Application of Adaptive Back Stepping Control Technique for Damping of Power System Oscillations with UPFC

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Abstract — Small disturbances in a power system such as random load changes or large disturbances such as faults may trigger electromechanical oscillations involving generators or group of generators, which may be intricate to control. This paper proposes Adaptive Back Stepping Control (ABSC) technique to damp power oscillations in a power transmission system incorporating UPFC. A single machine infinite bus (SMIB) power system with two transmission lines and UPFC installed in receiving end side of one of the transmission line is considered for the study. The power modulation control scheme is employed as auxiliary control scheme which varies the power reference dynamically for the UPFC internal operation. The effectiveness of the proposed adaptive controller is demonstrated through computer simulations using MATLAB/SIMULINK and the results are compared with those using PI based controller. It is found that the overall performance of the proposed controller is better

Keywords — Flexible AC Transmission System, Unified Power Flow Controller, Power oscillation damping, State space model, Adaptive Back Stepping

I. INTRODUCTION

Transmission congestion results when there is insufficient capacity to transmit power over existing lines and maintain the required safety margins for reliability. FACTS controllers enhance the stability of the power system owing to their superior speed of response and amenability to continuous control in real time. In the recent years UPFC has been proposed in the context of power transmission to increase power flow as well as an aid for improving the system stability. UPFC is one of the most important FACTS devices since it can provide various types of compensation, i.e., voltage regulation, phase shifting regulation, impedance compensation and reactive compensation.

The basic configuration of UPFC installed in a transmission line is shown in Fig.1 and the per phase equivalent circuit of UPFC is shown in Fig.2. The UPFC consists of two back-to-back connected voltage source inverters (VSIs) with an interconnecting dc storage capacitor. One VSI is connected to the system bus using a shunt transformer and the other VSI is connected using a series transformer. The power balance between the series and shunt connected VSIs is a prerequisite to maintain a constant voltage across the dc capacitor connected between the two VSIs. The series inverter is used to inject a controlled voltage, in series with the line and thereby to force the power flow to a desired value. The shunt inverter is controlled in such a way as to supply precisely the right amount of real power at its dc terminals to regulate the dc bus voltage.

The steady state characteristics and performance of a UPFC have been widely reported in literature [1-5]. The multi-variable and complex closed loop control of UPFC is still a challenge before the control engineers. Since the power system with UPFC involves multiple control variables, the design of
robust control strategy for UPFC into the framework of system theory is still in the development stage. The conventional multiple PI controller based techniques have been reported in the literature [2-4]. But in general, for a non-linear system the performance with PI based controllers varies widely with respect to the operating points. Moreover, the selection of gains for various PI controllers in a MIMO system is a tedious and imprecise task as it is based on a trial and error approach. Also it has been reported that control of UPFC based on the conventional PI based control strategy is prone to severe dynamic interaction between real and reactive power flows [6-9]

Thus in the context of complex closed loop control of UPFC which is a MIMO system, it is proposed to apply the Adaptive Back Stepping control technique to achieve effective control of the real and reactive power flows in the line, with minimum or zero dynamic interaction between them. The use of Adaptive Back Stepping control technique for the UPFC has not been reported earlier in literature. An attempt has been made here to implement an Adaptive Back Stepping controller for the power system with UPFC for enhanced power flow control. Results of the investigations indicate a noticeable improvement in the overall system performance, especially when compared to the PI based control schemes. Also dynamic interactions are very much reduced.

II. SYSTEM MODELING

i. Modeling of series converter:

To develop the series converter model, Kirchhoff’s voltage equations (KVL) for the phase ‘a’ of the series branch can be written

\[ L_{se} \frac{di_{a1}}{dt} + i_{a2}r_{se} = (V_{ta} - V_{ra} + V_{ca}) \]  \hspace{1cm} (1)

Similarly the KVL equations can be written for phases ‘b’ and ‘c’. The KVL equations for three phases in matrix form can be written as follows.

\[
\begin{bmatrix}
\frac{d}{dt}i_{a2} \\
\frac{d}{dt}i_{b2} \\
\frac{d}{dt}i_{c2}
\end{bmatrix}
= \begin{bmatrix}
\frac{-r_{se}}{L_{se}} & 0 & 0 \\
0 & \frac{-r_{se}}{L_{se}} & 0 \\
0 & 0 & \frac{-r_{se}}{L_{se}}
\end{bmatrix}
\begin{bmatrix}
i_{a2} \\
i_{b2} \\
i_{c2}
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{L_{se}}[V_{ta} - V_{ra} + V_{ca}] \\
\frac{1}{L_{se}}[V_{tb} - V_{rb} + V_{cb}] \\
\frac{1}{L_{se}}[V_{tc} - V_{rc} + V_{cc}]
\end{bmatrix} \hspace{1cm} (2)
\]

Equation (2) pertains to a-b-c reference frame. To ease the complexity, these equations are transformed from a-b-c reference frame to synchronous d-q reference frame keeping \(V_t\) as reference (\(V_{q0}=V_{x0}, V_{q1}=0\)). The differential equations for d-q components of series branch current can be written as

\[
\frac{d}{dt}i_{d1} = -\frac{r_{se}}{L_{se}}i_{q2} + \omega i_{q1} + \frac{1}{L_{se}}(V_{td} - V_{rd} + V_{cd}) \hspace{1cm} (3)
\]

\[
\frac{d}{dt}i_{q1} = -\frac{r_{se}}{L_{se}}i_{d2} - \omega i_{d1} + \frac{1}{L_{se}}(V_{qd} - V_{rq} + V_{cq}) \hspace{1cm} (4)
\]

ii. Modeling of shunt converter:

Proceeding in a similar way, the differential equations for the shunt converter currents are given by

\[
\frac{d}{dt}i_{d1} = -\frac{r_{sh}}{L_{sh}}i_{q1} + \omega i_{d1} + \frac{1}{L_{sh}}(V_{pd} - V_{ad}) \hspace{1cm} (5)
\]

\[
\frac{d}{dt}i_{q1} = -\frac{r_{sh}}{L_{sh}}i_{d1} - \omega i_{d1} + \frac{1}{L_{sh}}(V_{pq} - V_{q1}) \hspace{1cm} (6)
\]

iii. Modeling of DC link capacitor voltage:

The performance of UPFC depends on the stability of the dc link voltage between the series and shunt converters. In the case of ideal converters, the shunt converter must be capable of handling the amount of real power which is exchanged between the series converter and the line. Thus the UPFC as a whole exchanges zero real power with the transmission line. However, during dynamic conditions, the input power to the shunt converter should be equal to the sum of series injected power and the rate of change of stored energy in the capacitor on an instantaneous basis [2], [7], [8]. Thus, by power balance we obtain the equation below.

\[
P = \frac{3}{2} \left[ -V_{pd}\ i_{d1} - V_{pq}\ i_{q1} - V_{cd}\ i_{d2} - V_{cq}\ i_{q2} \right]
\]

\[
= CV_{dc}\ \frac{d}{dt}V_{dc} + \frac{V_{dc}^2}{R_{dc}}
\]

and hence

\[
V_{dc} = \frac{3}{2CV_{dc}} \left[ -V_{pd}\ i_{d1} - V_{pq}\ i_{q1} - V_{cd}\ i_{d2} - V_{cq}\ i_{q2} \right] - \frac{V_{dc}}{CR_{dc}} \hspace{1cm} (7)
\]

The above equation governs the dc-link capacitor voltage of UPFC. The dc voltage level is controlled by regulating the real power flow from the ac system into the common dc-link via the shunt converter.

iv. Modeling of Alternator

The model of the synchronous generator as discussed by P.C. Krause in [14] is adopted for the simulation in MATLAB/Simulink environment.

III. DEVELOPPEMENT OF ADAPTIVE BACK STEPPING CONTROL (ABSC)

Adaptive back stepping is a control scheme suitable for non-linear systems with unknown but constant nonlinear uncertainties [10-12]. The uncertainties arise due to change of system parameters such as line impedances. In practice, line impedances are designed according to the short-circuit capacity, which are bounded. The change of line impedances affect the system operating point. In such a case, the system states are uncertain but constant. Therefore, the uncertainties caused by change of system parameters must be constant and bounded, which can be reflected by the uncertainties \(\theta_{d1}, \theta_{q1}, \theta_{d2} \text{ and } \theta_{q2}\) in the model formulations. The adaptation control laws can be derived systematically. The control objective is to improve dynamic performance of UPFC system with minimum or zero dynamic interaction.

(a) Control Design of Shunt converter

The mathematical model for shunt converter (3, 4) is rewritten as

\[
\frac{d}{dt}i_{d1} = -\frac{r_{sh}}{L_{sh}}i_{q1} + \omega i_{d1} + \frac{1}{L_{sh}}(V_{pd} - V_{ad}) \hspace{1cm} (5)
\]

\[
\frac{d}{dt}i_{q1} = -\frac{r_{sh}}{L_{sh}}i_{d1} - \omega i_{d1} + \frac{1}{L_{sh}}(V_{pq} - V_{q1}) \hspace{1cm} (6)
\]
\[ \dot{x}_1 = -a x_1 + \omega x_2 + U_{d1} \\
\dot{x}_2 = -\omega x_1 + a x_2 + U_{q1} \]

where \[ \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix}, \quad \begin{bmatrix} U_{d1} \\ U_{q1} \end{bmatrix} = \begin{bmatrix} (v_{pd} - v_{sd})/L_{sh} \\ (v_{pq} - v_{sq})/L_{sh} \end{bmatrix} \] and \( a = \frac{r_{sh}}{L_{sh}} \).

The problem is reformulated in terms of \( Z_1 \) and \( Z_2 \) where \( Z_1 = x_{1\text{ref}} - x_1, \) \( Z_2 = x_{2\text{ref}} - x_2 \) and the time derivative of \( Z_1 \) and \( Z_2 \) is given by

\[ \begin{aligned}
\dot{Z}_1 &= \dot{x}_{1\text{ref}} - \dot{x}_1 = \dot{x}_{1\text{ref}} + a x_1 - a x_2 - U_{d1} - \theta_{d1} \\
\dot{Z}_2 &= \dot{x}_{2\text{ref}} - \dot{x}_2 = \dot{x}_{2\text{ref}} + a x_1 + a x_2 - U_{q1} - \theta_{q1}
\end{aligned} \tag{8} \]

where \( \theta_{d1} \) and \( \theta_{q1} \) are uncertainties.

For the system to be controllable and stable, a positive definite Lyapunov function is considered.

\[ V_{a0} = \frac{1}{2} L_{sh} (Z_1^2 + Z_2^2) + \frac{1}{2 m_1} (\hat{\theta}_{d1} - \theta_{d1})^2 + \frac{1}{2 m_2} (\hat{\theta}_{q1} - \theta_{q1})^2 \tag{9} \]

where \( \hat{\theta}_{d1}, \hat{\theta}_{q1} \) are estimates of \( \theta_{d1} \) and \( \theta_{q1} \); \( m_1, m_2 \) are adaptation gains. Thus we can write

\[ \begin{aligned}
\dot{V}_{a0} &= L_{sh} (\dot{Z}_1 Z_1 + \dot{Z}_2 Z_2) + \frac{1}{m_1} (\hat{\theta}_{d1} - \theta_{d1}) (\dot{\theta}_{d1} - \hat{\theta}_{d1}) + \frac{1}{m_2} (\hat{\theta}_{q1} - \theta_{q1}) (\dot{\theta}_{q1} - \hat{\theta}_{q1}) \\
&= \frac{d}{dt} \left( L_{sh} Z_1 Z_1 + \frac{\dot{\theta}_{d1}}{m_1} + \frac{\dot{\theta}_{q1}}{m_2} \right)
\end{aligned} \tag{10} \]

By Lyapunov theorem, the first derivative of the Lyapunov function has to be negative definite for the system to be asymptotically stable. So it is made negative definite by choosing

\[ \dot{\theta}_{d1} = -L_{sh} m_1 Z_1, \quad \dot{\theta}_{q1} = -L_{sh} m_2 Z_2, \]

\[ U_{d1} = \dot{x}_{1\text{ref}} + a x_1 - a x_2 - \dot{\theta}_{d1} + K_{n1} Z_1, \]

\[ U_{q1} = \dot{x}_{2\text{ref}} + a x_1 + a x_2 - \dot{\theta}_{q1} + K_{n2} Z_2. \]

Then \( \dot{V}_{a0} = -[K_{n1} L_{sh} Z_1^2 + K_{n2} L_{sh} Z_2^2] \) is negative definite for \( K_{n1} > 0 \) and \( K_{n2} > 0 \).

The block diagram of the proposed adaptive back stepping controller for the shunt converter is shown in Fig 3.

(b) Control Design of Series Converter

The mathematical model for series converter is rewritten as

\[ \begin{aligned}
\dot{x}_1 &= -b x_1 + a x_2 + U_{d2} \\
\dot{x}_2 &= -a x_3 - b x_4 + U_{q2}
\end{aligned} \tag{11} \]

\[ \text{Where} \quad \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} i_{d2} \\ i_{q2} \\ U_{d2} \\ U_{q2} \end{bmatrix} = \begin{bmatrix} (v_{pd} - v_{rd} + v_{rd})/L_{se} \\ (v_{pq} - v_{sq} + v_{sq})/L_{se} \end{bmatrix} \quad \text{and} \quad b = \frac{r_{se}}{L_{se}}. \]

Here, the problem is formulated in terms of \( Z_3 \) and \( Z_4 \) where \( Z_3 = x_{3\text{ref}} - x_3, \) \( Z_4 = x_{4\text{ref}} - x_4 \) and the time derivatives of \( Z_3 \) and \( Z_4 \) is given by

\[ \begin{aligned}
\dot{Z}_3 &= \dot{x}_{3\text{ref}} - \dot{x}_3 = \dot{x}_{3\text{ref}} + a x_3 - a x_4 - U_{d2} - \theta_{d2} \\
\dot{Z}_4 &= \dot{x}_{4\text{ref}} - \dot{x}_4 = \dot{x}_{4\text{ref}} + a x_3 + a x_4 - U_{q2} - \theta_{q2}
\end{aligned} \tag{12} \]

where \( \theta_{d2} \) and \( \theta_{q2} \) are uncertainties.

Again, for the system to be controllable and stable, a positive definite Lyapunov function is considered.

\[ V_{a0} = \frac{1}{2} L_{se} (Z_3^2 + Z_4^2) + \frac{1}{2 m_3} (\hat{\theta}_{d2} - \theta_{d2})^2 + \frac{1}{2 m_4} (\hat{\theta}_{q2} - \theta_{q2})^2, \]

where

Fig.3: Block diagram of adaptive back stepping controller for shunt converter
Fig.4: Block diagram of adaptive back stepping controller for series converter
Choosing $\dot{\theta}_{d2}$ and $\dot{\theta}_{q2}$ are estimates of $\theta_{d2}$ and $\theta_{q2}$; $m_3$, $m_4$ are adaptation gains. Proceeding in similar way as shunt converter, the control inputs for series converter are given by

$$U_{d2} = \dot{x}_{3_{\text{ref}}} + bx_3 - \dot{\theta}_{d2} + K_{n3}Z_3$$

$$U_{q2} = \dot{x}_{4_{\text{ref}}} + ax_3 + bx_4 - \dot{\theta}_{q2} + K_{n4}Z_4.$$ 

Choosing $\dot{\theta}_{d2} = -L m_1Z_3$ and $\dot{\theta}_{q2} = -L m_4Z_4$.

$$\dot{V}_{m0} = -[K_{n3}L_2(Z_3^2 + K_{n4}L_2Z_4^2)]$$ is made negative definite for $K_{n3} > 0$ and $K_{n4} > 0$. The block diagram of the proposed adaptive back stepping controller for the series converter is shown in Fig. 4.

IV. POWER MODULATION CONTROL SCHEME

The UPFC can be made to vary dynamically in response to the control-input signals so that the resulting changes in the power flow enhance the system damping. The power modulation results in a corresponding variation in the power flow. The UPFC can respond quickly to the changes in power, it is possible to improve damping and transient stability of the power system by coordinated control actions of the UPFC. Thus, power oscillations resulting from swings in rotor angles can be readily damped by using the series branch voltage of the UPFC to control the system power flow. The main control parameters of UPFC are magnitude and phase angle of the injected voltage. Real and reactive power flows can be controlled independently by injecting a series voltage with appropriate magnitude and angle.

$$\Delta \omega = \frac{K_p + K_2}{S} \Delta P_{\text{ref}}$$

Fig. 5: Power modulation control scheme

In order to generate the desired voltage for series injection, the necessary (reference) series branch current is calculated from the desired power commands (i.e., generation of $i_{d*}$ and $i_{q*}$). The measured currents $i_{1d}$ and $i_{1q}$ are fed back and compared with the reference currents to produce error signals. These error signals are used by the PI controller to regulate $V_{cd}$, $V_{cq}$ respectively. Finally, the power modulation scheme [4] shown in Fig. 5 is used here to control the power oscillations. This control uses the speed deviation signal $\Delta \omega$ of the desired machine to modify the active power flow reference $P_r$ for the series converter.

V. SIMULATION RESULTS AND DISCUSSIONS

The study system shown in Fig. 6 consists of a synchronous generator supplying power to a 400kV, 50-Hz infinite bus over two identical transmission lines of 140-km distance. The UPFC is installed at one of the transmission lines near the infinite bus and the nominal power flows in each line are $P_r = 0.315$ pu, $Q_r = -0.07$ pu (on 1000 MVA base) and generator load angle is 45°. The study-system data are given in Appendix.

Simulations are carried out using MATLAB/Simulink for performance investigation of the system with the two controllers. The alternator is synchronized with the infinite bus and is brought to the steady state. The power system is at steady state prior to $t=50$ s. At $t=50$ s, three-phase fault is applied at the middle of the non-UPFC line for 100 ms and is cleared without any change in the network configuration. The generator rotor speed, load angle and receiving end real power (i.e., power injection into the infinite bus) are shown in Fig. 7.1 & 7.2 for three different settings namely (a) without UPFC (b) PI based UPFC and (c) ABSC based UPFC.

The speed error ($\Delta \omega$) is selected as the input signal to the POD controller. The power modulation control regulates the line power flow dynamically in accordance with the error in speed. From the Fig. 7.1 (a) it is seen that the speed oscillations exist up to 6 s when UPFC is not connected in the system. When the PI based UPFC operates in active power damping mode, the speed oscillations are reduced and they exist only upto 2 s. But, the peak occurring soon after the fault is the same (1.0195 pu) as that of without UPFC.

The ABSC based UPFC (Fig. 7.2 (a)) reduces the first peak of speed oscillations considerably. The first peak overshoot is reduced to 1.0111 pu and the consequent oscillations are damped rapidly. The system reaches the steady state within one second.

From the Fig. 7.1 (b), it is seen that the generator load angle oscillations exist upto 6 s when UPFC is not connected in the system. When the PI based UPFC is included in the system, the load angle oscillation are reduced and exists only upto 2 s. But the peak occurring soon after the fault is the same value (59.9°) as that of without controller.
From Fig. 7.2(b), it is seen that the ABSC based UPFC reduces the first peak of generator load angle oscillations considerably. The first peak is reduced to 54.4° and the consequent oscillations are also damped rapidly. The system reaches the steady state within one second.

The receiving end real power (Pr) oscillations in non-UPFC line (Fig. 7.1 (c)) show improved damping with PI based UPFC. Without UPFC, the receiving end real power takes about 6 s to damp out. The peak of the receiving end real power is 0.555 pu (soon after the fault is cleared). When PI based UPFC is included, the oscillations are damped out within 2 s. But the peak overshoot of the receiving end real power (soon after the fault) is not reduced with PI based UPFC and it remains at the same value without UPFC.

The ABSC based UPFC is capable of reducing the peak overshoot significantly (Fig. 7.2 (c)). The first peak is reduced to 0.446 pu and the consequent oscillations are also damped rapidly. The receiving end real power oscillations are damped out within one second.

From the results, it is observed that the ABSC based UPFC reduces the first peak significantly. In addition to the reduction in the amplitude of the first swing, the system settles at the final steady state value within one second. From the above results, it is revealed that the ABSC based UPFC performs better than PI based UPFC in damping the power oscillations following a three phase fault.
VI. CONCLUSIONS

In this paper, the simulations results are presented for the SMIB-UPFC system with PI based and ABSC based controllers for power oscillation damping. A comparison of performance with the PI based UPFC and ABSC based UPFC has been made. It is seen that the UPFC with ABSC controller reduces the first peak of the power oscillations significantly and there is a notable reduction in the amplitude of subsequent oscillations and also the time to reach the steady state is reduced. Here, it is to be noted that the performance of the system with PI based UPFC could still be improved by optimizing the gain parameters. The less dynamic interactions and fast response gives a better damping compared to PI control scheme. From the simulation results, it is revealed that the PI based control for UPFC yields reasonably good performance and the ABSC based control for UPFC yields marginally better performance in power oscillation damping.

VII. APPENDIX

Appendix A

\[ V_r \] : Receiving end voltage, (V) 
\[ V_c \] : Series injected voltage, (V) 
\[ V_p \] : Shunt converter voltage, (V) 
\[ V_{dc} \] : DC link Capacitor voltage, (V) 
\[ V_t \] : UPFC bus voltage (V) 
\[ i_2 \] : Receiving end current, (A) 
\[ i_1 \] : Shunt branch current, (A) 
\[ r \] : Transmission line resistance, (Ω) 
\[ L \] : Transmission line inductance, (H) 
\[ C \] : DC link capacitor, (F) 
\[ r_{sh} \] : Shunt transformer resistance, (Ω) 
\[ L_{sh} \] : Shunt transformer leakage inductance, (H) 
\[ P_r \] : Receiving end real power, (W) 
\[ Q_r \] : Receiving end reactive power, (VAR) 
\[ \omega \] : Angular Frequency of synchronous reference frame (rad/s)

Appendix B

The Generator (on Its Own Base)

\[ S_n = 1110 \text{ MVA}; \ V_n = 22 \text{ kV}; \ f = 50 \text{ Hz}; \ R_n = 0.0036 \text{ pu}; \]
\[ x_l = 0.21 \text{ pu}; \ R_o = 0; \ x_o = 0.195\text{pu}; \ T_{do}^* = 6.66 \text{ s}; \ T_{qo}^* = 0.44 \text{ s}; \]
\[ T_{do}^* = 0.032 \text{ s}; \ T_{qo}^* = 0.057 \text{ s}; \ x_d = 1.933 \text{ pu}; \ x_q = 1.743 \text{ pu}; \]
\[ x'_d = 0.467 \text{ pu}; \ x'_q = 1.144 \text{ pu}; \ x''_d = 0.312 \text{ pu}; \ x''_q = 0.312 \text{ pu}; \]
\[ H = 3.22 \text{ s}; \ D = 0 \]

The Automatic Voltage Regulator (IEEE Type 1 Rotating Exciter)

\[ T_R = 0 \text{ s}; \ K_A = 400 \text{ pu}; \ T_A = 0.02 \text{ s}; \ K_E = 1 \text{ pu}; \ T_E = 1 \text{ s}; \ K_F = 0.06 \text{ pu}; \ T_F = 0.06 \text{ pu}; \]

The power-system stabilizer (PSS) and governor control are not considered

The Transmission Line

Resistance (R) = 0.0885 Ω/ph/km
Reactance (X_L) = 0.8368 Ω/ph/km

REFERENCES