A Wide-Area Continuous Time Model Predictive Control Scheme for Multi-Machine Power System

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Abstract: This paper presents a systematic procedure for designing a wide-area centralized Continuous Time Model Predictive Controller (CTMPC) to improve the angular stability of a multi-machine power system. In this scheme, each generator is assumed to be provided with a local controller to damp out the local mode of oscillations and also employs a global signal from the centralized controller to damp out the inter-area mode of oscillations. The proposed control scheme has been implemented on a two-area four-machine power system. The performance of the controller has been compared with a coordinated Genetic Algorithm (GA)-tuned Conventional Power System Stabilizer (CPSS).

Index Terms: Continuous time model predictive controller, wide area controller, genetic algorithm and, power system stabilizer.

I. INTRODUCTION

In the past few years, small signal oscillations have been observed in the power systems, which are mainly caused by transmission of bulk amount of power over a long distance through relatively weak tie lines and use of high gain exciters. These oscillations have also resulted into instability and blackouts in the power system. The traditional approach to damp out these oscillations is through conventional Power System Stabilizer (PSS) forming part of the generator excitation system. These controllers usually employ local signals as inputs and may not always be effective to damp out the inter area modes of oscillations. The PSS is, generally, designed based on linearization of the system model at an operating point. However, power systems constantly experience changes in its operating conditions due to variations in generation, load and transmission network switching. Hence, the conventional PSS may not provide satisfactory results under wide variation in system conditions. Several efforts have been made, in the past, to develop adaptive or self-tuned PSS schemes [6], [7]. Further, the local controllers lack global observation of the inter-area modes, and hence, may not be effective in damping the oscillations.

The synchrophasor technology, using phasor measurement units (PMUs), provide synchronized, time stamped, real-time measurement data from remote locations to the phasor data concentrator (PDC) at control center [10]. This can be effectively utilized to design wide area damping controllers. It has been found that if the remote signals from one or more distant locations of the power system can be utilized to design the local controllers, the system dynamic performance can be enhanced, which, in turn, increases the transmission capacity [6]. Many researchers have proposed wide-area damping controllers to improve the transient stability. A robust H2/H∞ centralized wide-area damping controller has been proposed in [12]. A wide area signal based neuro-controller has been proposed for the unified power-flow controller (UPFC) in [10].

In this paper, a wide-area centralized CTMPC controller is developed for multi-machine power systems. The Model Predictive Controller (MPC), has been developed in continuous time domain. It has been mentioned in the literature [14] that the discrete time approach is accompanied by problems, such as numerical sensitivity, sample interval selection, non-minimum phase zeros etc. These problems can be avoided by the continuous time approach. In the present work, the feasibility of a wide-area CTMPC damping controller has been successfully tested on a two-area four machine power system [13]. As per our assumption, the signal transmission delay has been neglected. The results show that the proposed CTMPC damping controller provides effective damping to the inter-area modes of oscillations.

II. CONTINUOUS TIME MODEL PREDICTIVE CONTROLLER

The basic philosophy of model predictive control is to calculate the future behavior of the plant inputs by optimizing the plant output within a fixed time window $T_f$. The window can be from an initial time $T_i$ to $T_i + T_f$. The key issue in designing the controller is that the derivative of the controller input converges to zero when the system is stable. For designing the controller, the power system model has been linearized at a pre-fault operating point. The linearized state space model of a power system can be represented as,

$$X_0 (t) = A X_0 (t) + B U_0 (t)$$

$$Y_0 (t) = C X_0 (t)$$

(1)
where, the dimensions of $A_m$, $B_m$, and $C_m$ are $n \times n$, $n \times m$, and $p \times n$, respectively. The above system model, given in equation (1), can be converted into an augmented state space model, by considering,

$$X_m(t) = Z(t)$$

and,

$$Y_m(t) = C_m X_m(t)$$

$$= C_m Z(t)$$

(2)

The augmented state space model can be written as,

$$X(t) = A X(t) + B U(t)$$

$$Y(t) = C X(t)$$

(3)

where, the states of the augmented model are defined as,

$$X(t) = \begin{bmatrix} Z(t)^T & Y(t)^T \end{bmatrix}^T$$

$$A = \begin{bmatrix} A_m & B_m^T & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} B_m & 0_{q \times m} \end{bmatrix}$$

$$C = \begin{bmatrix} 0_m & I_{q \times q} \end{bmatrix}$$

$I$ is the identity matrix. The derivative of the control input, $\dot{U}(t)$, can be expressed in terms of Laguerre functions as,

$$\dot{U}(t / t_i) = L^T(t) \eta$$

(4)

where, $\eta = \begin{bmatrix} \eta_1 \\ \eta_2 \\ . \\ . \\ \eta_m \end{bmatrix}$ and $L^T(t) = \begin{bmatrix} l_1(t)^T \\ l_2(t)^T \\ . \\ . \\ l_m(t)^T \end{bmatrix}$.

By assuming the initial time $t_i$, and the initial state variables as $X(t_i)$, the predicted state variables at time $t$, can be expressed as,

$$X(t_i+t / t_i) = e^{A(t-t_i)} X(t_i) + \int_{t_i}^{t} e^{A(t-t)} B U(t) dt$$

$$Y(t / t_i) = C X(t / t_i)$$

(5)

Consider that the set point of the outputs, $r(t / t_i) = [r(t / t_i) \quad r(t / t_i) \quad . \quad . \quad r(t / t_i)]$, $0 < t < T_p$, are available where, $T_p$ is the prediction time horizon. The purpose of the CTMPC is to drive the system output as close as possible to the future trajectory of the set point. When the set-point signal is constants within the time window $T_p$, by subtracting the variable window $Y(t_i + t / t_i)$, the augmented model takes the form of,

$$\begin{bmatrix} Z(t_i+t / t_i) \\ e(t_i+t / t_i) \end{bmatrix} = \begin{bmatrix} A_m & 0_m^T \\ C_m & 0_{q \times q} \end{bmatrix} \begin{bmatrix} Z(t_i+t / t_i) \\ e(t_i+t / t_i) \end{bmatrix} + \begin{bmatrix} B_m \\ 0_{q \times m} \end{bmatrix} U(t)$$

(6)

To obtain the optimal control input to the system, it is required to minimize the objective function,

$$J = \int_{0}^{T_p} [X(t_i+t / t_i)]^T Q [X(t_i+t / t_i)] dt + \int_{0}^{T_p} [u(t)]^T R u(t) dt$$

(7)

To find out the optimal solution, the objective function $J$ can be formulated as a function of the parameter $\eta$. Minimizing the objective function $J$, provides the optimal value of $\eta$ as,

$$\eta = -\Omega^{-1} \psi X(t_i)$$

(8)

where,

$$\Omega = \int_{0}^{T_p} [\phi(t) \phi(t)^T] dt + R_L$$

$$\psi = \int_{0}^{T_p} [\phi(t) Q e^{Atl} dt$$

By applying the principle of receding control, the initial value of the control input can be expressed as,

$$U(t_i) = \begin{bmatrix} L_1(0)^T \\ 0_1 \\ L_2(0)^T \\ 0_2 \\ . \\ . \\ . \\ L_m(0)^T \\ 0_m \end{bmatrix} \eta$$

For any other time $t$, the control input can be expressed as,

$$U(t) = -K_{MPC} X(t)$$

(9)

Substituting the value of $X(t)$ from equation (4), the derivative of the control inputs to the system can be expressed as,

$$U(t) = -K_{MPC} \begin{bmatrix} X_m(t) \\ Y(t)-r(t) \end{bmatrix}$$

(10)
III. CONTROLLER DESIGN

The two-area power system, considered for the study in this work, is shown in Fig.1. The system parameters are taken from ref [13]. Each area consists of two-generators, connected with tie-lines between buses 7-8 and 8-9. The generators of the system are represented by 4th order dynamical model with states \( [\delta, \omega, E_q, E_d] \) variables, where \( \delta \) is the machine angle in pu, \( \omega \) is the machine speed deviation in pu, \( E_q \) is the quadrature axis induced voltage behind the transient reactance, and \( E_d \) is the direct axis induced voltage behind the transient reactance. Each generator is assumed to be connected with AVR and IEEE ST1A type static exciter. The loads in the system are assumed to be constant impedance type. To damp out local modes of oscillations, each generator is assumed to be provided with a conventional power system stabilizer (CPSS). Additional global signal is assumed to be provided to the stabilizer of the generator from the through a centralized wide area controller to damp out the inter-area modes of oscillations. Both the local and the global signals are applied to the voltage reference signal of the exciter system. The block diagram of the AVR-exciter model, along with the local and the global wide area signals, is shown in Fig.2.

Generally, the CPSS are designed for each generator separately to damp out the low frequency oscillations assuming the Single Machine Infinite Bus (SMIB) system model. In multi-machine power system, having a multi-PSS, the PSS parameters need to be coordinated together. Else, this may result in adverse effect rather than improving the stability of the system. Hence in this paper, a coordinated CPSS has been designed using a Genetic Algorithm (GA) based approach.

A. Coordinated CPSS Design by GA

The transfer function of a CPSS [6], [7] is considered as,

\[
G_{pss} = \frac{K_{pss} T_w}{1 + s T_w} \left( \frac{1 + s T_1}{1 + s T_2} \right) \left( \frac{1 + s T_3}{1 + s T_4} \right)
\]

where, \( K_{pss} \) is the stabilizer gain, \( T_w \) is the washout block time constant, \( T_1, T_2 \) are the 1st lead lag time constants and \( T_3, T_4 \) are the 2nd lead lag time constant of the CPSS. For the coordinated design, the four CPSS are tuned simultaneously using GA. For tuning, the PSS parameter the following optimization formulation has been considered,

\[
\text{Maximize } (J) = \min (\zeta) \quad \text{subject to,}
\]

\[
K_{pss}^{\min} \leq K_{pss} \leq K_{pss}^{\max}
\]
\[
T_1^{\min} \leq T_1 \leq T_1^{\max}
\]
\[
T_2^{\min} \leq T_2 \leq T_2^{\max}
\]
\[
T_3^{\min} \leq T_3 \leq T_3^{\max}
\]
\[
T_4^{\min} \leq T_4 \leq T_4^{\max}
\]

where, \( \zeta = \text{Damping factor of the electromechanical modes of oscillations of the system} \). \( J \) is taken as the fitness function of the GA. The damping factor of i\textsuperscript{th} mode,

\[
\zeta_i = \frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}, \quad \text{where, } \sigma_i \text{ and } \omega_i \text{ are the real and the imaginary part of the i\textsuperscript{th} eigen value.}
\]

The GA parameters utilized are given in Table I. These parameters have been selected through trial-and-error basis and their optimal values were obtained as those resulting in the maximum value of the fitness function.
The washout time constant \( T_w \) is set at 20s. During the tuning process, the parameters of the PSS-1 & the PSS-2 are maintained identical. Similarly the parameters of the PSS-3 & the PSS-4 are kept the same. The damping ratio of the most critical mode is maximized by GA search method. For this purpose, the MATLAB GA-toolbox has been used. The damping ratio of the critical mode is kept above 0.2pu. The optimal tuned values of the parameters, obtained from the GA, are given in Table-I.

### TABLE I

<table>
<thead>
<tr>
<th>GA parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encoding</td>
<td>Real</td>
</tr>
<tr>
<td>Population Size</td>
<td>100</td>
</tr>
<tr>
<td>Maximum generation</td>
<td>50</td>
</tr>
<tr>
<td>Crossover</td>
<td>Two point</td>
</tr>
<tr>
<td>Mutation rate</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The derivative of the inputs of the signals \( \dot{U}(t) \) is determined from the optimal solution of the predictive control strategy, as described in section IV. For optimization, the length of the moving horizon time window \( T_p \) is set at 10s, which is assumed to remain constant over the simulation. The future trajectory set point signals \( r(t) \) are taken to be zero since the speed deviations, are taken as plant outputs, which will converge to zero under system stable steady state condition.

To implement the derivative control inputs, \( \dot{U}(t) \) in digital form, define:

\[
\dot{U}(t) = \frac{U(t) - U(t - \Delta t)}{\Delta t}
\]

Hence, the control inputs

\[
U(t) = U(t - \Delta t) + \dot{U}(t)\Delta t
\]

where, the sampling time step for the simulation, \( \Delta t \) is taken as, 0.02s \( U(t - \Delta t) \) is the control input at time \( t - \Delta t \) and \( U(t) \) is the control input at time \( t \).

The controller outputs are applied to the exciter through a limiter block. The minimum and maximum values of limiter are set at -0.05 and 0.2 pu, respectively.

### IV. SIMULATION RESULTS

The proposed wide-area CTMPC controller has been tested on the two-area system. The CTMPC controller has been developed using MATLAB programming. The Table-III shows few critical eigen values of the system without any controller in the system. The undamped critical mode corresponds to a freq. of 0.5606, which is in the range of inter-area mode of oscillations [13].

### TABLE II

<table>
<thead>
<tr>
<th>Gen. no.</th>
<th>( K_{pss} )</th>
<th>( T_1 ) (sec)</th>
<th>( T_2 ) (sec)</th>
<th>( T_3 ) (sec)</th>
<th>( T_4 ) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>320</td>
<td>0.4376</td>
<td>0.0370</td>
<td>0.2462</td>
<td>0.02533</td>
</tr>
<tr>
<td>2</td>
<td>320</td>
<td>0.4376</td>
<td>0.0370</td>
<td>0.2462</td>
<td>0.02533</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>0.5273</td>
<td>0.0243</td>
<td>0.1725</td>
<td>0.07422</td>
</tr>
<tr>
<td>4</td>
<td>280</td>
<td>0.5273</td>
<td>0.0243</td>
<td>0.1725</td>
<td>0.07422</td>
</tr>
</tbody>
</table>

**B. Wide Area CTMPC Controller Design**

A multi-input and multi-output wide-area CTMPC controller has been designed for the two-area system. The controller provides a feedback connection between the generator’s speed deviation signal and the voltage set point of the exciter of each generator. For designing the CTMPC controller, the linearized model of the two-area power system is derived around the prefault operating point. The state space linearization model of the plant is formed with the four inputs and the four outputs. The inputs of the plant are taken as the voltage set point of the exciters and outputs are taken as the speed deviations of the generators.

The derivative of the inputs of the signals \( \dot{U}(t) \) is determined from the optimal solution of the predictive control strategy, as described in section IV. For optimization, the length of the moving horizon time window \( T_p \) is set at 10s, which is assumed to remain constant over the simulation. The future trajectory set point signals \( r(t) \) are taken to be zero since the speed deviations, are taken as plant outputs, which will converge to zero under system stable steady state condition.

To implement the derivative control inputs, \( \dot{U}(t) \) in digital form, define,

\[
\dot{U}(t) = \frac{U(t) - U(t - \Delta t)}{\Delta t}
\]

For the non-linear simulation a 3-\( \Phi \) fault has been applied at bus 7. The circuit breakers are assumed to clear the fault at bus-7 after 100ms and permanently opens the line 7-8 after 150ms from the application of the fault. The fault has been applied after 1s from starting the non-linear simulation.

The performance of the CTMPC controller has been evaluated and compared with the coordinated GA-based PSS for the above disturbance. Fig.3.a shows the speed deviation response of GEN-1 after the application of the 3-\( \Phi \) fault. The results show that, when there is no controller (dotted-line) by opening the switch S1 and S2 in Fig. 2, the system is unstable, due to presence of a pair of, eigenvalues on the right hand half of complex-plane. With the application of only wide-area CTMPC control (dash dot-line), by closing the switch S1 and opening the switch S2 in Fig.2, the peak overshoot and amplitude of the response has decreased as compared to the CPSS control (dashed-line), realized by opening the switch S1 and closing the switch S2 in fig.2. However, the settling time has increased. With the application of both CPSS and the wide-area CTMPC control actions (solid-line), achieved by closing both S1 and S2 in fig.2, the overall performance has improved as compared to the individual control actions. Similar results have also been observed in the speed deviation of generator-3 (Fig. 3.b) and the
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The generator-2 has been taken as the reference machine.

An adaptive wide-area damping controller, based on CTMPC, has been proposed in this paper. The validity and performance of the proposed controller is evaluated on a two-area power system. The performance results, obtained for a 3-Φ fault condition, show that the proposed wide-area controller efficiently damps out the inter-area mode of oscillations. With the application of the wide-area signal, the peak-overshoot, peak-undershoot and settling time of the response has improved. The combined action of both the CPSS and the CTMPC provides better performance than with the individual controllers.

V. CONCLUSION

REFERENCES


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