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DESIGN OF STABILIZING SIGNALS BY USING MODEL PREDICTIVE CONTROL

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Abstract- This paper investigates the ability of Model Predictive Control (MPC) in coordinate design of two Power System Stabilizers (PSSs) and a supplementary controller for Static Var Compensators (SVC) to damp the power system inter-area oscillation. For this the parameters of the PSSs and the supplementary controller are determined simultaneously by a method in MPC, known as Generalized Predictive Control (GPC). The numerical results are presented on a 2-area 4-machine system to illustrate the feasibility of GPC algorithm. To show the effectiveness of the designed controllers, a three phase fault is applied at a bus. The simulation study shows that the designed controller by GPC performs well.

Keywords: Model Predictive Control, Generalized Predictive Control, Low-Frequency Oscillations, PSS, SVC.

I. INTRODUCTION

Due to rapid development of the power electronics industry, an increasing number of high power semiconductor devices are available for power system applications. These devices have made it possible to consider an attractive technology such as the Flexible AC Transmission System (FACTS) for power flow control and damping of power system oscillations.

Poorly damped low-frequency (0.1–3 Hz) oscillations are inherent in inter-connected power systems. In the last three decades, the applications of FACTS devices for damping inter-area oscillations have been investigated and proven to have additional benefits for increasing system damping, in addition to their primary functions, for instance, voltage control and power flow control. These devices are usually installed on transmission lines and, therefore, have direct access to the variables, which have the highest sensitivity to the inter-area oscillatory modes [1]. Many modern control techniques have been adopted around the world to design a supplementary controller for FACTS devices [2]-[19].

PID is the most commonly used control algorithm in the process industry. Also, this technique is employed to the control of FACTS devices [2]. However, the non-linear nature of the FACTS devices and the other power system elements, as well as the uncertainties which exist in the system make it difficult to design an effective controller for the FACTS devices that guarantees fast and stable regulation under all operating conditions. This problem has led to study of applying adaptive controllers, non-linear controllers, intelligence control and robust control in the power system stability control. The work carried out in [3]-[19] are examples of such studies.

In this paper, an alternative design is considered by using Model predictive control (MPC). MPC refers to a class of computer control algorithms that utilize an explicit process model to predict the future response of a plant [20]. At each control interval an MPC algorithm attempts to optimize future plant behavior by computing a sequence of future manipulated variable adjustments. The first input in the optimal sequence is then sent into the plant, and the entire calculation is repeated at subsequent control intervals.

Some of the popular names associated with model predictive control are Dynamic Matrix Control (DMC), Generalized Predictive Control (GPC), etc. While these algorithms differ in certain details; the main ideas behind them are very similar. The concept of MPC is used in power system in [21]-[25] by using different algorithms. In this paper, the authors used the concept of GPC to simultaneous design of two PSSs and a supplementary controller for Static Var Compensators (SVC) to damp oscillations.

II. OVERVIEW OF GPC

Most control laws such as PID, do not explicitly consider the future implication of current control actions. To some extent this is only accounted for by the expected closed-loop dynamics while MPC explicitly computes the predicted behavior over some horizon. The MPC process has the following elements:

1. Prediction. The future behavior of the system is predicted for a certain time horizon. The prediction is based on: the current state of the system, the expected disturbances and the planned control signal.
2. Performance evaluation**.** The performance is evaluated according to a user specified objective function. This objective function is typically based on:
- the (evolution of the) states and outputs of the system during the prediction period,

- planned control signal, since some signals may be more desirable than others (e.g., signals with frequent variations or higher cost may be less desirable).
3. Optimization. The controller finds the control signal that optimizes the objective function.
4. Control action. The first sample of the optimal control signals is applied to the process.

The remaining part of the control signal is recalculated in the rolling horizon scheme. In this scheme the optimal control signal is recalculated every controller sample step to take into account the unpredictable disturbances and the prediction error. The controller sampling time is typically many times smaller than the prediction horizon. For each recalculation the start and the end of the prediction horizon is shifted. The basic concept of a MPC method is shown in Figure1.

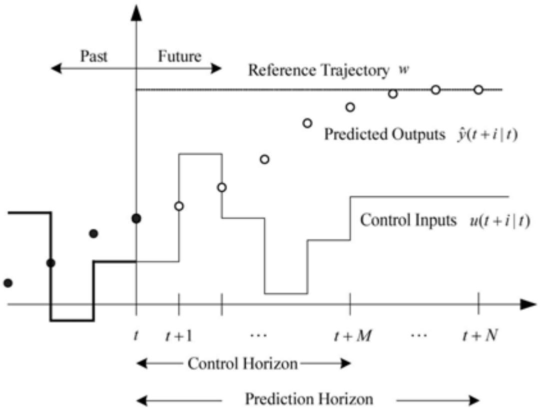

Figure 1. A Model Predictive Control method

A brief description of GPC is given below.

The basic idea of GPC is to calculate a sequence of future control signals in such a way that it minimizes a multistage cost function defined over a prediction horizon. The index to be optimized is the expectation of a quadratic function measuring the distance between the predicted system output and some predicted reference sequence over the horizon plus a quadratic function measuring the control effort.

For a plant with the control signal $u(t)$, output sequence of the plant $y(t)$ and a zero mean white noise $e(t)$, the integrated controller Auto-Regressive Moving-Average (CARIMA) is given by:

$$A(z^{-1})y(t) = z^{-d}B(z^{-1})u(t-1) + C(z^{-1})e(t) \tag{1}$$

with $\Delta = 1 - z^{-1}$, in which A, B and C are given by:

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_{na} z^{-na} \tag{2}$$

$$B(z^{-1}) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_{nb} z^{-nb} \tag{3}$$

$$C(z^{-1}) = 1 + c_1 z^{-1} + c_2 z^{-2} + \cdots + c_{nc} z^{-nc} \tag{4}$$

In order to obtain the predicted out put, the Diophantine equation is used as follows:

$$\begin{gathered} 1 = E_j(z^{-1})\tilde{A}(z^{-1}) + z^{-j}F_j(z^{-1}) \\ \tilde{A}(z^{-1}) = \Delta A(z^{-1}) \end{gathered} \tag{5}$$

where the polynomials of F_j and E_j are defined according to the polynomials of A and prediction horizon. The best prediction of $y(t+j)$ is:

$$\begin{gathered} \hat{y}(t+j|t) = G_j(z^{-1})\Delta u(t+j-1) + F_j(z^{-1})y(t) \\ G_j(z^{-1}) = E_j(z^{-1})B(z^{-1}) \end{gathered} \tag{6}$$

GPC minimizes the following multistage cost function:

$$\begin{gathered} J(N_1, N_2, N_u) = \sum_{j=N_1}^{N_2} \delta(j)[\hat{y}(t+j|t) - w(t+j)]^2 \\ + \sum_{j=1}^{N_u} \lambda(j)[\Delta u(t+j-1)]^2 \end{gathered} \tag{7}$$

where $\hat{y}(t+j|t)$ is an optimum j-step ahead prediction of the system output on data up to time t, N_1 and N_2 are the minimum and maximum costing horizons, N_u is the control horizon, $\delta(j)$ and $\lambda(j)$ are weighting sequences, $w(t+j)$ is the future reference trajectory.

Based on the equation (6) a set of j ahead optimal prediction can be defined as:

$$\begin{gathered} \hat{y}(t+1|t) = G_1(z^{-1})\Delta u(t) + F_1(z^{-1})y(t) \\ \hat{y}(t+2|t) = G_2(z^{-1})\Delta u(t+1) + F_2(z^{-1})y(t) \\ \vdots \\ \hat{y}(t+N|t) = G_N(z^{-1})\Delta u(t+N-1) + F_N(z^{-1})y(t) \end{gathered} \tag{8}$$

Therefore the following equation exists:

$$Y = GU + F \tag{9}$$

where

$$Y = [y(k+1), y(k+2), \cdots, y(k+N)]^T \tag{10}$$

$$U = [\Delta u(k), \Delta u(k+1), \cdots, \Delta u(k+N_u-1)]^T \tag{11}$$

$$F = [f(k+1), f(k+2), \cdots, f(k+N)]^T \tag{12}$$

$$G = \begin{bmatrix} g_0 & 0 & \cdots & 0 \\ g_1 & g_0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ g_{N_u-1} & g_{N_u-2} & \cdots & g_0 \\ \vdots & \vdots & & \vdots \\ g_{N-1} & g_{N-1} & \cdots & g_{N-N_u} \end{bmatrix} \tag{13}$$

The cost function defined in (7) can be written as:

$$J = (Gu + f - w)^T (Gu + f - w) + \lambda u^T u \tag{14}$$

The minimum of J can be found by making the gradient of J equal to zero which leads to:

$$u = \left(G^T G + \lambda I\right)^{-1} G^T (w - f) \tag{15}$$

The control signal that is actually sent to the process is the first element of vector u, which is given by:

$$\Delta u(t) = k(w - f) \tag{16}$$

where k is the first row of matrix $\left(G^T G + \lambda I\right)^{-1} G^T$. Also, the future reference trajectory can be defined as:

$$w(t) = y(t) \tag{17}$$

$$\begin{gathered} w(t+k) = \alpha w(t+k-1) + (1-\alpha) r(t+k) \\ k = 1, 2, \cdots, N \end{gathered} \tag{18}$$

where r is the set point and α is a value in the [0,1].

III. STUDY SYSTEM

A 2-area-4-machine system is used. This test system is illustrated in Figure 2. The subtransient model for the generators, and the IEEE-type DC1 and DC2 excitation systems are used for machines 1 and 4, respectively. The IEEE-type ST3 compound source rectifier exciter model is used for machine 2, and the first-order simplified model for the excitation systems is used for machine 3.

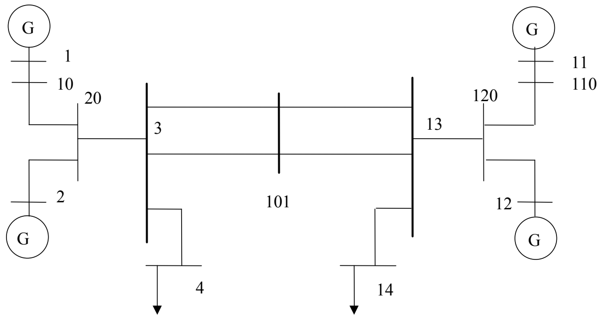

Figure 2. Single-line diagram of a 2-area study system

Two PSSs are going to be designed using MPC for the above system and placed on machines 2 and 3. The input to PSS could be generator speed (GS) or the generator electrical torque (GET). In this paper, the generator speed (GS) is considered as input.

Furthermore, one SVC is located at bus 101, where voltage swings are the greatest without the SVC. A supplementary controller for SVC is going to be designed simultaneously with other two PSSs. The input to the controller could be the real power of line 13-120 [8].

IV. DESIGNING OF PSSs AND SUPPLEMENTARY CONTROLLER USING GPC

To design a controller by GPC, based on the formulation in Section II, first of all the CARIMA description is obtained. The prediction horizon and the control horizon are considered to be $p=5$ and $m=3$, respectively.

As has been shown, predicted values of the process output over the horizon are first calculated and rewritten in the form of equation (9) and then the control law is computed using expression (15).

Also, the predictor polynomials F_j and E_j will be calculated solving the Diophantine equation.

The elements of the matrix G in (13) are calculated followed by obtaining the predicted outputs. By considering λ as a constant (in equation (14)), $r=1$ and $\alpha=0.75$, the $\Delta u(t)$ in (16) is obtained.

The obtained PSSs and supplementary controller for SVC by GPC are placed in the study system (Figure 2). To show the effectiveness of the designed controllers, a time-domain analysis is performed for the study system. A three-phase fault is applied in one of the tie circuits at bus 3. The fault persisted for 70.0 ms; following this, the faulted circuit was disconnected by appropriate circuit breaker. The system operated with one tie circuit connecting buses 3 and 101. The dynamic behavior of the system was evaluated for 15s. The machine angles, δ, with respect to a particular machine, were computed over the simulation period and shown in Figures 3 and 4. These figures show that the ability of the MPC algorithms in damping of the oscillations.

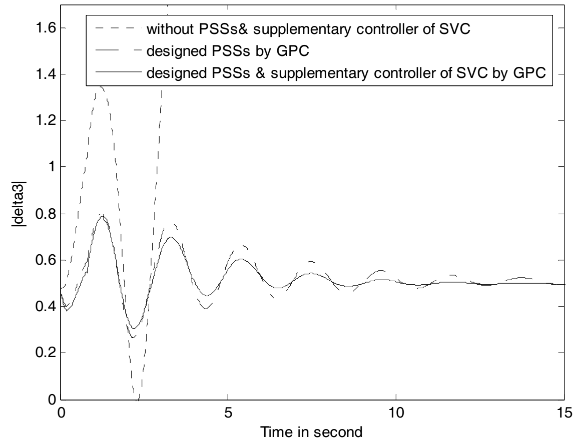

Figure 3. The response of generator 3 to a three-phase fault

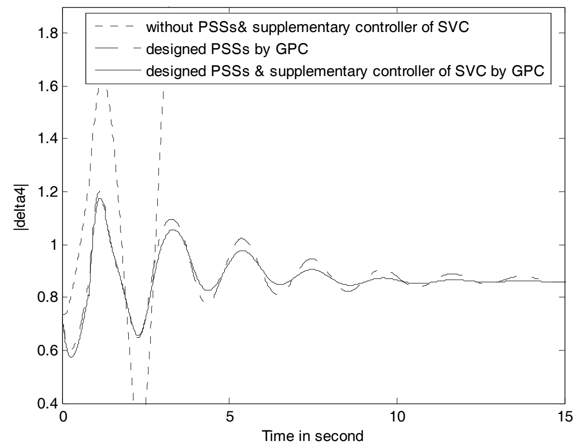

Figure 4. The response of generator 4 to a three-phase fault

V. CONCLUSIONS

In this paper GPC algorithm is used to simultaneous design of two PSSs and a supplementary controller for SVC to damp low-frequency oscillations. To show the effectiveness of the designed controllers, a three-phase fault is applied. The simulation study shows that the designed controllers improve the stability of the system. Also, this study shows that the concept of MPC can be easily applied to any MIMO system.

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BIOGRAPHIES

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