Robust PID-Sliding Mode Control of a Synchronous Machine

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Abstract Stable power systems in adverse operating conditions remain a constant quest of power companies and clients alike. Installed capacities are being used to their utmost levels and longer transmission lines to disserve remote areas are heavily relied upon in effort to avoid costly new installations. These reasons and the apparition of low frequency local and inter area oscillations hindering power flow have caused a renewed interest in robust PSS techniques.

Inspired by the work of Bhattacharya (BHA93), in which an integral type PSS was used to enhance damping to better robustness and performances of a power systems, we consider in this paper the robust control of a single synchronous generator connected to an infinite bus by means of a sliding mode based PSS regulator with a PID stabilizing signal. A systematic switching vector design allowing for desired dynamic behaviour in the sliding mode phase through a pole placement procedure is also applied alone and in conjunction with a linear state observer to account for non measurable system states and measurement noise. Stability being guaranteed under Lyapunov stability second law, simulation results show improvement in performances and better robustness.

Introduction

A stable power system in adverse operating conditions is still a quest for utility companies and customers alike. The need for more reliable electrical energy source and service continuity has apparently prompted a renewed interest in robust PSS to enhance damping of low frequency oscillations which curb power flow and may even cause loss of synchronism in network connected synchronous machine. In an effort to lower production cost, power companies have been using utmost installed capacities and calling upon longer transmission lines thus reducing stability margins this in turn has motivated a need for more robust closed loop dynamics through PSS performances improvement.

First power system stabilizers have been installed in Canada and in the USA in the early 60s which witnessed the expansion of system excitation task by using auxiliary stabilizing signals to control the field voltage to damp system oscillations in addition to the terminal voltage error signal. It is this part of excitation control which has been coined as PSS, i.e. power system stabilizer (KUN94). Many approaches have been proposed and several applied since the emergence of this new methodology. In this paper we briefly introduce a fourth order state model of a synchronous machine connected via a transmission line to an infinite bus, used in the first part of this paper, followed by a section describing the basic sliding mode control and the application of the pole placement technique in the sliding phase as well as the use of Luenberger type state observer followed by simulation and conclusion.

Single Machine System

The power system being investigated consists of a single synchronous machine connected to an infinite bus through a transmission line characterized by a fourth order linearized state model.
Under a specific operating point the state representation of the nominal system may be written as a fourth order state space model:

\[ y(t) = \Delta w(t) \quad (2) \]

State vector being defined as

\[ x(t) = [\Delta w(t) \quad \Delta \delta(t) \quad \Delta e'_q(t) \quad \Delta e_{ex}(t)]^T \quad (3) \]

where:

- \( \Delta w \) is the rotor angular speed variation
- \( \Delta \delta \) is the rotor angle variation
- \( \Delta e'_q \) is the transient voltage variation
- \( \Delta e_{ex} \) is the excitation voltage variation

It is obvious that matrices A and B depend on the instantaneous operating conditions through the operating point sensitive \( K_i \) factors. Uncertainties on A and B must therefore be taken into consideration via robust control techniques among which sliding mode control.

**Sliding Mode Control**

It’s not the intention of the authors to make an exhaustive list of papers and surveys on the subject but only few seminal articles will be mentioned for convenience to introduce sliding mode technique which basically consist in forcing state system trajectories to intersect a predefined sliding surface on the state space (UTK74). It is a well established fact that variable structure systems and controllers VSS and VSC respectively are the product of the early days’ russian research through the work of pioneers like Elmyanov, Fillipov, Drazenovic. More recent work on the subject has been undertaken by Utkin (UTK78) and Slotine (SLO91) among many others who turned sliding mode techniques into a well established robust methodology in robust control. In fact robustness of sliding mode control has become a well recognized fact (DRA69) and a confirmed solid tool of robust control just as Hinf or Fuzzy logic control. The severe drawbacks inherent to the sliding mode control such as chattering of the control signal causing sometimes dangerous actuators vibrations, the lack of systematic design procedures of the switching surface as well as the seemingly inevitable reaching phase are being lifted gradually and a profusion of related work has appeared during the last two decades.

**SMC BASICS**

Given a state model of the nominal system defined by equations:

![Small perturbation model of connected synchronous machine with PSS showing system parameters including operating-point-dependent Ki factors.](image-url)
\[ x = Ax(t) + Bu(t) ; \quad x_0 \quad (6) \]
\[ y = Cx(t) \]
and a sliding surface with desired dynamics given by
\[ S = Gx(t) \quad (7) \]
In order to maintain the dynamic motion of the controlled nominal system on the sliding surface a control law, the so called equivalent control, should enforce the following condition allowing for poles placement technique to be used
\[ S(x,t) = 0 \quad (8) \]
The system's dynamics is then completely determined by \( S = 0 \), therefore independent of uncertainties.
The equivalent control given by (8) is of the general form
\[ u_E = -[GB(x,t)]^{-1}GA(x,t) \quad (9) \]
Assuming \( (GB)^{-1} \) exists and that the nominal system is linear, we may rewrite the equivalent control as:
\[ u_E = -kx(t) \quad (10) \]
Where \( k = (GB)^{-1}GA \) is obtained through poles placement technique (BHA93), thus allowing for \( G \) to be calculated imposing the desired dynamics in the sliding phase.
Under matching conditions and in the presence of lumped uncertainties, the system state equation can be written as
\[ x = Ax(t) + Bu(t) + z(x,t) ; \quad x_0 \quad (11) \]
\[ y = Cx(t) \]
Where \( z = Bv \) represents lumped bounded perturbations and uncertainties such that
\[ |v(x,t)| \leq v_0(t) \quad (12) \]
It is desired to elaborate a robust PSS such that response performance doesn't deteriorate in presence of bounded uncertainties.
A fast switching control component must therefore be added to the equivalent control to uphold the so called reaching condition and to permit sliding to occur.
Let the classic Lyapunov function candidate be
\[ V(x,t) = \frac{1}{2} S^T S \quad (13) \]
from which arises the reaching condition
\[ V(x,t) = S^T S < 0 \quad (14) \]
\[ V = S^T \left( \frac{\partial S}{\partial x} (Ax + B(u+v)) + \frac{\partial S}{\partial t} \right) \quad (15) \]
where \( u = u_E + u_R \) is a discontinuous control signal to account for uncertainties.
Using (9) and (16) into (15) we obtain
\[ V = S^T \frac{\partial S}{\partial x} B(u_R + v) \quad (HA99) \]
here \( u_{PID} \) is used as the control signal \( u_R \)
This requires a robust control law given by:
\[ u = u_E + u_{PID} \quad (14) \]
A stabilizing signal \( u_{PID} \) is used such that:
\[ u_{PID} = -\xi (\Delta w + \beta \int \Delta w dt + \beta_2 \frac{\partial \Delta w}{\partial t}) - v_0 \quad (17) \]
The gains \( \beta_i \) appropriately chosen can lead with a convenient switching scheme to a stable sliding mode (BHA93), given by
\[ \beta_i = \begin{cases} \alpha_i & \text{if } x_i S > 0 \\ -\alpha_i & \text{if } x_i < 0 \end{cases} \quad i = 1,2 \]
The interested reader will find a detailed stability study in the papers (BHA93&96).

**PID O/SMC STABILIZER**

The previously proposed scheme is elaborated relying on a Luenberger state observer and a PID control signal (17) to counter bounded perturbations using the variation of the angular speed as its input.
The linear observer is mainly used to eliminate measurement noise in our case but could also be used for preventive diagnosis and alarm.
**Fig. 2** Observer based – PID-SM Controlled power system.

**SIMULATION RESULTS**

A fourth order state space model of synchronous machine connected via a transmission line to an infinite bus (PAR96) was used in the simulation with 0.01 rad rotor angle initial condition.

\[
A = \begin{bmatrix}
0 & -0.0622 & -0.1052 & 0 \\
377 & 0 & 0 & 0 \\
0 & -0.0679 & -0.1957 & 0.1289 \\
0 & 49.3876 & -845.0022 & -20
\end{bmatrix} \quad ; \quad B = \begin{bmatrix}
0 \\
0 \\
0 \\
1000
\end{bmatrix} \quad ; \quad x_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\]

The desired eigenvalues used are $[-8.0, -8.5, -9.0]$ and represents the predominant eigenvalues set in Bhatta’s paper which led in our case to determine $G$ as:

\[
G = [-14236.47 \quad -3.27 \quad 196.3 \quad 1].
\]

The following PID parameters were used:

\[
\xi = 110; \quad \beta_1 = 0.02; \quad \beta_2 = 2.64 \times 10^{-4}
\]

In order to assess efficiency of the proposed O/PID –SMC regulator it’s first compared to the PI scheme under the same initial conditions.

The responses obtained show a perceptible improvement in settling time in the rotor speed variation with naturally an acceptable insignificant overshoot. The same remark can be made concerning the rotor angle variation, a noticeable performance improvement, which seem to indicate the soundness of the proposed scheme.
To further assess robustness of the proposed stabilizer, different operating conditions were used and we show the results of a perturbation in the excitation voltage of 0.5 p.u. whose effect is swiftly eliminated with 0.1 sec as indicated in Fig. 7 & 8.

Conclusion
An observer based sliding mode PSS with PID type robust control signal using the rotor speed variation as its input has been proposed and simulation on a fourth order perturbed single machine power system conducted, showing enhancement of performances over a similar PI based PSS as well as good robustness standing.

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