Application of Higher Order Sliding Mode Observer and Super Twisting Observer based Super Twisting Control in Hydroelectric power plants

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Abstract: Speed control of hydro Turbine is an important issue and a shorter settling time is desired. In case of operation of drives with speed sensors, the performance of the drive is not satisfactory. To get satisfactory performance, a sensorless speed control system for hydro Turbine driving a synchronous generator in the hydroelectric power plants is developed. This work, we apply the approach of two methods of regulation: Super Twisting Control (STC) based on super-twisting observer (STO) and Super Twisting Control (STC) based on Higher Order Sliding Mode Observer (HOSMO). Simulation model in the presence of stochastic disturbance has been established in Matlab-Simulink. Simulation results demonstrate and validate the productiveness and performances of the proposed control method.

II. SYSTEM DESCRIPTION AND MODELING

Transfer function of the model of the Francis turbine is given by [1]:

\[ G_f(p) = \frac{0.663}{1 + 42.55s} \]  

Modeling the servovalve with the parameters of the power station makes it possible to obtain the following transfer function [1]:

\[ G(s) = \frac{20}{1 + 0.645s + 0.00645s^2} \]  

The correspondence between winnowing (v) and the turbine water flow (d) is represented by [1]:

\[ d = 0.7967v + 0.9874 \]  

MATLAB /Simulink diagram of the power chain is acquired from the equations 4 and 5.

\[ Q = 16 + 90 \frac{P}{H_b} \]  

\[ P = \frac{1}{90} (Q - 16) H_b \]  

Table 1 presents the parameters of the hydroelectric plant.

| Parameter | Description | Units |
|-----------|-------------|-------|
| Q         | Water flow rate | m³/s |
| H_b       | Height of waterfall | m |
| P_f       | Power of the load | Watts |
| T_f       | Resistant torque | N.m |
| P_m       | Power produced | Watts |
| T_m       | Motor torque | Nm |
| \omega_{mes} | Speed measured | rad/s |
| \omega_o | Disturbance | |

III. METHOD OF SYNTHESIS OF SUPER TWISTING CONTROL (STC)

A. Method of Synthesis of STC based on STO

Consider the dynamical system described by the following state equation

\[ \begin{align*}
    x_1 &= x_2 \\
    x_2 &= u + p_i \\
    y &= x_1
\end{align*} \]
y is measured the system, u is order and ρ₁ is a non-vanishing Lipschitz disturbance.

The dynamic equation of STO for the estimate of the equation (6) is given by [3]:
\[
\dot{x}_1 = x_2 + k_1 |x| \text{sign}(e_1) \\
\dot{x}_2 = u - k_2 \text{sign}(e_1)
\] (7)

Where the error \( e_1 = x_1 - \hat{x}_1 \)
The equation of error dynamic is given by [3]:
\[
\dot{e}_1 = -k_1 |e_1| \text{sign}(e_1) + e_2 \\
\dot{e}_2 = -k_2 \text{sign}(e_1)
\] (8)

So \( e_1 \) and \( e_2 \) will converge to zero in specific time \( t > T_0 \) by selecting the appropriate gains \( k_1 \) and \( k_2 \).

For this, one can say that \( \hat{x}_1 = x_1 \) and \( \hat{x}_2 = x_2 \) after specific time \( t > T_0 \) [3].

Consider the sliding manifold of the form
\[ s = c_1 x_1 + x_2 \, \text{ where } c_1 > 0 \] (9)

The time derivative of (9) is written as
\[ \dot{s} = c_1 \dot{x}_1 + \dot{x}_2 \] (10)

After specific time \( t > T_0 \), one substitute \( \dot{x}_1 = \hat{x}_2 \) [4].

Also using (7) and (10), one can further be written
\[ \dot{s} = c_1 \hat{x}_2 + u + k_2 \text{sign}(e_1) \] (11)

The transformation of the equation (1) in the co-ordinate of \( x_1 \) and \( \hat{s} \) by using (9) and (10) is writing by [4]:
\[ \dot{x}_1 = \hat{s} - c_1 x_1 \]
\[ \dot{s} = c_1 \hat{x}_2 + u + k_2 \text{sign}(e_1) \] (12)

The design of the Super-twisting control as defined in [5] can be obtained:
\[ u = -c_1 \hat{x}_2 - \lambda_1 |\hat{s}|^{\frac{1}{2}} \text{sign}(\hat{s}) - \lambda_2 \int_0^t |\text{sign}(\hat{s})| \, ds \] (13)

Where \( \lambda_1 \) and \( \lambda_2 > 0 \) are selecting according to [7].

IV. APPLICATION OF STO AND HOSMO BASED STC FOR THE SPEED CONTROL OF HYDROTURBINE

A. System model
The transfer function of the nominal regime of the model of the system is given by:
\[ G(s) = \frac{-12.57 s + 46.73}{42.84 s^2 + 160.3 s + 3.717} \] (21)

From equation (21), one can derive the state representation as follow:
\[ \dot{x}_1 = -3.7418 x_2 - 0.3471 x_2 + 2 u \]
\[ \dot{x}_2 = 0.25 x_1 \]
\[ y = -0.1467 x_1 + 2.1816 x_2 \] (22)

B. Method of Synthesis of STC based on HOSMO
The estimation of the states from equation (6) using the dynamics of the HOSMO is [10]:
\[
\dot{x}_1 = \hat{x}_2 + k_1 |x| \text{sign}(e_1) \\
\dot{x}_2 = \hat{x}_1 + u + k_2 |x| \text{sign}(e_1) \\
\dot{x}_3 = k_3 \text{sign}(e_1)
\] (14)

Let us define the error \( e_1 = x_1 - \hat{x}_1 \) and \( e_2 = x_2 - \hat{x}_2 \). Using [3], the error can be obtained as follow:
\[
\dot{e}_1 = e_2 - k_1 |e_1| \text{sign}(e_1) \\
\dot{e}_2 = -\dot{x}_3 - k_2 |x| \text{sign}(e_1) + \rho_1 \\
\dot{\rho}_1 = k_3 \text{sign}(e_1)
\] (15)

Now define the new \( e_3 = -\hat{x}_3 + \rho_1 \) and \( |\tilde{e}_3| < |\rho_0| \).

One can further write (15) as:
\[
\dot{e}_3 = -k_1 |e_1| \text{sign}(e_1) \\
\dot{e}_2 = e_1 - k_2 |e_1| \text{sign}(e_1) + \rho_1 \\
\dot{\rho}_1 = -k_3 \text{sign}(e_1) + \rho_1
\] (16)

So \( e_1 \), \( e_2 \) and \( e_3 \) will converge to zero in specific time \( t > T_0 \), by selecting the appropriate gains \( k_1 \), \( k_2 \) and \( k_3 \).

After the convergence of the error, one can find that \( x_1 = \hat{x}_1 \), \( x_2 = \hat{x}_2 \) and \( \hat{x}_3 = \rho_1 \) after specific time \( t > T_0 \).

Consider the sliding surface (9) and its time derivative is
\[ \dot{s} = c_1 \hat{x}_1 + \hat{x}_2 \] (17)

Also using (15) and (17), one can further write:
\[ \dot{s} = c_1 \hat{x}_2 + u + k_1 |e_1| \text{sign}(e_1) + \int_0^t k_3 \text{sign}(e_1) \, ds \] (18)

The equation (6) in the co-ordinate of \( x_1 \) and \( s \) by using (9) and (18).
\[ \hat{x}_1 = \tilde{s} - c_1 x_1 \]
\[ \dot{s} = c_1 \hat{x}_2 + u + k_2 |e_1| \text{sign}(e_1) + \int_0^t k_3 \text{sign}(e_1) \, ds \] (19)

Where \( \lambda_1 \) and \( \lambda_2 > 0 \) are selecting according to [7].
C. Design of STC based on HOSMO for speed control of hydroturbine

The STC based on HOSMO algorithms proposed for hydro turbine is giving by:

\[
\begin{align*}
\dot{x}_1 &= \dot{x}_2 + k_1 |e_1|^\frac{3}{2} \text{sign}(e_1) \\
\dot{x}_2 &= \dot{x}_3 + u + k_2 |e_1|^\frac{3}{2} \text{sign}(e_1) \\
\dot{x}_3 &= k_3 \text{sign}(e_1) \\
\end{align*}
\]

\[
\begin{align*}
u &= -0.25 \dot{x}_1 - c_1 \dot{x}_2 - \lambda_1 s |s|^\frac{3}{2} \text{sign}(s) - k_3 \int_0^t \text{sign}(e_1) \, dt \\
&\quad - \lambda_2 \int_0^t \text{sign}(s) \, dt
\end{align*}
\]

(25)

(26)

Table 2- Simulation parameters for STC based on STO.

| Parameter | Value |
|-----------|-------|
| STC-HOSMO |       |
| STC       | 2000  |
| STO       | 2000  |

Table 3- Simulation parameters for STC based on HOSMO.

| Parameter | Value |
|-----------|-------|
| STC-STO   |       |
| STC       | 2000  |
| HOSMO     |       |
| k_1       | 1500  |
| k_2       | 1100  |
| k_3       | 22    |
| k_4       | 78    |
| k_5       | 300   |

From Table 2 and Table 3, one can choose the parameters for the controllers to implement in these studies [7]. Fig.1 show the structure of STC based on STO/HOSMO proposed for hydro turbine.

From the model of hydroelectric plant and the Simulink models of STC-STO and STC-HOSMO, we obtain the Simulink models of power plant (Fig.2 and Fig.3).

Fig.1. Structure of STC based on STO /HOSMO for hydro turbine.

Fig.2. Simulink Model of the Power Plant controlled by STC based on STO.

Fig.3. Simulink Model of the Power Plant controlled by STC based on HOSMO.
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V. RESULT DISSECTION

Fig. 4. The result of actual (a) and estimated (b) speed for the STC based on HOSMO and STC based on STO.

Fig. 5. Actual (a) and estimated (b) speed for the STC based on HOSMO and STO.

Fig. 6. Error between actual speed (a) and estimated speed (b) of the STC based on HOSMO and STO under noisy measurement.

Fig. 7. Evolution of sliding manifold (a) for the STC based on HOSMO and STO under noisy measurement (b).

The Fig.4 and Fig.5 presents the simulation results obtained by applying STC-STO and STC-HOSMO on the system of regulating the speed of the hydro turbine. We note that both methods achieves desired speed, but from Fig.4a and Fig.5a we can say that precision of speed in STC-HOSMO is...
expanded than STC-STO. Evolution of observer error in simulation is visible in Fig.6; we can notice that the errors are more significant when order STC-STO is used; on Fig.7 we can see the evolution of the sliding surface; by using the precision as a criteria of comparison, the sliding variable of STC-HOSMO give us better results.

VI. CONCLUSION

The results relating to the application of a new STC based on sliding mode observers for the speed control of hydroturbine in hydroelectric power plants has been presented in this article. The simulation results of the various commands presented are satisfactory from the point of view of the error estimation and stability of the overall system under various operating conditions. A compromise between the speed of convergence of the observer and the robustness degree with respect to noise measurement is obtained with the STC based on HOSMO.

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