APPLICATION OF ADAPTIVE CONTROL TO SYNCHRONOUS MACHINE EXCITATION

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Abstract Self-tuning adaptive control technique has the advantage of being able to track the system operating conditions so that satisfactory control action can always be produced. Self-tuning algorithms can be implemented easily. Because the power systems are usually time varying non-linear systems and their parameters vary, adaptive controllers are very suitable for power systems. Characteristics of a few adaptive control algorithms are discussed from the point of view of their application to generator excitation control. Basic principles and application of self-tuning controllers to an electric generating unit are given.

چکیده تکنیک کنترل «خودسازگار کننده اداپتیو» این مزیت را دارد که قادر است شرایط کار سیستم را تعقیب کرده و در هر نقطهٔ کار، کنترل رضایتبخشی را تولید واعمال نماید. در این رابطه الگوریتمهای خودسازگار کننده بسادگی قابل‌کاربرد هستند. نظر به اینکه یک سیستم قدرت عموماً رفتاری غیرخطی و غیرمستقل از زمان از خود نشان میدهد و سیستمی است که پارامترهای آن با زمان تغییر میکند استفاده از کنترل کننده های اداپتیودر آنها بسیار مناسب است. در این مقاله مشخصات بعضی از الگوریتمهای اداپتیو از نقطه نظر کاربرد آنها برای کنترل تحریک ژنراتورها مورد بحث قرار گرفته؛ اصول اصلی و کاربرد کنترل کننده های خودسازگار کننده در یک ژنراتور بیان شده است.

INTRODUCTION

Conventional controllers have long been used in many aspects of power systems. Such controllers are based on the deterministic control theory. The controlled system is represented by a mathematical model of known parameters linearized around an operating point. The controller is designed based on the known parameter mathematical model according to a certain control strategy or a criterion.

A controller designed as above has a transfer function with fixed parameters. Such a controller always works very well for small disturbances around the operating point for which the controller is designed, and if the system variable measurements are noise free.

Most physical systems are non-linear and their parameters change with operating conditions. There is, therefore, no assurance that the system performance with the fixed parameter controller will be satisfactory for large disturbances, for controlled system operating conditions other than for which the controller is designed or if the system and the measurements are corrupted by noise.

Adaptive control offers a way to provide satisfactory control for the above conditions. Although one of the first attempts at adaptive control was made in the 1950s, it was only in the seventies that the developments in control theory made it possible to better understand adaptive control [1]. Simultaneous rapid developments in micro-computer technology made it feasible to implement adaptive control algorithms for real-time control of physical systems.

Synchronous machine excitation control and its role in improving the power system stability has been an important topic of investigation since the early 1940s. Supplementary stabilizing signal is added to the excitation system at the input to the AVR/exciter to enhance system damping by producing a torque in phase with the speed.

Power system stabilizer operates through the exciter, generator and the transmission system. The characteristics of the plant are non-linear. Thus controller parameters which are optimum for one set of operating conditions may not be optimum for another set of operating conditions. In general, it would be desirable to track the operating conditions and to compute, in real time, control that would provide optimum performance. Adaptive regulators provide a satisfactory solution to meet such a requirement.

Self-tuning control, as one kind of adaptive control, was first proposed in [1]. One of the earliest attempts at introducing the adaptive control technique to the power systems was reported in [2]. Since then, many investigations have been conducted. Results of these investigations show that self-tuning control is a promising technique suitable for application to the power systems. Self-tuning control technique and a review of its applications in power systems are presented in this paper.

SELF--TUNING CONTROL

Self-tuning control can be described as the changing of controller parameters based on the changes in system operating conditions. Whenever the controller detects changes in system operating conditions, it responds by determining a new set of control parameters. Therefore, the application of self-tuning control strategy to power system control is attractive because the effective system response changes with load level and system configuration.

A general configuration of the self-tuning control is shown in Figure 1. The basic functions can be described as:

(i) identification of unknown parameters
(ii) decision of the control strategy, and
(iii) on-line modification of controller parameters.

Depending upon how these functions are synthesized, different algorithms for adaptive controllers are obtained. Certain algorithms exhibit characteristics which are more suitable for application in power systems. Description of the identification and control techniques and their application in generator excitation control are described below.

System Parameter Identification

The problem of system parameter indentification can be formulated as the evaluation of a set of parameters associated with a preselected system model structure which represents the essential characteristics of the system. For on-line control, since the data must be processed in real-time, the identification algorithms take the recursive form.

Recursive identification algorithms can track time varying parameters in real-time. Three different identification techniques in their recursive form are commonly used. They are the Least Squares, Extended Least Squares and the Maximum Likelihood identification techniques. As the Recursive Least-Squares (RLS) technique has the advantages of simple calculation and good convergence properties, it is the preferred-technique in the design of the self-tuning control for real-time applications and is described below.

Let the plant output, $y(t)$, at time t be given in terms of the past measurements in difference equation form as

$$y(t) = -a_1 y(t-1) - \cdots - a_n y(t-n) + b_1 u(t-1) + \cdots + b_m u(t-m) + e(t) \qquad (1)$$

where u is the input

$t = kT,\ k = 1, 2, \cdots$

T is the sampling period and

$e(t)$ is a sequence of independent random variables with zero mean.

Equation (1) can be written as

$$A(z^{-1})\, y(t) = B(z^{-1})\, u(t) + e(t) \qquad (2)$$

where the polynomials A and B are given by

$$A(z^{-1}) = 1 + a_1 z^{-1} + \cdots + a_n z^{-n} \qquad (3)$$

$$B(z^{-1}) = b_1 z^{-1} + \cdots + b_m z^{-m} \qquad (4)$$

The criterion of the least squares identification is to determine the "most likely" value, $\hat{\theta}(t)$, of $\theta(t)$ which will minimize the sum of the squares of the prediction errors, i.e.,

$$J(N)=\frac{1}{N}\sum_{k=1}^{N}[\varepsilon(t)]^2 \qquad (5)$$

whereindicates the estimated value,

$$\varepsilon(t)=y(t)-h^T(t)\theta(t-1)$$

is the prediction error,

$$[\theta]=[a_1\cdots a_n\ b_1\cdots b_m]^T$$

and

$$h(t)=[-y(t-1)\cdots-y(t-n)u(t-1)\cdots u(t-m)]$$

The least squares identification algorithm is described by the following set of recursive equation [3]

$$\hat{\theta}(t)=\hat{\theta}(t-1)+K(t)[y(t)-\hat{\theta}^T(t-1)h(t)] \qquad (6)$$

$$K(t)=P(t-1)h(t)[1+h^T(t)P(t-1)h(t)]^{-1} \qquad (7)$$

$$P(t)=[1-K^T(t)h(t)]P(t-1)/\lambda \qquad (8)$$

where $K(t)$ is the correction or gain matrix, $P(t)$ is the error covariance matrix and λ is the forgetting factor used to discount old data when the parameters vary with time.

The forgetting factor helps improve the tracking property of the identification routine. It may be fixed at less than 1 or variable and calculated in each iteration [4,5].

To correctly identify the system, there must always be some variation in the system output. In many physical systems, this variation may be present in normal operation. However, if that variation does not register on the measurement system, the estimated B parameters will be very small and the controller performance will deteriorate. To overcome this problem, a barely perceptible amount of uncorrelated noise signal may be superimposed on the control signal.

For practical use of the RLS identification technique, attention must be paid to the following points:

(a) selection of the appropriate injected noise signal and its level.
(b) appropriate scaling of the input/output measurements.
(c) correct selection of the sampling period.
(d) appropriate mathematical model.
(e) correct use of the forgetting factor.
(f) use of suitable filters in the input and output circuits.

Control Strategies

Almost all control strategies used in the deterministic control can be used in the self-tuning control, because if the parameters of the system can be correctly identified, self-tuning control problem is really a deterministic control problem. The control strategies can be roughly classified into two groups, classical control and optimal control. Two commonly used control strategies in the self-tuning control derived from the above-mentioned classes of control are given below.

Minimum Variance Control

The minimum variance control [1] is based on the optimal control theory. The control output $u(t)$ is calculated based on minimizing the performance index

$$J=E[y(t+1)-y_r(t+1)]^2 \qquad (9)$$

where y_r is a reference signal.

A minimum variance controller first predicts the next measurement for zero control, and then chooses the control value so that the predicted output error is zero. This form of adaptive control is very easy to compute. A drawback of this control strategy is the possibility that the control computation may become unstable [6] particularly under non-minimum phase conditions. Also, if the control signal is limited, the resulting control can give rise to poor damping.

Other control strategies which belong to this category are:

(i) Generalized Minimum Variance Control

In this control, the performance index is chosen to contain both system output variation and the control action [1]. This control can solve the non-minimum phase problem.

(ii) Optimal Linear Quadratic Control

In this method, the identified system model is re-arranged into the control canonic state space form. The determination of the optimal control involves the solution of the discrete Riccati equation which is usually very time consuming [7]. This controller has the advantage that, if the parameter estimates are true, the controller will always be stable.

Pole Shifting Control

The pole shifting control strategy deals with the closed-loop system poles. It shifts all the system poles radially towards the center of the unit circle in the z domain by a factor α less than one [7]. By using this control, the closed-loop system stability is increased by a certain degree.

For the system given by equation (1), the control is computed from.

$$u(t)=-\frac{G(z^{-1})}{F(z^{-1})}y(t) \tag{10}$$

wher F and G are polynomials in z^{-1}.

Selecting a desired closed-loop system characteristic equation

$$T(z^{-1})=A[\alpha(z^{-1})]=1+\alpha\hat{a}_1 z^{-1}+\cdots+\alpha^n\hat{a}_n z^{-n} \tag{11}$$

control parameters f_i and g_i are computed from:

$$A(z^{-1})F(z^{-1})+B(z^{-1})G(z^{-1})=T(z^{-1}) \tag{12}$$

For $n=m$ in equation (1), solution of equation (12) can be written as:

$$Z=M^{-1}L \tag{13}$$

where M is a $(m+n-1)x(m+n-1)$matrix having as its elements the estimated value $\hat{A}$ and $\hat{B}$ of the A and B parameters [7], and its inverse exists provided that the polynomials $\hat{A}$ and $\hat{B}$ have no common factors [8].

$$[Z]=[f_1\cdots f_{m-1}\ g_o\cdots g_{n-1}]^T \tag{14}$$

$$[L]=\hat{a}_1(\alpha-1)\hat{a}_2(\alpha^2-1)\cdots\hat{a}_n(\alpha^n-1)\,o \quad o]^T \tag{15}$$

With α close to one, elements of "L" are close to zero, elements of polynomials F and G are small and a stable controller is achieved. So for a stable plant, a properly identified pole-shift controller always yields a stable controller provided that the polynomials $\hat{A}$ and $\hat{B}$ have no common factors. This approach has the advantage of having a single parameter, α, trade-off for best and stable control.

The adaptive controller is achieved by computing on-line the closed-loop characteristic equation (11) using the system parameters identified by the recursive relationships of equation (6) to (8). The control, u, is computed as.

$$u(t)=[-y(t)\cdots-y(t-n-1)-u(t-1)\cdots -u(t-m-1)][Z] \tag{16}$$

based on controller parameters calculated from equation (14). For high order systems, the solution can be computationally expensive. But because of the special nature of the matrix [M] in equation (13), this equation can be simplified considerably.

Other control strategies which belong to this category are:

(i) Variable Pole-shifting Factor Control.

In this method,all the identified open-loop poles of the controlled system are shifted as close as possible to the center of the unit circle without violating the system control constraints [9]. The pole-shifting factor is calculated in each sampling period to obtain the most stable closed-loop system.

(ii) Pole Assignment Control.

In this controller, the desired response is prespecified by specifying the desired system closed-loop poles. It thus offers the freedom to place them at any location [10]. This permits a trade-off between the performance and the control effort.

(iii) Pole-zero Assignment Control.

The aim of this control strategy is to place the closed-loop poles and zeros at pre-selected positions so that the desired closed-loop system response can be obtained [11]. One important aspect of this strategy is that the unstable open-loop zeros cannot be cancelled by the controller as it will produce an unstable control loop. As both poles and zeros have to be treated, the calculation of the control output is quite complicated.

POWER SYSTEM APPLICATIONS

Desirable properties of a good power system adaptive controller may be described as:

(a) the controller should not saturate under transient conditions.

(b) the controller should guarantee stability under the non-minimum phase conditions.

(c) as an 'a priori' decision cannot be made on the parameters, preselection of the required performance be avoided.

(d) trade-off between control effort and control action should preferably be made by adjusting a single parameter.

The linear quadratic and pole-shifting controllers are not constrained by the first three properties and they possess the desirable fourth property. They, therefore, seem to be more suitable for application in power systems.

Adaptive Power System Stabilizer

Studies have been performed on a power system consisting of a generating unit connected to a fixed voltage bus through a long double-circuit transmission line. The effect of the self-tuning controller acting as an adaptive power system stabilizer was investigated in these studies.

Simulation Studies

In the simulation studes, the generating unit was simulated by a set of non-linear differential equations based on the Park's equations. Incorporating a simple governor and an AVR gave a tenth order non-linear model of the system. Electrical power output was used as the auxiliary stabilizing signal as shown in Figure 2. The system between the control input, u, and the output, P, was identified as a third order system with m=n=3. Response of the power system to a 50 percent step change in input torque is shown in Figure 3 for the case of no-stabilizer, a conventional stabilizer and the pole - shift stabilizer with variable λ and α The variation of λ and α, and the output of the adaptive stabilizer are shown in Figures 4 and 5, respectively. These results are for a sampling period of 100 ms.

RESULTS

A self-tuning power system stabilizer based on the RLS identification technique with variable forgetting factor, λ, and the pole-shifting control strategy with variable pole-shifting factor, α, has been realized with three Intel 8086 micro-computers. The stabilizer was tested on a physical model of a power system consisting of a 3 KVA micro-machine connected to a fixed voltage bus through a 300 km double-circuit transmission line physical model. System configuration used was very similar to that shown in Figure 2. System response to a 0.28 pu step-change in the input power is shown in Figure 6.

In this case also, the system was identified as a third order system. The results shown are for a dual-rate technique [12] in which the sampling rate for identification is 80 ms and that for the control calculation is 20 ms.

Adaptive Excitation Controller

Using a generalized self-tuning control technique, an adaptive excitation controller that performs the functions of AVR and stabilizer has been implemented using the same hardware as that used for the adaptive stabilizer described above and tested on the same physical model of a power system [13]. This algorithm is also based on RLS identification technique with variable forgetting factor and the variable pole-shifting control strategy.

With the generator operating at 0.8 pu power 0.85 pf lead, an illustrative result for 0.15 pu step change in power input is shown in Figure 7. Comparison is also shown with an AVR and conventional fixed parameter power system stabilizer.

CONCLUSIONS

An overall view of the applicability of an adaptive control scheme to improve power system stability has been presented. An important characteristic of an adaptive controller is that it continually tunes itself to the current operating conditions and can thus improve both the dynamic and transient stability. Real-time operation of the adaptive controller applied to an electric generating unit has demonstrated the viability of the microcomputer implementation of such controllers.

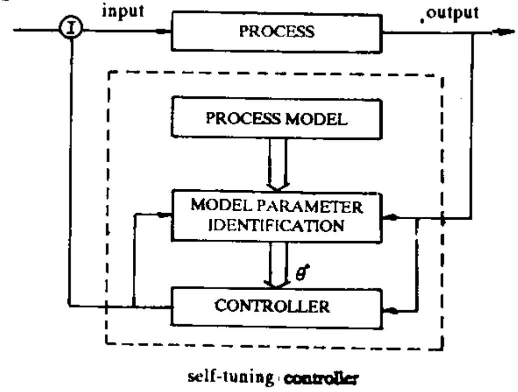

Figure 1. Block diagram of a self-tuning controller

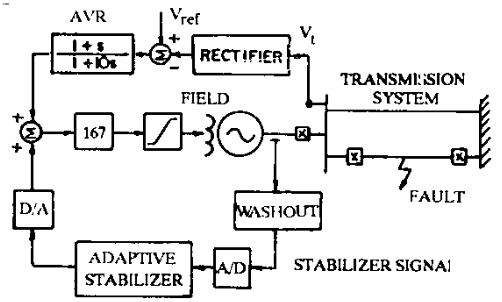

Figure 2. Power system model with excitation control scheme and adaptive stabilizer

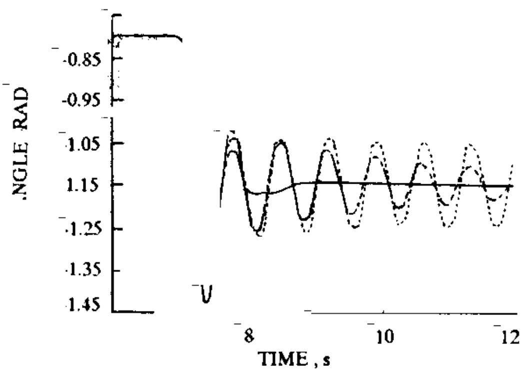

Figure 3. Response to a 50% step increase in torque

.... No stabilizer

- - -Fixed ω, α stabilizer

— Variable ω, α stabilizer

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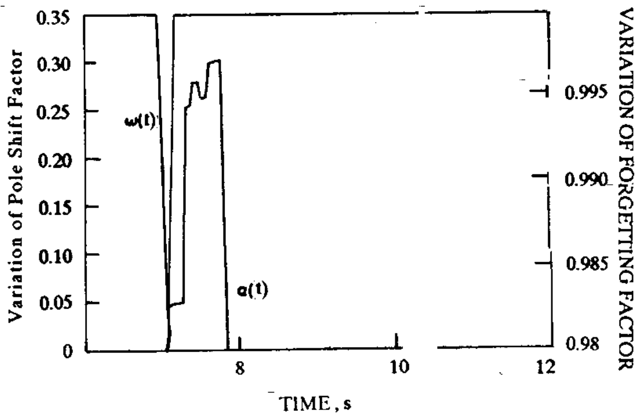


Figure 4. Variation of forgetting, ω, and pole-shift, α, factors

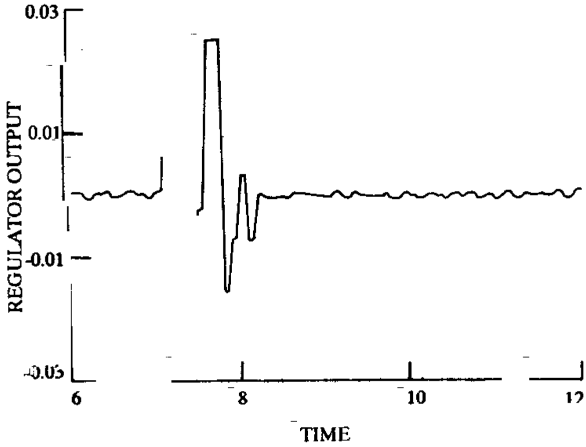
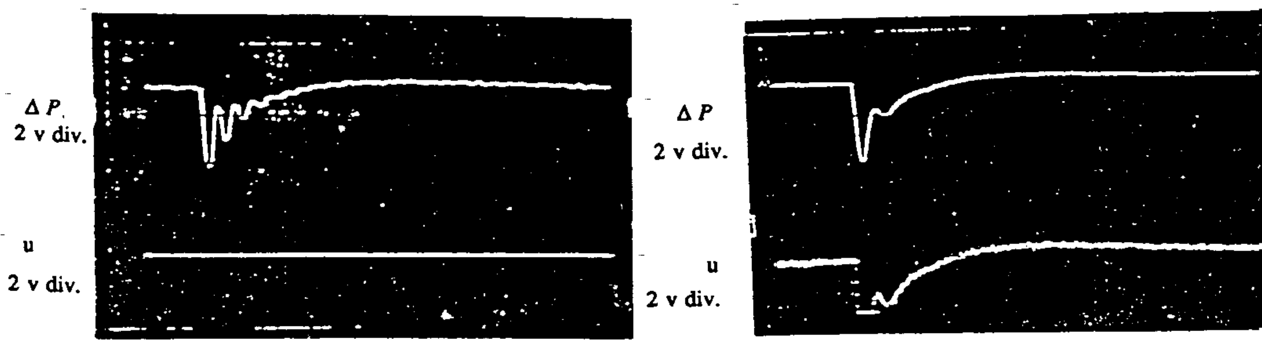


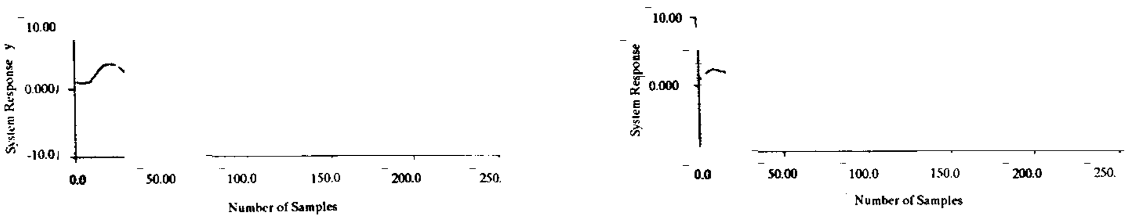
Figure 5. Output of adaptive stabilizer



(a) without SPSS

(b) with SPSS
Time 2 sec/div

Figure 6. Response to a 0.28 p.u. decrease in the input power



(a) with conventional controller

(b) with proposed controller

Figure 7. Response to a 0.15 p.u. step change in the input power