ADAPTIVE CONTROL IN THE APPLICATION OF ELECTRICAL DRIVE TECHNICS

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(Received March 5, 1975)

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1. Introduction

In electrical drive technics the possibilities offered by automatic control have been widely applied and intentionally utilized right from the beginning. For instance, the simple current-dependently controlled start permitted to realize a starting process of optimum armature losses, in addition to the overcurrent protection of the mains and the motor.

In the first period of the controlled electrical drives the main goal was to ensure the prescribed accuracy and *stability*. But soon the improvement of the quality characteristics and *optimum control* came to the foreground. In order to ensure the successful (stable), or in some sense best (optimum) operation of the system, the parameters or the algorithm of the control equipment must also be varied.

The systems, in which the parameters, or the algorithm of the control device vary automatically in a purposeful way on the basis of informations obtained from the system are called automatically self-adjusting, or *adaptive systems*.

One of their first applications was — in addition to the field of process and production control — the pitch control of rockets and high-performance supersonic aircraft in the high speed and altitude ranges, i. e. under highly variable aerodynamical conditions with variations over several orders of magnitude.

In the field of electric drive control no such great variations of the parameters are unlikely to occur, but in several cases satisfactory results are obtained only by controls of the adaptive character.

In the following the necessity and aim of such systems and the mode of their realization are described on the basis of the related literature, leaving detailed problems of the individual variations out of consideration, but surveying and classifying the subject.

2. A short survey of the adaptive systems

2.1 *The concept of adaptive systems*

The denomination of adaption was used and interpreted in connection with the technical systems in multiple ways [10].

The adaptive control systems as defined by Tsypkin ensure a satisfactory unequivocality for the technical systems. Accordingly "adaption is called the process of variation of the controlling influence according to the parameters, the structure and the possibilities of the system realized on the basis of continuous informations and aimed at attaining a certain, usually the optimum state of the system under the conditions of initial uncertainty and varying operational circumstances", i. e. ". . . adaption is essentially an optimization realized on the basis of insufficient a priori informations" [9, 47], where the deficient a priori informations on the system are completed by informations gained by the learning process.

So the adaptive systems may be divided, with regard to their basic mode of operation, in two or more hierarchically related systems, the *basic system* and the *adaptive controller* (AC). The adaptive controller influences the basic system (e. g. the control system) in a way that its functional properties, its quality characteristics possibly remain within the prescribed range. In the following we shall take this aspect into consideration in the first place and will call also such systems adaptive, which are not functioning on the basis of the learning process in the first place, but are constructed by the a priori knowledge of the basic system in a way, as to act in the interest of the desired aim.

Naturally the control of systems of variable structures and parameters may be solved not only by adaptive control. In numerous cases the utilization of the sensitivity-reducing effect of the negative feedback, or the application of low parameter-sensitive systems is sufficient.

2.2 *The construction of the adaptive control systems*

The adaptive systems are constructed hierarchically, as we have seen, therefore the adaption is realized at two levels at least, of parallel operation, in a hierarchical relationship with each other.

The hierarchically lower level *basic system is the fundamental system.* In the adaptive control systems the basic system is a control, usually a closed loop control system. It is meaningless to apply the adaptive control, without exploiting the advantages of the negative feedback.

In the basic system shown in Fig. 1, the input of the controller C receives — in addition to the feedback signal x_e — also the control input x_a containing the informations obtained from the environment on the prescribed value of the controlled quantity x_s. In addition the system is influenced by the noises and disturbance effects x_{z1} and x_{z2}. This system is optimum in the case where it is led by the leading effect from the initial state $x_s(0)$ into the final state $x_s(T)$ in a way that the functional

$$I = \int_0^T Q\left(x_a(t), x_s(t), u(t), t\right) \mathrm{d}t \tag{1}$$

formed from a purposefully selected target function Q has a minimum for the given $x_a(t)$ [19].

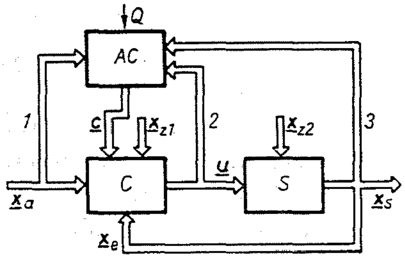

Fig. 1. Adaptive control system

The function of the basic control system may also be characterized by the trend to the minimum of more than one functional simultaneously (e. g. energy and error signal criteria). The condition of the optimum in this case is:

$$\begin{aligned} I_1 &= \min \\ &\cdot \\ &\cdot \\ &\cdot \\ I_n &= \min. \end{aligned} \tag{2}$$

If the state of the system deviates from condition (2), then the adaptive controller AC varies the algorithm (structure), or the parameters of the controller C by the effect $c(t)$. So the hierarchically higher level system does not act directly on the state $x_s(t)$ of the controlled equipment, but on its "properties", on the basis of the informations gained from the basic control system. Accordingly *the leading effect of the higher level system (adaptive controller) is the target function Q characterizing the operation of the basic system, its controlling effect is the effect c(t) acting on the controller C and the aim of the control is to meet condition* (2).

Accordingly the adaptive controller performs considerably more complex operations than the basic system, therefore its function is slower than that of the basic system. So both hierarchic levels of the control operate at non-identical rates.

2.3 *The classification of the adaptive control systems*

The adaptive systems may be classified in several ways. A system may be generally assigned simultaneously to several groups [10].

Adaptive closed loop control and *adaptive open loop control* are spoken of depending on whether the adaptive effect passing through the adaptive controller AC is of a closed loop, or of an open chain character. In these cases AC is called *adaptive closed loop controller* (ACC) or *adaptive open loop controller*, respectively (AOC).

In the system shown schematically in Fig. 1 the adaptive open loop control is realized, if any of the informations 1, 2, 3 is available by itself, or the informations 2 and 3 are available simultaneously. Closed adaption loops are created in processing the informations 1—2, or 1—3.

The adaptive open loop controls are faster than the adaptive closed loop controls, but they compensate only the foreseen interference effect. Another restriction of their application is to require more a priori knowledge on the system for their construction. In some adaptive open loop controls the identification may be substituted be the measurement of the signals; in this way the adaptive open loop controller operates at the same rate as the basic system. For this system the denomination adaptable (English), or adaptabel (German) is also used [45].

3. Adaptive controlled electric drives

In the field of electric drive control the application of the adaptive control may have two reasons. On the one hand, in cases where the aim could be attained also by deterministic methods, the controller completed by an adaptive control applied as a unit controller releases the user from the "care" of adjusting the controller [29, 38]. This is still illusory, but an imaginable prospect. The present state is characterized by the application of the adaptive control for the adaption to the changing circumstances (Table 1).

In the majority of the studied systems the transfer function of the motor — assuming a subordinate current control circuit — may be approximated by a first order lag integration element (IT_1) where the time constant of the time lag element (T_S) is the equivalent time constant of the armature circuit, while the transfer factor of the integrator is the reciprocal value of the nominal starting time T_{IN}. The variable flux, or the moment of inertia may be derived by multiplication or division between both elements.

The influence schemes refer to time functions. The terms are given by their unit step responses, or their transfer functions. The usual assumption has been made that the effect c and the characteristics of the controlled path are varying slowly, so the LAPLACE-transformation may be applied [24].

Table 1

The possibilities of adaptive control application in systems equipped with electric machines

Reason of the deviation from the linear case of constant parameter			Effect on the control system	Reason evoked in the control system	Examples of literary references
Load and environment	The moment of inertia of the driven mass varies	continuously	The electromechanical time constant varies	The quality characteristics and the range of stability vary	27, 29, 30, 34, 37, 38, 44, 46
		jumplike at the drive gear switch-over			
	The parameters of the elastic coupling between the load and the driven shaft vary	The rope length of the mine elevator (spring constant) and the mass of the transported load vary	The natural frequency of the system varies		31, 44, 46
	The resistors of the motor and the controller are warming up by the effect of the load and over-load especially	The resistors vary	The time constants vary		8, 35, 39
	The quantitative and qualitative characteristics of the reference signals and the disturbing interference effects vary		The system deviates from the optimum mode of operation	The quality characteristics vary	12, 18, 21, 22, 28
	The viscous damping varies	depending on the down-time and operation time respectively	The damping of the drive motor varies		14, 16, 27, 45, 46

Construction of the electric machine and the mechanical system; mode of disturbance and control	The flux varies	due to the limitation of the excited voltage over the nominal speed	The controlled plant contains a dynamic nonlinearity, its parameters are workpoint-dependent	The quality characteristics and the stability range vary	1, 8, 13, 17, 21, 29, 30, 32, 33, 34, 40
		for attaining optimum control			25, 26, 32
		by the serial, or compound excitation motor, or due to the armature reaction respectively			3, 8, 17, 25, 26, 32, 34, 42
		by technological reasons			13, 14, 33, 40
	The structure of the transfer function of the motor varies	Current supply control at the boundary of the continuous and intermittent runs	The parameters and the structure of the controlled path are workpoint-dependent		4, 5, 6, 7, 11, 15, 17, 21, 27, 30, 34, 41, 43, 48
	The speed of the driving machine varies	due to the varying running speed of the vehicle	The loop transfer factor of the voltage control circuit varies		17
	The compensation of the control circuit varies	due to the limitation of the signals	The phase margin varies		20, 27

The survey of references is facilitated by Table 1, grouping the adaptive controls according to the reasons of their application [25].

3.1 *Reasons of the application of adaptive control; disturbing effects by the environment and the load*

3.1.1 *Changes in the moment of inertia of the masses reduced to the driven shaft*

Several authors mention that — in the case of unchanged masses — switching over the drive gear is sufficient to supply satisfactory a priori information for applying the simple adaptive controller [27, 34]. By switching over the adaptive controller adjusts the control parameters to the present values.

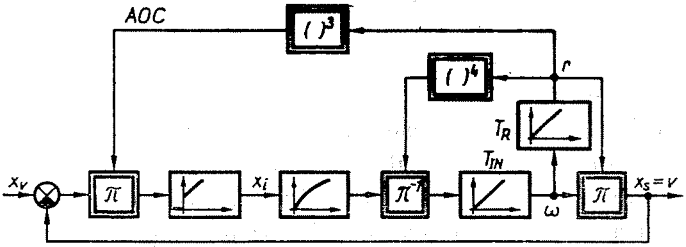

Fig. 2. Band speed control of a reel drive [34]

The variation of the moment of inertia is continuous in the case of reel drives and is relatively easy to measure. Ströle describes the band speed control circuit of such a system [34]. The controlled path is a motor of constant flux supplied with a subordinated current control. In the course of reeling, the radius r grows at a speed proportional to the angular speed and the band thickness; this is expressed by the element of the integration time T_R. Two nonlinear effects are present in the control circuit (Fig. 2):

— the control signal is formed by multiplication ($v = r\omega$),

— the moment of inertia, and along with it T_{IN} is proportional to r^4, so the integrator simulating the mechanical equation of the motor face as division by r^4.

So the control loop contains in the resultant a division by r^3, which is compensated by a multiplication by r^3 on the part of the adaptive control.

Weber suggests adaptive control for the position control of the transport cage of a deep mine shaft [44, 46]. The cage traverses several levels, so in addition to moving it between the surface and the mine galleries it must also be levelled for loading in and out. The natural frequency of the controlled path varies due to the variation of the spring constant, of the varying rope length and the varying masses of the varying loads.

Spiegel suggests a speed control completed with an adaptive controller for a drive of variable moment of inertia [37]. The paper presents the operation of the drive with a variation of the proportion 1:2 of the moment of inertia.

Rumold and Speth describe a speed controlled d. c. drive with alternating parameters [29]. The model of the controlled part is an IT_1-element, the two parameters of which are varying. For the identification of the parameters and the disturbance a self-adjusting series model is used (Fig. 3). The parameters of the controller are calculated from the estimated parameters by an analogue circuit. An adaptive open loop control is used (Fig. 4). The good quality of the working of the system is shown by analogue simulations.

Speth [38] published another simpler solution of the adaptive controller in connection with the above problem. The reduction is based on the recognition that the time constant of the element IT_1 substituting the motor is practically constant and it is only the integration time which varies (due to the variation of the flux, or the driven mass). $Y_c(s)$ in Fig. 5 is a constant part of the controller, K_i is the variable transfer factor of the mechanical integrator of the motor; the measured or identified quantities are referred to by the subscript m. A and B are the parameters of the differentiating element.

For ensuring a constant transfer factor K_i must be introduced as a divisor into the control circuit. But K_i cannot be measured directly. The identification method of Speth [38] sets out from the mechanical equation of the motor with the result of

$$K_i = \frac{\ddot{\omega}}{\dot{m}}. \tag{3}$$

An additional problem is that the torque m and the angular speed ω cannot be measured directly. The momentum m_m can be taken off the output of the element of time constant T_m. The measured angular speed ω_m is mixed with noise causing a considerable distortion after the twofold integration. Therefore the author suggests, instead of the direct division, the division scheme shown in the figure, where the signal K_m appears on the integrator output.

The second example in [38] presents the so-called logarithmic control for a loop control circuit of a reel drive. The basic system agrees with that of the preceding example. A deviation appears in the identifier, where the division is reduced to subtraction by applying nonlinearities of logarithmic characteristics and the logarithm of the quotient is retransformed by an element of exponential characteristic (Fig. 6). The nonlinear characteristics are simulated by transistors.

Raatz describes also the application of the adaptive control for solving a control task identical with the preceding ones [30]. The deviation appears

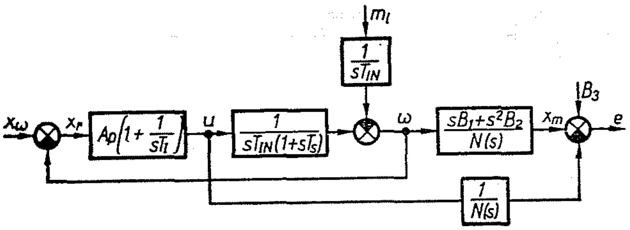

Fig. 3. Serial model identification of a controlled drive motor with subordinated current control [29]

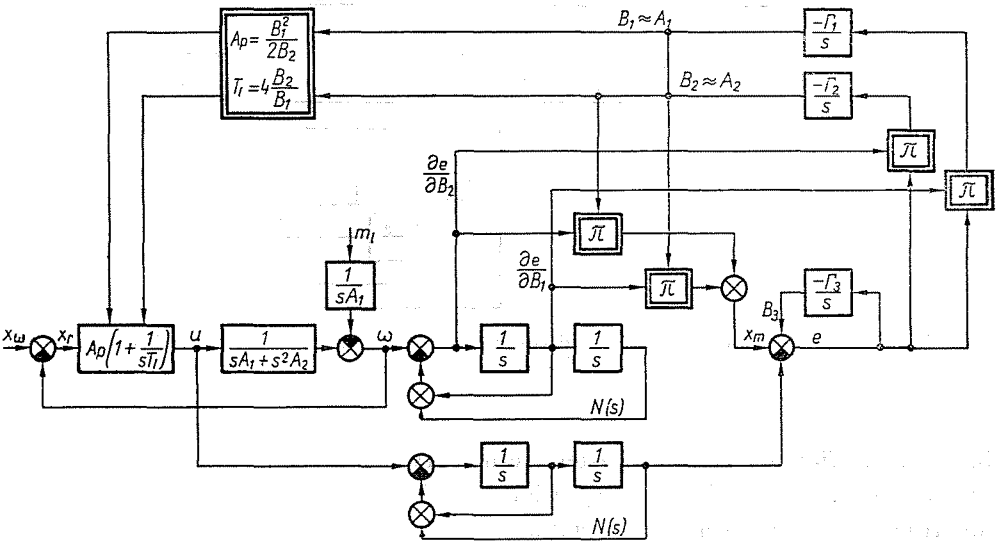

Fig. 4. Adaptive open loop angular speed control circuit with serial model identification of the motor [29]

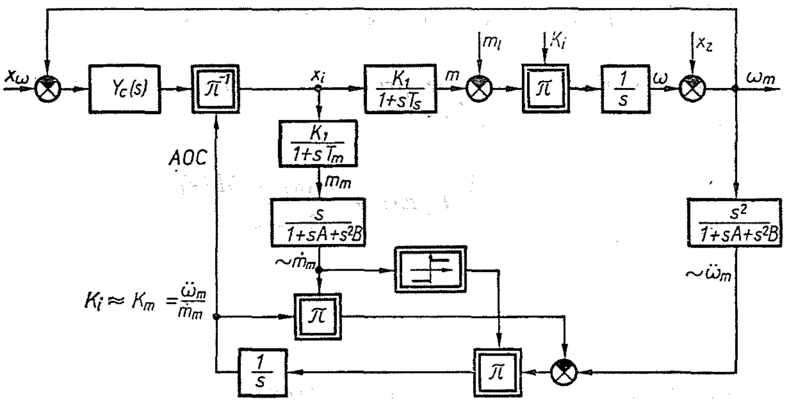

Fig. 5. Open loop angular speed control of a drive of variable moment of inertia [38]

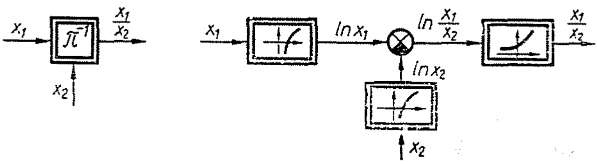

Fig. 6. Division of the analogue signals in the logarithmic control circuit [38]

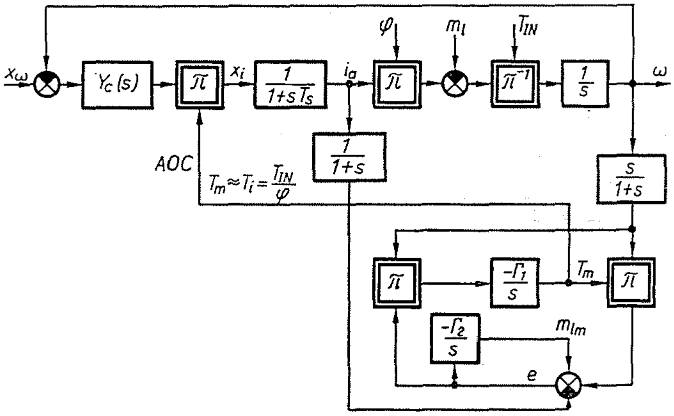

Fig. 7. Adaptive open loop angular speed control of a drive of variable flux and moment of inertia [30]

in the identification of the transfer factor between the current-angular speed of the motor. The resultant integration time $T_i = T_{IN}/\varphi$ is determined by an identifier based on a reciprocal serial model. On the basis of Fig. 7, the approximate LAPLACE-transform of the error signal $e(t)$ for slow parameter variations is

$$E(s) = T_m \frac{\Phi}{T_{IN}} \frac{I_a(s)}{1+s} - \frac{I_a(s)}{1+s} - \frac{T_m}{T_{IN}} \frac{M_l(s)}{1+s} + M_{lm}(s) . \tag{4}$$

The required variables may be produced on the basis of the gradient method [24, 29] by the following equations:

$$T_m(s) = -\frac{1}{s} \Gamma_1 E(s) * \frac{I_a(s) - M_l(s)}{(1+s) T_{IN}} \tag{5}$$

$$M_{lm}(s) = -\frac{1}{s} \Gamma_2 E(s).$$

T_m, as determined by Eq. (5) must be introduced by way of the multiplicator into the control circuit (Fig. 7).

3.1.2 *Varying parameters of the elastic coupling between the driven mass and the motor shaft*

The paper of WEBER [44, 46] describes the position control of the elevator cage of a deep mine shaft. The spring constant of the elastic coupling between the drum and the load varies upon the variation of the rope length, and the mass suspended on the rope varies upon the variation of the load. In the given case the natural frequency variation was 1:5, leading to instability. By applying adaptive control the position control circuit could be satisfactorily compensated.

RAATZ [31] describes the speed control of a drive coupled to the work machine by an elastic shaft. The controlled characteristic is the angular speed of the work machine. This arrangement is found with high capacity roll stands, where both rolls are driven by separate motors mounted on the same side. So the shaft of one of the motors is as long (~ 5 m) as to show an observable distortional deformation.

The control described in [31] is designed to prevent the output shaft vibration in spite of the low vibration damping system available in the control circuit. For the correct control the non-measurable motor angular speed and load momentum must be introduced into the control circuit. These signals may be taken from the model of the controlled path with the use of the observability of the system. The model is of constant parameter with sufficient a priori information. The vibrations of the system are damped in the unsaturated state of the current controller by the (essentially dual) control formed in this way.

3.1.3 *Warming-up of coils and control resistor*

Warming up is caused by the load and especially by overloads. The temperature variations lead to variations in the resistance of the corresponding coils. The operational warming up has generally no significant effect on the quality characteristics.

STRÖLE describes a case where high warming up occurred in the speed control liquid resistor (R_2) of the rotor circuit of a 3-phase lifter motor, i. e. not the coils themselves were warming up [35, 8]. The position control of the liquid resistor in the control circuit is subordinated to the speed control. The control circuit is basically nonlinear, as the quotient of the rotor voltage by the modified characteristic (R_2) is proportional to the current, or the momentum. This effect may be compensated by multiplying by the signal proportional to R_2.

With temperature variation (ϑ), the position of the electrode is not the measure any more of the resistance R_2, but it is completed by a nonlinear functional relationship $R_2(\vartheta)$. But this can be predetermined by measurement, so its effect may be compensated by the corresponding inverse nonlinearity, by temperature sensing.

According to the above, the speed control must be completed by two adaptive control chains [35].

Ref. [39] deals with the temperature-dependent operational behaviour of the control of an asynchronous machine supplied by an inverter. The heat transfer factor and the temperature coefficient of the rotor are also varying due to the speed-dependent thermal resistance of the air gap in the drive motor of high speed control range. All this leads to the variation of the static accuracy and the dynamic properties of the drive. In a presented example the stalling slip frequency increased e. g. to 28.5 c/s as a consequence of warming up.

3.1.4 *Varying characteristics of the reference signals and the disturbance effects*

Ref. [28] describes the environmental disturbance effects on the example of the control of a band roll train and the compensation by adaptive control based on a learning model. The aim of the control is to maintain the quality of the final product (roll and fine steel band) within a predetermined range.

The model (a mathematical model simulated on a computer) consists of two main parts, the mechanical and the thermal rolling models. Both parts of the model contain information concerning the quality of the steel, the dimensions and the temperature of the bloomed reel, as well as the geometrical and mechanical data of the roll train. The most important disturbance signals are the variations of the steel quality, the band temperature, the blooming dimensions and the condition of the roll train (wear, cooling down, warming up), deviating from the specified (expected) values. The desired final values are the prescribed thickness, the final temperature and the rolling speed of the sheet. During the rolling operation the weight, the temperature and the band thickness are measured.

Kiss [22] describes the control of the main drive of a fine band roll stand and of the roll adjustment and reel drives. Due to the low sheet thickness the tensile strength must be controlled. High productivity is reached by the exclusion of band breaks, therefore the unchanged quality characteristics must be maintained even under variable conditions. In the described solution of the control the current and angular speed control circuits of the drive system are adjusted to the variable conditions by an adaptive controller.

Ref. [21] proposes adaptive control for a coupled multimotor system. For instance, in the drive system of the band roll train the couplings vary with the sheet thickness variations and the band breakages, then the control algorithms must be changed by the adaptive controller.

The transfer function of the controlled path is affected also by the nonlinear characteristic of the load. For instance, the speed-dependent load momentum means the feedback of the mechanical integrator of the motor, while with the variation of the load momentum — angular speed transfer factor the transfer function involving the angular speed becomes work point-dependent. Extremal values of the m-characteristic may also occur, meaning the reversal of the sign of the linearized feedback factor. The frequency functions for this case are given in [18].

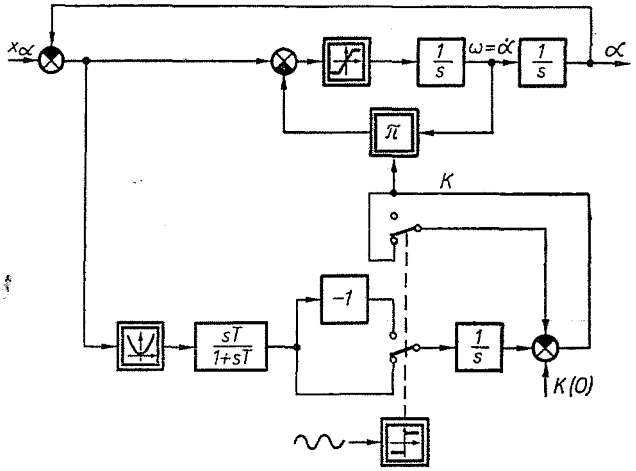

Fig. 8. Adaptive control of a servo-system with parameter perturbation [12]

The adaptive control of a servo-system is described in [12] demonstrating the existence of the relative error variance square extremal value depending on the transfer factor of the differentiating feedback, when the spectral width of the reference signal varies. The optimum feedback factor decreases with the increase of the spectrum width. The aim of the control is to minimize the square of the error variance for any input signal. So the adaptive control has to adjust the system to the minimum of the functional (variance square) by varying the differentiation feedback factor. This task has been solved by the parameter finding adaptive control (Fig. 8).

3.1.5 *Variation of the viscous damping*

Haberstock applied adaptive control to the optimum-time position control of the roll stop drive of a high performance, reversing roll stand [16], with the speed control subordinated to the position control and the torque control of the motor supplied by a rectifier subordinated to the speed control (Fig. 9). With the above mentioned assumptions the condition of the optimum-time operation according to [16] is the course

$$x_\omega = \sqrt{2\,\frac{T_2}{T_1}\,|M_{BM}|\;|x_r|\;\mathrm{sign}\;(x_r)} \tag{8}$$

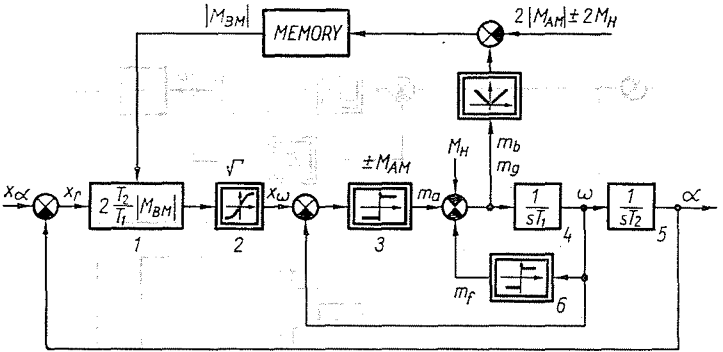

Fig. 9. Optimum-time position control completed by an open loop adaptive controller [16]

of the speed reference signal, where M_{BM} is the maximum brake moment, T_1 and T_2 are the drive characteristics. Eq. (8) is simulated by the blocks 1, 2 (Fig. 9). The torque may be identified by Eq.

$$M_{BM} = 2M_{AM} \pm 2M_H \;-\; M_{GM}\,. \tag{9}$$

Ref. [16] does not deal with the measurement of M_{GM}. The problems of the torque identification were bypassed by FRANKE, SCHIEFER, WEBER [14] and WEBER [45, 46] by utilizing the acceleration current peak for adaptive control.

An adaptive control has been suggested for the optimum-time position control also by PAVLIK and STRÖLE [27]. The optimum transition process is ensured by a quadratic feedback of the derivate of the controlled characteristic in the basic system. But in this case deflections around the equilibrium state appear after the optimum transition process due to the parasitic storages of the integrating elements. According to the authors the most favourable solution is a suboptimum control, with the feedback implemented through the proportional element, with a transfer factor depending on the reference signal, corresponding to an adaptation to the input signal.

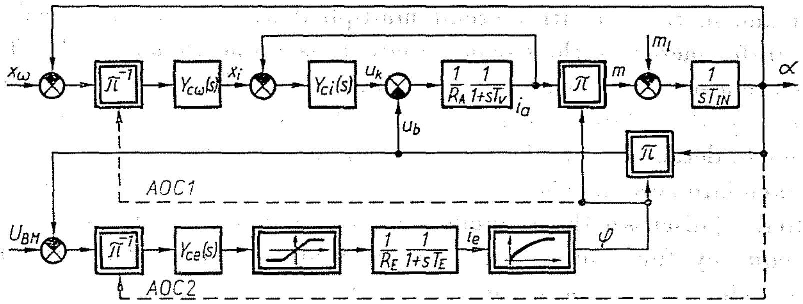

Fig. 10. Block diagram of an angular speed control performing the intervention by flux decrease as soon as the electromotor voltage is reached [34]

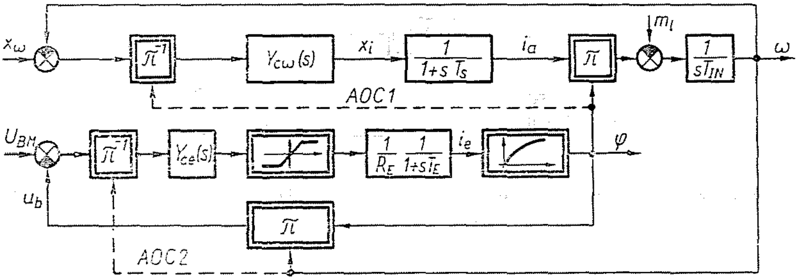

Fig. 11. Reduced block diagram [34]

3.2 *The property of the electrical machine, the construction of the control circuit and the mode of intervention as reasons for the application of adaptive control*

3.2.1 *Varying the speed by flux damping*

The speed of the externally excitated DC motors is varied up to the nominal speed by varying the terminal voltage with constant flux, and above the nominal speed by decreasing the flux at constant voltage. This type is necessary e. g. for the reel drives [22, 62].

The intervention by flux decrease over the nominal speed — i. e. a speed control to the maximum internal voltage U_{BM} of the motor — is shown in Fig. 9 [8, 34].

The control circuit of Fig. 10 contains three control loops: that of the speed control, the subordinated current control and the internal voltage control circuit, controlled completely up to the nominal angular speed. The transfer functions of the individual controls are — in the above sequence — $Y_{c\omega}(s)$, $Y_{ci}(s)$, $Y_{ce}(s)$. The current control circuit may be approximated by the first order lag element of the time constant T_S, so the flux variation appears according to Fig. 11 in two places: in the ω-control circuit multiplied by the armature current and in the u_b-control circuit multiplied by the angular speed. So the loop transfer factor of the ω-control circuit is proportional to the flux and that of the u_b-control circuit to the angular speed. These effects may be compensated by the adaptive control feedback shown by dashed line. **Ströle** examines in detail also the best location of the modification, with the restrictions taken into account [34].

Ref. [1] discusses the dynamic study of the modification with the generalized frequency function, giving precalculated diagrams for determining the time behaviour of the speed control circuit.

The papers of **Raatz** [30], **Rumold** and **Speth** [29] and **Speth** [38], referred to in chapter 3.1.2, deal with speed controls completed by an adaptive controller for compensating the varying transfer factor of the mechanical integrator of the motor. By these arrangements not alone the moment of inertia, but also the flux variation is compensated. But these systems are slower than that of **Ströle** [34], due to the necessity of identification.

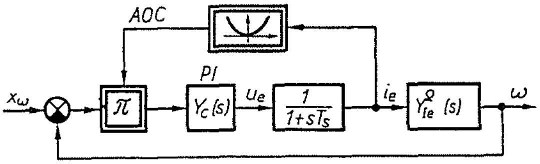

Fig. 12. Angular speed control with an open loop adaptive controller performing excitation circuit intervention [17]

Hugel [17] describes the speed control of an externally induced motor by the intervention implemented on the induction side. The studied system became unstable at the flux reduction of 1:3 ratio. The applied adaptive control varies the transfer factor of the PI speed controller proportionally to the square of the induction on current (Fig. 12), compensating well the work point dependence of the quality characteristics.

3.2.2 *Varying the flux for optimum control*

Previous papers [32, 35] deal with the minimum loss (minimum power) control in the static operational state. The optimum condition is given for the copper losses alone in [35], and for the copper and iron losses in [32]. Refs [25, 26] consider also the effect of the nonlinear magnetization curve. The obtained result showed that the optimum flux in the optimum mode of operation is described by the nonlinear equation

$$\Phi_0 = f_1(\sqrt{M}, \Omega) = f_2(I_A, \Omega) \tag{10}$$

where M is the armature torque, I_A the armature current and Ω the angular speed of the motor.

For realizing optimum control **Ströle** [35] suggested a system varying the flux and finding the minimum effective power consumption from the mains. But this suggestion disregards the fact that the effective power contains beside the loss also the useful power, so the operation of the finding system would be greatly impeded by the load variations. For eliminating this problem [25] and [26] produce — after determining the nonlinear function (10) — the optimum excitation in the knowledge of the magnetization curve, by the nonlinear element of the form

$$I_{EO} = f(I_A, \Omega). \tag{11}$$

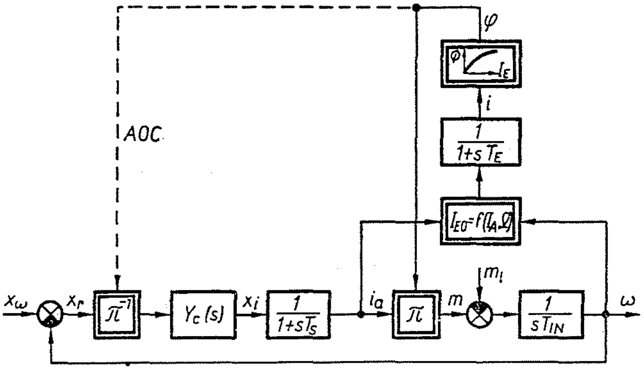

Fig. 13. Optimum flux shunt motor drive [25, 26]

(Fig. 13). The effect of the variable flux is compensated also here by the known adaptive control. The minimum loss control based on the flux variation may be attained only for the static state due to the delaying effect of the time constant of the induction circuit.

3.2.3 *The speed control of the serial motor drives*

In general, for controlled drives the externally induced DC motors of favourable control-technical properties are used. But for controlled current drives of lower static and dynamic requirements the serial motor may be more economical [3] as the serial coil may replace the smoothing choke altogether, but it reduces it in any case. An additional advantage is the absence of the induction circuit rectifier and the higher torque overload capacity of the serial motor, while a significant disadvantage is the work point dependence of the parameters.

The block schemes linearized for low variations of the externally induced and the serial motors are identical, but their parameters are different (Table 2).

Table 2

Parameters of the 3.5 kW DC motor of type GMB4 (VEB Elbtalwerk Heidenau) [3]

Parameter	External excitation	Serial excitation
$1/R_A$	5.6	0.55 – 5.6 (2.4)
T_V	12.4 ms	2.4 – 24.5 ms (5.2 ms)
C_1	1	0.41 – 1.3 (1.3)
C_2	0.22	27 – 0.17 (0.4)
T_M	0.28 s	34 – 0.21 s (0.5 s)

Ref. [3] gives the parameters of a serial motor in both modes of operation for the block diagram of relative units shown in Fig. 14. The external excitation corresponds to the nominal constant excitation. The nominal work point values for serial induction appear in brackets after the variation range of the parameters.

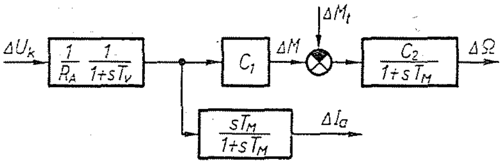

Fig. 14. Reduced block diagram of a DC motor for low variations [3]

As the parameters vary over a wide range, the serial motor drive may be applied for constant work point operation, or supplied with an adaptive controller. Similar problems arise with the application of noncompensated machines due to the retroaction of the armature, and with the double induction machine systems [42].

One reason for the application of the serial motor is its suboptimum character as to the motor losses; namely the flux of the serial motor varies with the armature current, so it approximates the optimum flux value given by Eq. (10), as referred to also in [26].

Refs [8] and [34] describe the speed control of serial motors. Neither of these papers discusses the reason, or the aim of the application of serial motors.

STRÖLE points out the possibility of applying an adaptive controller on the basis of his model experiments performed with the help of an analogue computer [34]. The block diagram of the speed control circuit, with assumed fast subordinated current control and a linear magnetization curve, and with the time constant of the eddy-current circuits and other secondary effects neglected, is shown in Fig. 15. The additional multiplication by the current

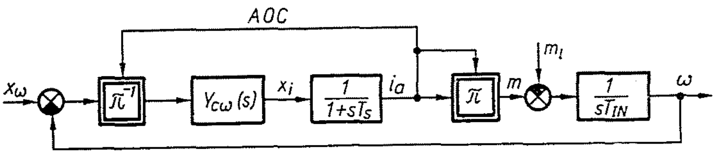

Fig. 15. Serial motor angular speed adaptive open loop control [34]

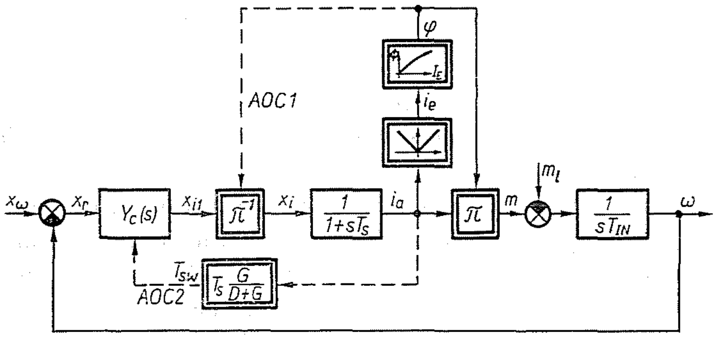

Fig. 16. Serial motor controlled drive completed by two adaptive open loop controllers [26]

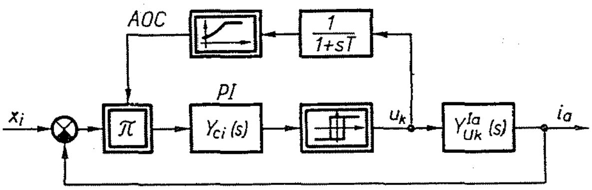

Fig. 17. Two-stage current control of a serial motor fed by a DC chopper, with an adaptive open loop controller [17]

at the torque formation point is compensated by the division before the controller. Yet a high initial overshot in the unit step response of the analogue model due to the existence of power storages between the points of the parameter variation and the modification is observed.

Assessing the adjustment conditions with due allowance for the above results in a substantial improvement [25, 26]. Accordingly not alone the transfer factor of the controller, but also its corresponding time constant must be varied depending on the work point (Fig. 16).

Ref. [17] discusses the current control circuit of a serial motor supplied with a DC chopper. The two-position control circuit of the armature current shows a work point-dependent stability. The author suggests, on the basis of analogue computer simulation, the application of an adaptive control for varying the transfer factor of the PI-controller through a nonlinear element, by measuring the output voltage of the interrupter (Fig. 17).

3.2.4 *Varying the flux according to the technological requirements*

Typical examples of the variable flux control circuits containing work point-dependent controlled sections are given in [13, 40, 22]. Several examples of the adaptive control for flux variation compensation were presented in the preceding chapters.

3.2.5 *The current control of rectifier fed motors in the continuous and the intermittent current ranges*

The reversing DC drives are generally supplied by cross-, or anti-parallelly connected four-quadrant rectifiers, operable with, or without circular currents, depending on their control.

In circuits with no circular current the operation of the current control changes substantially at the boundary between the continuous and the intermittent current ranges. The current control circuit is closed during the continuous current conduction and is open during the conduction pause, i. e. it becomes a work point-dependent loop amplifying system with dead time [4]. The structural variation of the control circuit necessitates a self-organizing type adaptive control for changing the control algorithm. Reference to this is made in several studies [27, 34, 30, 21, 7, 43], while the modes of its realization are treated by others [4, 5, 6, 15, 11, 41]. The first solution in principle was described by BUXBAUM [4], with the effective realization given in [6]; a substantially identical variety was published by ČERNÝ [11], while other solutions were supplied by GOLDE and RIEBSCHLÄGER [15] and SEEFRIED [41].

The adaptive current controller must be a PI-type controller for the period of the continuous current and an I-type controller of work point-dependent integration time for the intermittent current. Various authors approximated this condition in various ways.

In BUXBAUM's solution the controller consists of two parts: a PD element and an integrator connected serially to it. The PD element, — after shorting the differentiating capacitor by the electronic switch (FET) — becomes a P-element with the result that the controller changes from a type PI-controller to a type I-controller. The structure is changed over by the comparator, controlled by the rectifier current in a way that under a determined signal level it performs the I-function and over this level the PI-function (Fig. 18). This means that the controller has a pulse width modulated structure. This solution is very favourable, as it eliminates the necessity of the circumstantial boundary sensing of the intermittent current range. The output integrator ensures that no jump in the output signal is caused by the structural change-over. According to experiences on already realized current controls, the continuous adjustment of the variable gain in the range of the intermittent current is not necessary.

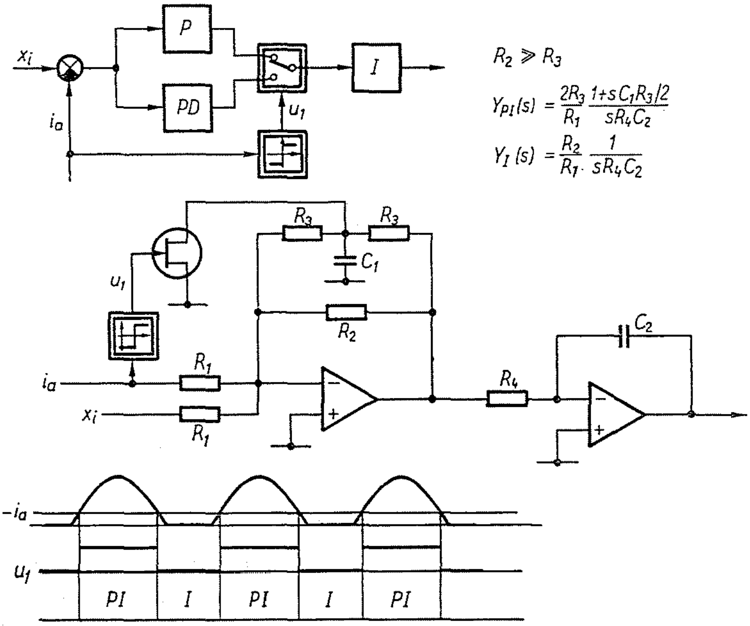

Fig. 18. Adaptive current controller [6]

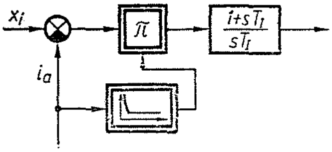

Fig. 19. Adaptive current controller [41]

GOLDE and RIEBSCHLÄGER apply a PI-controller, but in the intermittent current range they linearize the control circuit by a $\sqrt[3]{I_{AV}}$ function generator connected in parallel with the current controller [15], while SEEFRIED [41] increases the gain of the controller as soon as the intermittent current appears (Fig. 19).

Ref. [41] gives the results of a comparative measurement series performed over a 200 kW drive, showing well the necessity of the adaptive current control (Table 3).

We have found a reference to the adaptive current control for a drive with no rectifier. ZENTAI applied for controlling the armature current of the reversing WARD—LEONARD drive of a roll stand a PI-controller of an integration time constant varying proportionally to $1/\Phi^2$. This compensates the variation of the parameters of the excitation circuit [48].

Table 3

Current control comparison of 200 kW drives with current controller of various types [41]

Current controllers	Control time	
	for intermittent currents	for continuous currents
PI-type, non-adaptive	3800 ms	12 ms
PI-type, adaptive of BUXBAUM	6 ms	7 ms
PI-type, adaptive of SEEFRIED	6 ms	13 ms

3.2.6 *The speed variation of the generator drive of controlled terminal voltage as the disturbance effect*

HUGEL describes the adaptive voltage control circuit of vehicles, where the generator is connected to the vehicle main drive, so its speed is a function of the driving speed [17]. As the voltage control circuit amplification is proportional to the driving speed, i. e. the generator speed, the circuit can be compensated by division by the tachometer signal. This corresponds to a voltage control completed by an open loop adaptive controller. The power control of the synchronus machine leads to a wholly similar structure [17]. The effective power is the product of the voltage by the effective component of the current and this nonlinearity can be compensated by division before the subordinated voltage control loop by the control signal.

3.2.7 *The control circuit compensation varied by the saturations*

Certain compensation effects are ineffective, mainly in system compensated by PID and PD-type controllers due to the signal limitations at high reference signal and interference signal jumps. Ref. [27] suggests the open loop adaptive controller for the elimination of this failure.

The limitation of the signals may be regarded in fact as a structural variation of the system [20], so a self-organizing adaptive controller must be applied.

4. Conclusion

The majority of the electric machine systems are electric drive. Accordingly the literature of the adaptive control of the electric machine systems deals nearly exclusively with electric drives of adaptive control. From among the discussed references the voltage and power control treated in [17] alone are other than drive systems. On the basis of the special literature it can be stated that mainly open loop adaptive drive controls are applied. This development is due to alone to the speed demands of the drive controls, but also to the absence of sufficient a priori data for the design of controls with open adaptive action chains. A non-negligible fact is also the simpler implementation of the open loop as compared to the closed loop adaptive control, permitting not alone a cost reduction, but what is still more important, a higher reliability as well.

Especially numerous references are found on two adaptive drive controls. These are the speed control of the (generally reel) drive of variable flux and moment of inertia and the current control of the DC motor fed by a rectifier. The rest of the adaptive drive controls is rather specific.

The future trend of the development will be probably characterized by the nonlinear feedback of identical rate with the basic control system rather than by non-identical rate adaptive controls. For creating the closed loop adaptive control the method of modelling appears to be most appropriate, due especially to the favourable operation speed attained as a consequence of ample information available in the model [23]. The working speed may be increased mainly by selecting the predominant characteristics, as allowing for too many effects requires a highly complicated controller of a longer operation time than permitted by the technology [28]. The application of typically slow operation adaptive controllers for the electrical drives cannot be expected in the future either. A principal reference to the same is the most that can be found, as e. g. the adaptive control of STRÖLE based on the calculation of the correlation function for minimizing the effects of the disturbance signals [36].

Outstanding among the authors in the field of the considered thematics are BUXBAUM, STRÖLE, SPETH and WEBER.

5. Acknowledgements

The author expresses his thanks to Professor Dr. Frigyes Csáki, who contributed greatly to the preparation of this paper by his most helpful support.

Summary

After the brief survey of the adaptive systems, the necessity and the aim of the application of adaptive control in electrical drives are discussed. The paper gives a systematic summary of the literature, presenting some typical examples and characteristic details too.

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