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A SURVEY OF THE POWER SYSTEM CONTROL PROBLEM

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ABSTRACT

The problem of stabilization and control of power systems represents an important field for power systems control engineers. Several techniques have been developed in the literature, to solve this problem. Integrated single-level techniques and hierarchical techniques are considered the two main categories.

In this paper, a survey of these methods is presented. Advantages and drawbacks of each are given. A recently developed method of decomposition-coordination which leads to a partial feedback control laws is also included.

An application to a power system, for comparing the computational time of each method, shows the effectiveness of hierarchical techniques over the single level techniques.

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1. INTRODUCTION

The problem of stabilisation and control of power systems represents an important field of investigations for power systems control engineers. The problem given in this domain of application are widely varied and useful for training purposes. An elementery system of production of energy, like a synchronous machine, is considered as a process having non-linearities with undamped complex poles. For a group of turbo-generators, the problems resulting from variation of mechanical torque or by change of structure due to short-circuits on the line must be taken into account.

Several techniques were proposed, either by using the classical methods[1] of automatic control, or by utilising the optimal control [2-12]. It is found clearly that the second approach is well adapted for treating the non-linear problems and for those requiring the design of output feed-back controllers. However, a certain number of difficulties in this approach appear and especially in the on-line implementation. Hierarchical techniques [13-17] have been recently used to overcome some of these difficulties.

This paper presents a comprehensive survey of the main different techniques, developed in the literature, for solving these types of problems stating the difficulties due to their applications.

2. REVIEW OF POWER SYSTEM CONTROL PROBLEM

The problem of the control of an electric power system, like any dynamical system, depends not only on the nature of the equations describing this system, but also on its dimension. The power system models are often linearised to allow the application of classical methods for multi-variables systems control, leading to centralised control laws. Since a synchronous machine or a turbo-generator may be considered as a severly non-linear system, it was necessary to develop optimisation methods that do not require these two limiting assumptions. The behaviour of the dynamical system is characterised by a performance index that must be minimized.

The methods which are developed in the literature for dealing with the power system control problem may be classified into two main categories:

1. integreated single-level techniques.
2. hierachical techniques.

In this paper the details of the main methods used to design centeralised and hierarchical control structures are given.

3. INTEGRATED SINGLE LEVEL SOLUTIONS FOR DYNAMIC OPTIMISATION OF POWER SYSTEMS

3.1. Non-linear Optimisation

The objective here, is to solve the optimisation problem given by:

$$\text{Min} \quad J = \int_{o}^{t_f} g\ (x,u,t\ )dt \tag{1}$$

Subject to the dynamical constraints:

$$\dot{X}(t) \quad = f\ (x,u,t) \tag{2}$$

where x and f are n vectors, g is a scaler and u is an m vector.

This problem may be solved using either the pontryagin's. Maximum principle (P.M.P) [2] or Dynamic programming approach [2]. On using P.M.P. it is necessary to define a Hamiltonian function:

$$H(x(t),\ u(t),\ \lambda(t),\ t) = g(x(t),u(t),t)+\lambda^{t}(t).\ f(x(t),u(t),t) \tag{3}$$

where λ is a lagrange multiplier.

The optimal states and controls solutions must satisfy the necessary conditions:

$$\dot{X}(t) \quad = \frac{\partial H}{\partial \lambda} = f(x,u,t) \tag{4}$$

$$\dot{\lambda}(t) \quad = -\frac{\partial H}{\partial X} \tag{5}$$

$$\frac{\partial H}{\partial u} \quad = 0 \tag{6}$$

$$X(t_o) \ = X_o \tag{7}$$

and $$\lambda(t_f) \ = 0 \tag{8}$$

It is obvious that the use of P.M.P leads to a well-known two-point boundary value problem (T.P.B.V.P) which requires solving the differential equations (4,5,6) subject to known initial and terminal conditions [7,8].

When an open loop solution is desired, an iterative technique called "gradient method" [6] is used to solve the T.P.B.V.P. A quasi-linearisation technique, used by Makhopadhyay and Malik [3], for solving the optimisation problem may be applied to obtain partial feed-back control laws which are preferred for practical implementation. This technique suffers from divergence of the algorithm if the initial guess trajectory is not well selected. Also difficult calculations appears for higher order models. Therefore necessary modifications of this technique must take place to be adapted to the more realistic systems. In a general case, it is impossible to obtain closed loop solutions. It has been noted that a closed-loop control may obtained when using dynamic programming approach if the Hamiltonain Jaccobi equation can be solved [2] . In the last approach the obtained solution is globally optimal solution.

A simultaneous control in the field excitation and the turbine input is used to improve the transient performance by dynamic optimisation techniques. Second order algorithms based on continous form of differential dynamic programming [4] are employed to calculate the optimum controls for the minimisation of a quadratic integral performance index. An optimal control of non-linear power systems by an imbeding method has been proposed in [5].

The non-linear dynamical systems are often linearised to allow the design of optimal closed loop feedback control laws.

3.2. Linear System Dynamic Optimisation

3.2.1. Control laws depending on the system states

In this case, the system model may be described by the state equation.

$$\dot{X}(t) = A\,x(t) + B\,u(t) \tag{9}$$

The cost function to be minimised may by given by

$$J = \tfrac{1}{2}\int_{t_o}^{t_f} [\,x^t(t)\,Q\,x(t) + u^t(t) R\,u(t)]dt \tag{10}$$

Under these assumptions, a closed loop feedback control law $u(t) = G(t)\ x(t)$, is obtained. The gain matrix $G(t)$ is given by:

$$G = -\,R^{-1}\,B^t\,P(t) \tag{11}$$

where the matrix $P(t)$ is given by the Riccati equation

$$\dot{P}(t) = -\,P(t)A - A^tP(t) + P(t)\ BRB^tP(t) - Q$$

$$\text{with} \quad P(t_f) = 0 \tag{12}$$

The obtained control laws are function of the system states, accordingly the control structures require observers for states reconstructing. In addition, the numerical calculation of an exact optimal control is impacticable for large scale system. Anderson et al [8] have designed the integrated optimal control for linear and non-linear models, while El-Metwally et al [7] have obtained satisfactory experimental results on the implementation of an optimal control for synchronous machines.

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3.2.2. Control laws depending on the output

In this section, we are concerned with generating the control variables instead of reconstructing the states via Kalman filter or state observers.

The optimisation problem begins with a time-invarient system given by:-

$$\dot{X}(t) = A\,x(t) + B\,u(t)$$

$$y(t) = C\,x(t) \qquad (13)$$

A reasonable measure may be selected such that

$$J = \tfrac{1}{2} \int_{0}^{\infty} [x^{t}(t) Q\, x(t) + u^{t}(t) R\, u(t)]\, dt \qquad (14)$$

The constraint on u(t) may be generated via output linear feedback with a time-invarient feedback gains, i.e.:

$$u(t) = - Fy(t) = - FC\,x(t) \qquad (15)$$

where F is the gain to be determined. Combining (13) and (15) leads to:

$$\dot{X}(t) = (A - BFC)\,x(t) \qquad (16)$$

Athans and Levine have proposed the first technique to solve this problem [9]. Different algorithms [10,11] have been also proposed depending on the selection of stabilising initial gain matrix F° Such that $A = (A - BF^{\circ}C)$ is stable. These algorithms are based on direct search of these matrices by using gradient techniques or others. It is evident that these techniques need too much computational time for convergence. These algorithms are also impractically realised for the case of large scale systems where the gain matrices are of large dimensions. Amongst the investigations concerned with the design of optimal output feedback control laws for power systems, one can mention the work achieved by Davison et al [12].

4. DYNAMIC OPTIMISATION ADOPTING HIERARCHICAL THCHNIQUES

It has been seen that the hierarchical methods are basically more attractive than the previous global methods since at any stage low order sub-problems are manipulated. This makes the calculations more accurate since manipulations on low order sub-problems ensure that the truncation and rounding-off errors are smaller. In this case a hierarchy of computers operates independently, and a higher one coordinates the local optimal solutions in an iterative fashion in order to achieve the overall optimum. It is also quite evident that the hierarchical optimisation may lead to computational saving in both storage and computer time. Amongst these techniques are the methods given in [6,13,14] which are characherised by the simplicity of the corresponding algorithms. These techniques are often limited to off-line computations of open-loop control laws.

A recently developed method [15-17] of decomposition coordiation leads to a partial feedback control laws which are always feasible. In this approach the optimisation problem may be formulated as:

$$\min_{u} \sum_{k=0}^{K} J(x_{k+1}, u_k)$$

$$\text{Subject to } x_{k+1} = f(x_k , u_k) \tag{17}$$

The principle of this method depends on the decomposition of the criterion in the following manner:

$$J = J_k + \bar{J}_k \tag{18}$$

where J_k is a local criterion which is chosen arbitrarily and $\bar{J}_k$ represents that part of criterion $J(x,u)$ not relained in the local criterion.

The optimal control may be obtained by applying the stationarity conditions:

$$\frac{\partial J_k}{\partial u_k} + \frac{\partial \bar{J}_k}{\partial u_k} = 0 \quad \forall \quad k = 1, \ldots K \tag{19}$$

Now, we have K sub-problems, which can be made independent by assuming that $\partial \bar{J}_k / \partial u_k$ is constant or

$$\rho_k = \partial \bar{J}_k / \partial u_k \qquad \forall \quad k = 1, 2, \ldots K \tag{20}$$

where ρ_k is the cordination vector, colculated in the upper level, and of the same dimension as control vector

Thus the local subproblems

$$\frac{\partial J_k}{\partial u_k} + \rho_k = 0 \quad \forall \quad k = 1, 2, \ldots K \tag{21}$$

can be thought of the results of another optimisation problem, since each optimal control vectrol u_k minimises the local criterion $C_k = J_k + \rho_k^t u_k$

This is true if J_k is a convex function. It is proposed to replace the initial problem by K subproblems:-

$$\min_{u_k} C_k = J_k + \rho_k^t u_k ;$$

$$f(x_k , u_k) = 0 \tag{22}$$

The details of this new method is given in [16,17].

Amongst the several advantages of this technique are the possibility of realisation of new on-line control structres depending on this approach and the robustness to disturbances.

5. TEST EXAMPLE

A 6th order model of a turbogenerator , given in refererce[3], has been taken as a test example for comparing the computation time required to achieve the objective:

$$\underset{u}{\text{Min}} \quad J = \int_{o}^{t_f} [A_1(x_1-x_f)^2+A_2(x_3-x_{3_f})^2+A_3(u_1-u_{1_f})^2 + A_4(u_2-u_{2_f})^2]dt$$

Subject to:

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_5/M-c_1x_2-(c_2.\ \sin x_1)x_3-\tfrac{1}{2}\ c_3 \sin 2x_1 \\
\dot{x}_3 &= x_6-c_4x_3+c_5.\ \cos x_1 \\
\dot{x}_4 &= k_1.u_1-k_2x_2-k_3x_4 \\
\dot{x}_5 &= k_4x_4-k_5x_5 \\
\dot{x}_6 &= k_6.u_2-k_7.x_6
\end{aligned}$$

where

$x_1 = \delta$; rotor angle in radians

$x_2 = \frac{d\delta}{dt}$

$x_3 = \Psi_f$; field flux linkage of the machine

$x_4 = P_s$; shaft power

$x_5 = T_m$; mechanical troque.

$x_6 = e_{fd}.\ \frac{x_{md}}{r_f}$

where

e_{fd} ; field voltage, x_{md}; direct magnetising reactance and r_f; field resistance

This problem is solved by different techniques. the paragraphs below gives a comparison between the different cases.

6. COMPARISON BETWEEN THE NON-LINEAR DYNAMIC OPTIMISATION TECHNIQUES AS APPLIED TO POWER SYSTEMS

We shall present here some of the results obtained from applying the above-mentioned techniques, namely: gradient, quasilinearisation, dynamic programming and hierachical methods.

The non-linear six order power system model, developed in reference [3], has been used for testing these techniques.

It has been shown that quasi-linearisation technique is more advantageous than the gradient dynamic programming techniques since:-

1) it gives partial feedback solutions utilising considerably less computer time compared to the open-loop solutions obtained by the gradient methods. However the core requirements for this method is greater than those of gradient methods extept if t_f is large enough.
2) it results in fast convergence, while the gradient method disadvantage lies in its inherently slow rate of convergence.
3) the modified quasi-linearisation techniques do not need any storage while the differential programming reguires the storage of certain solutions which may create a problem if it is required to use smaller step lengths.

On the other hand, the hierarchical techniques have advantages in both storage and computation time over the integrated single-level solutions. These techniques lead to more accurate calculations since the truncation and rounding-off errors are smaller. Morever most of these techniques are characterised by the easiness of the solutions of the subproblems at the different levels.

Using the same six order model, it has been found that the gradient methods require more than 60 iteration and 218 seconds of computer time to reach a convergence accuracy of 1×10^{-4} where as the hyprid quasi-linearisation approach, aided by continuation technique reachs an accuracy of 5×10^{-5} in 8 complete iterations with a computing time of 153 seconds on a CDC 6400 computer.

On the other hand, using Differential Dynamic Programming to optimise the same model, Iyer and Cory [4] found a difficulty in obtaining a proper set of the weighting cofficients in order to avoid instability. When the same example is dealt with the proposed hierarchical technique [16], the respective algorithm proved the convergence accuracy of 1×10^{-4} in 6 iterations which took 5.2 seconds executed on an IBM 370/165 computer.

7. CONCLUSIONS

A comprehensive review for power system control problem has been presented. This review gives briefly the different techniques mainly used for dynamic optimisation of non-linear and linearised power systems. It has been clearly shown that most of the hierachical techniques are characterised by the simplicity of the corresponding algorithms. It also quite evident that these techniques yield to computational saving in both storage and computing time. This ensures the effectiveness of these techniques to solve power systems optimisation problems.

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