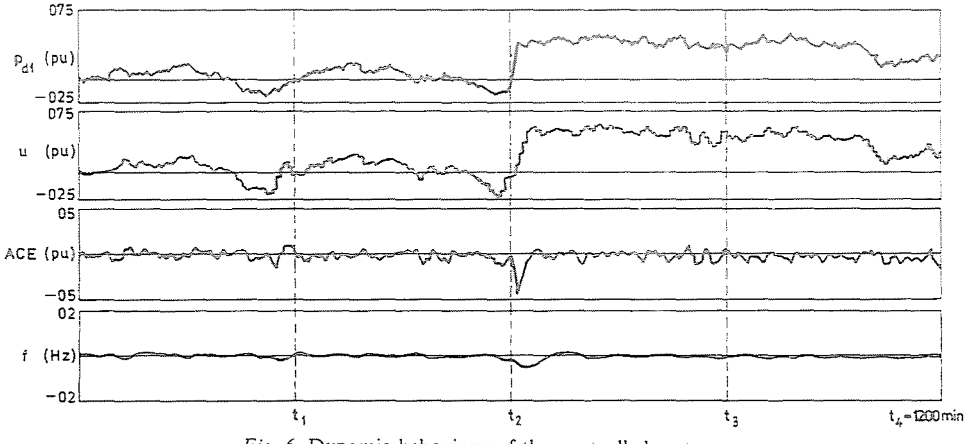

Fig. 6. Dynamic behaviour of the controlled system

sampling time is 1 minute. The time of the simulation is 120 minutes. In the disturbances a step of 0.05 pu is found in addition to the stochastic component. The cost values at the accounting time instants are given in Table I both for adaptive and conventional regulators. The figure and the table show that the adaptive controller is able to compensate both the deterministic and the stochastic component of the disturbances, and finally the loss functions are significantly better using the self-tuning regulator.

Table I

	$e(t_1)$	$e(t_2)$	$e(t_3)$	$e(t_4)$
conventional controller	1.03	0.51	−7.39	2.15
adaptive controller	−0.79	−0.40	0.13	0.08

Summary

Among the techniques of the modern control theory the best method for practical applications is the self-tuning regulator developed by Peterka and by Aström and Wittenmark. In the case of the load frequency control of interconnected power systems a modified version of the basic control algorithm ensures that the parameters of the regulator converge to their optimum values, independent of their initial value, they vary according to the system disturbances and the control algorithm guarantees that the tie-line exchange energy is the scheduled one. This value plays fundamental role in the international accounting system. The paper varifies the above statements by simulation examples.

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