

Non Linear Modelling and Control of Unified Power Flow Controller

N. V. A. Ravikumar, Vasupalli Manoj and R.S.R. Krishnam Naidu

Dr. N. V. A. Ravikumar, Sr. Assistant Professor, Department of Electrical & Electronics Engineering, GMR Institute of Technology, Rajam, Vizianagaram – 532127. A.P., India.

Dr. Vasupalli Manoj, Assistant Professor, Department of Electrical and Electronics Engineering, GMR Institute of Technology, Rajam, Vizianagaram, Andhra Pradesh, India – 532127.

Dr. R.S.R. Krishnam Naidu, Associate Professor, Department of Electrical and Electronics Engineering, NS Raju Institute of Technology, Sontyam, Visakhapatnam, India.

Abstract: Unified Power Flow Controller is modeled as a non linear system in order to apply a non linear control technique for the improvement of power flow in a Single Machine Infinite Bus system. The non linear system is linearized by Feedback Linearization technique .FBLC is able to linearize the non linear states of the system under all uncertainty conditions present. FBLC will also be track the references and control the converter operation. The non linear modelling of UPFC along with the FBLC control is done in MATLAB software. The UPFC along with FBLC control gives promising results on the stability of linearized system with guarantee that state information remains unaltered.

Keywords: Non linear control; Feedback linearization control; UPFC; FACTS.

1. Introduction

Power systems are subjected to dynamic load variations and there exists a congested situation for the active power flow among the transmission lines. This situation can be overcome by increasing the generation and built new transmission lines.

Corresponding Author: ravikumar.nva@gmrit.edu.in, nvaravikumar@gmail.com

The growth of demand met by upgrading the system components is not economical and therefore modified control methods or more flexible devices have to be developed to completely utilize the existing transmission line capacity [1].

In the bulk transmission system, power flow can alter by the deployment of Flexible AC Transmission systems (FACTS) in the network. Power system equipped with FACTS will have fast control actions on voltage security, power flow, and stability of the power system. These devices will help to increase reliability and reduce the cost of power delivered. It modifies the power transmission capacity by injecting inductive or capacitive reactive power to the line [2]. The FACTS controllers are classified as shunt compensators, series compensators and combined of series and shunt compensators. Unified Power Flow Controller (UPFC) is one of the FACTS devices which can unify all the control activities which can enhance the power flow as well as the stability of the power system. UPFC is the combination of two voltage source converters connected back to back through a DC link capacitor [1]. A variety of control approaches for the shunt and series converter of UPFC were investigated in most of the literatures. Conventionally linear control techniques like PI is used for control of UPFC, assuming linearized operating conditions. But because of the increase in demand, power system dynamics are very fast and linear control techniques are no longer applicable [3]. The Artificial Intelligence(AI) techniques along with adaptive learning algorithm can be used for wide operating range. AI techniques such as ANN, fuzzy logic, PSO and H_{∞} are some of the methods used in the control of UPFC [4,5]. But the implementations of these controllers are challenging in nature. The performance of the power system could be affected if a delay exists between control action of UPFC and power system time constants.

Non linear modeling and control of the power system are the recent research topics to get better performance of the power system [7]. The non linear control techniques will help to improve the time response characteristics such as peak overshoot, settling time, and fast tracking of references than any other linear control techniques. The UPFC comprised of two voltage source converters. The voltage source converter power balance equations are non linear in nature and a non linear control is the best option for the effective control system design for the voltage source converters [6]. As we know that some of the FACTS devices are the combination of voltage source converters, non linear controllers can be applied on it. In the literature [10] STATCOM is modeled as a third order non linear system. Likewise a non linear control technique can employ to analyze the performance of a UPFC which can modeled as fifth order system. Feedback Linearizing Technique is one of the nonlinear control technique to convert a nonlinear system to a linear system. Then the linearized system can be controlled using linear control techniques such as PI, pole placement, LQR(linear quadratic regulator), H_{∞} etc [8]. FBLC is stable over wide operating range while a linear control technique acts only at a particular operating point. This paper proposes an effective controller for UPFC using FBLC to enhance the power flow in the power system network.

This paper is organized as follows, In Section 2, the overall system with FBLC is explained. In Section 3, non linear state space model of UPFC is explained. In Section 4, the FBLC is explained for Unified Power Flow Controller for Power Flow Enhancement. Section 5 gives the detailed analysis of the proposed control strategy followed by conclusion in section 6.

2. System description

The study system consists of three phase source (100kV, 50Hz, 3 ϕ) is connected to Single Machine Infinite Bus system (SMIB) through the transmission line and a UPFC as shown in Fig.1. The UPFC consists of two switching converters VSC 1 and VSC 2 are voltage source inverters using GTOs or IGBT switches. The voltage source converters

connected through a DC link capacitor. The Unified Power Flow Controller (UPFC) establishes a complete circuit for real power and is capable of bidirectional movement between the AC terminals of the back-to-back converters. Voltage Source Converter 1 (VSC 1) and Voltage Source Converter 2 (VSC 2) can either produce or consume reactive power at the connection point to the line. The UPFC can effectively achieve control goals like shunt compensation, series compensation, and phase angle regulation. This can be obtained by injecting a series voltage ($v_{inj} \angle \sigma$). The VSC 2 controls the complex power demand of the load and the VSC 1 controls the dc voltage and the bus voltage at the point of coupling in the line. In this paper, a non linear control strategy (FBLC) for shunt and series converter is used. The FBLC algorithm requires non linear state modeling of the UPFC. The states are obtained from the original system. The equivalent circuit is developed to model UPFC. The voltage equations of the equivalent circuit are rearranged to form a non linear state space model. The selected state variables are shunt and series transformer current as well as dc link capacitor voltage. This non linear state model will linearize by the FBLC control algorithm and do the control actions on the linearized system. The UPFC requires four reference inputs for its proper functioning, namely the active power (P_{ref}), reactive power (Q_{ref}), voltage at the shunt transformer coupling point (V_{1ref}), and DC link capacitor voltage (V_{DCref}). These reference inputs are given to the shunt and series transformer control blocks, and it is crucial to track these set points accurately for the two converters of the UPFC.

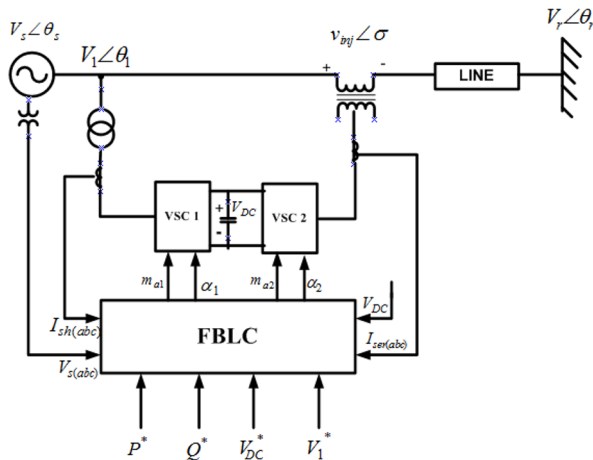


Fig. 1. UPFC with FBLC is connected to SMIB system.

3. Non linear modeling of UPFC

The Unified Power Flow Controller (UPFC) consists of two back-to-back converters linked by a DC capacitor. In Figure 2, the UPFC's equivalent circuit displays two controlled current sources representing the converters. This equivalent circuit is utilized to simulate the non-linear behavior of the UPFC. The sending end voltage is $V_s \angle \theta_s$, $V_r \angle \theta_r$ is the receiving end voltage. The modulation index and triggering angle required for the functioning of shunt and series converter are obtained from FBLC algorithm.

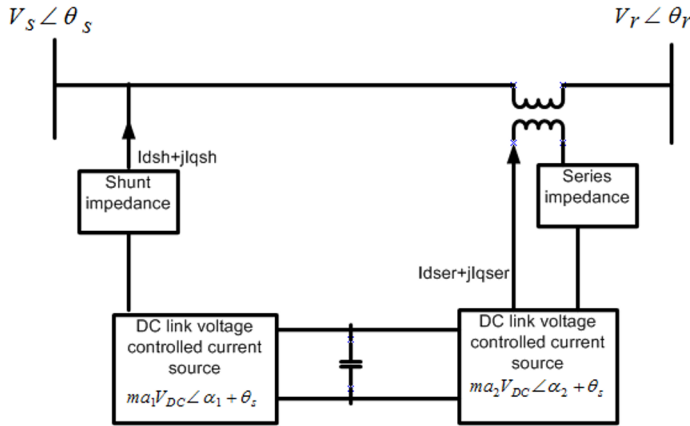


Fig. 2.The equivalent circuit of UPFC.

A non linear Multiple Input Multiple Output (MIMO) system is represented as in (1).

$$\dot{x} = f(x) + \sum_{i=1}^n g_i(x)u_i$$

$$y(x) = V(x) \tag{1}$$

The UPFC is modeled as fifth order system because five state variables are selected for the system modeling. The KVL equations for the equivalent circuit [3,9] is arranged as a state space model as in (2). Where f, g_i are smooth vector fields. $V(x)$ is the output vector and selected as the energy equation. The state vector $\dot{x} = [id_{sh} \ iq_{sh} \ id_{ser} \ iq_{ser} \ v_{DC}]$ are the d-q components of shunt converter current, series converter current and DC link capacitor voltage.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix} = \begin{bmatrix} \frac{-R_{sh} \omega s}{L_{sh}} x_1 + \omega x_2 - \frac{\omega s v_{sd}}{L_{sh}} \\ \frac{-R_{sh} \omega s}{L_{sh}} x_2 + \omega x_1 - \frac{\omega s v_{sq}}{L_{sh}} \\ \frac{-R_{ser} \omega s}{L_{ser}} x_3 + \omega x_4 + \frac{\omega s (v_{sd} - v_{rd})}{L_{ser}} \\ \frac{-R_{ser} \omega s}{L_{ser}} x_4 - \omega x_3 + \frac{\omega s (v_{sq} - v_{rq})}{L_{ser}} \\ -\frac{\omega s}{C_{dc} R_d} x_5 \end{bmatrix} + \begin{bmatrix} \frac{\omega s}{L_{sh}} x_5 & 0 & 0 & 0 \\ 0 & \frac{\omega s}{L_{sh}} x_5 & 0 & 0 \\ 0 & 0 & \frac{\omega s}{L_{ser}} x_5 & 0 \\ -\frac{\omega s}{C_{dc}} x_1 & -\frac{\omega s}{C_{dc}} x_2 & -\frac{\omega s}{C_{dc}} x_3 & -\frac{\omega s}{C_{dc}} x_4 \end{bmatrix} \begin{bmatrix} u_{11} \\ u_{21} \\ u_{31} \\ u_{41} \end{bmatrix}$$

$$y(x) = V(x) = \frac{Ls_1}{2} (x_1^2 + x_2^2) + \frac{Ls_2}{2} (x_3^2 + x_4^2) + \frac{C_{dc}}{2} (x_5^2) \tag{2}$$

And the control input matrix is
$$\begin{bmatrix} u_{11} \\ u_{21} \\ u_{31} \\ u_{41} \end{bmatrix} = \begin{bmatrix} m_{a1} \cos(\alpha_1 + \theta_s) \\ m_{a1} \sin(\alpha_1 + \theta_s) \\ m_{a2} \cos(\alpha_2 + \theta_s) \\ m_{a2} \sin(\alpha_2 + \theta_s) \end{bmatrix}.$$

4. Feedback Linearization Technique

Feedback linearization is a method employed to linearize a non-linear system by means of a coordinate transformation [8]. It works in two control loops, one is cancels all non linearities present in the system and another is tracking the control objectives. The next stage involves employing a linear control technique. Essentially, FBLC is a method used to achieve input-output linearization of the MIMO system by iteratively differentiating the system's output y until the inputs become apparent [11]. The derivatives obtained is known as Lie derivatives which can be written as $L_f h(x)$, $L_g h(x)$ etc where:

$$L_f h(x) = \frac{\partial h(x)}{\partial x} f(x) \quad (3)$$

$$L_g h(x) = \frac{\partial h(x)}{\partial x} g(x) \quad (4)$$

The block schematic of the algorithm describes all the necessary steps of FBLC is shown in Fig. 3.

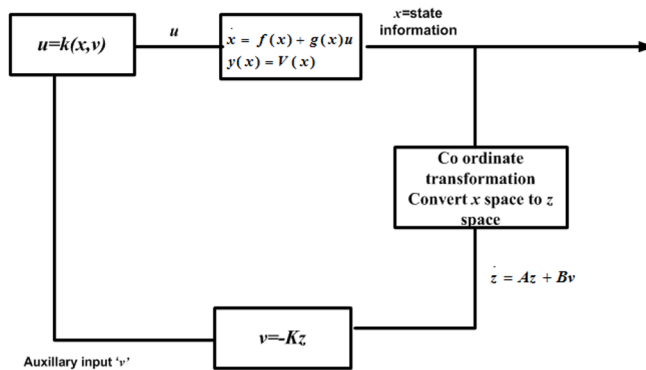


Fig. 3. Block schematic of FBLC

The non linear system is first modelled as an affine system that can be used for FBLC algorithm [9]. The state information is obtained from the UPFC and coordinate transformation is applied. For this transformation, the output vector $V(x)$ is selected as a positive definite function and doing Lie derivatives of the output vector until the input vector appears in the equation. The resultant new systems of equations are represented in 'z' space. So it appears like, the coordinate transformation is converting 'x' space to 'z' space which is linear in nature. The coordinate transformation will result in a linear system given by (5).

$$\dot{z} = Az + Bv \quad (5)$$

The linearized system matrix is denoted as A , the input matrix as B , and the auxiliary input vector as v .

In the z space, it is possible to utilize any linear control technique to determine the auxiliary input vector 'v'. In this research paper, the Linear Quadratic Regulator (LQR) technique is employed to calculate 'v' as mentioned in equation (6). The newly modified control input 'u', which is applied to the non-linear system, is dependent on both the auxiliary input vector 'v' and the state vector 'x' as indicated in equation (7). The relationship between 'u' and 'x' is established through the inverse coordinate transformation. By utilizing the control input 'u', the system exhibits a linear response to all non-linear functions.

$$v = -Kz \quad (6)$$

$$u = \begin{bmatrix} L_{g1}L_fV(x) & L_{g2}L_fV(x) & L_{g3}L_fV(x) & L_{g4}L_fV(x) \\ L_{g1}\varphi_3(x) & L_{g2}\varphi_3(x) & L_{g3}\varphi_3(x) & L_{g4}\varphi_3(x) \\ L_{g1}\varphi_4(x) & L_{g2}\varphi_4(x) & L_{g3}\varphi_4(x) & L_{g4}\varphi_4(x) \\ L_{g1}\varphi_5(x) & L_{g2}\varphi_5(x) & L_{g3}\varphi_5(x) & L_{g4}\varphi_5(x) \end{bmatrix}^{-1} \begin{bmatrix} v_1 - L_f^2V(x) \\ v_2 - L_f\varphi_3(x) \\ v_3 - L_f\varphi_4(x) \\ v_4 - L_f\varphi_5(x) \end{bmatrix} \quad (7)$$

ie. $u=k(x,v)$.

5. LQR control Technique

The UPFC is linearized by using Feedback linearization technique. Now the system is in z space and is a continuous time linear system. The optimal feedback gain matrix K of LQR matrix is $v = -Kz$ used for minimizing the quadratic cost function.

$$J = \int_0^N (x^T Q x + u^T R u) dt \quad (8)$$

Subjected to the constraints $Q \geq 0$, $R > 0$ where Q is state cost matrix and R is the control weighted matrix. The optimal feedback gain matrix K can be computed by $K = R^{-1} B^T P$. Where P is a positive definite matrix and is solved from Riccati equation. $\dot{x} = (A - BK)x$ is the output closed loop system which is a linear time varying system and have a full-state feedback regulator that minimizes the quadratic cost function.

6. Simulation results

The linearized state space model after coordinate transformation is given by (9).

$$\dot{z} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} \quad \text{and} \quad y =$$

$$[1 \ 0 \ 0 \ 0 \ 0] \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \end{bmatrix} + [0]v \quad (9)$$

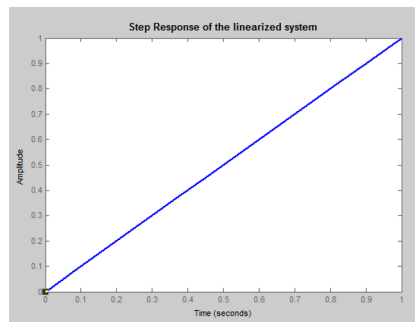


Fig. 4. Step response of the linearized system.

The transfer function model of the system is found by using the A, B, C, D matrices of the linearized system. The step response of the linear system is shown in Fig. 4. The graph shows that UPFC behaves like a linear system after FBLC. Pole zero mapping for different inputs shows that some of the poles are located at the origin making the system marginally stable condition as shown in Fig. 5(a). So to make the system stable, it has to be controlled

through the linear control techniques. LQR controller is one of the best linear controller is used here.

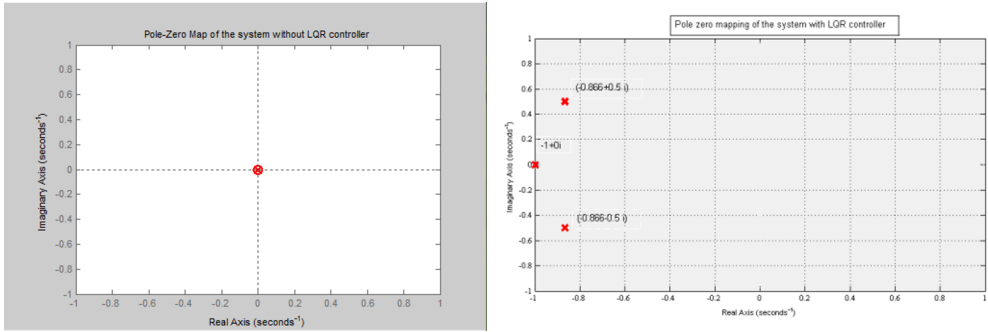


Fig. 5. Pole zero mapping of the system (a) without LQR controller; (b) with LQR controller.

The LQR controller ensures the stability by finding out the feedback gain matrix K . Depending on the location of eigen values, stability can be analyzed. If the eigen values are on the left half of s plane, system is stable, if it is on the right half of s plane, the system is unstable. If the eigen values on the imaginary axis, the system is marginally stable and any parameter variations can make the system in unstable condition. The eigen values of the linearized system is found to be $-0.866\pm 0.5i, -1, -1, -1$. The pole locations after LQR controller shown in Fig. 5(b). All poles located on the left half of s plane and stability is guaranteed. This is the main advantage of LQR control techniques.

The design parameters for UPFC is listed in the Table 1. Reference signals needed for shunt and series converter control are found out from the design details. The linear states from the UPFC are controlled by PI controller and are used for generating change in modulation index and phase shift required for the converters. The control logic for generating pulses is shown in Fig. 6.

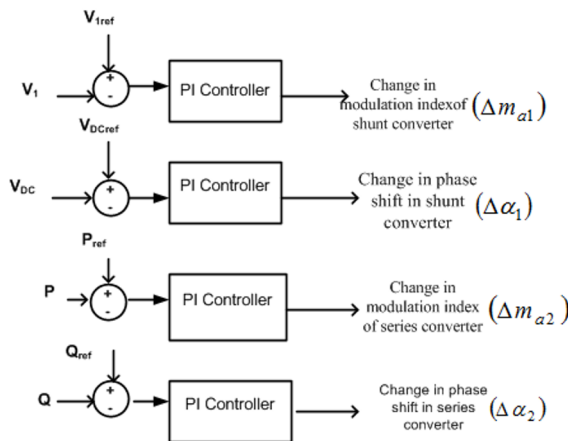


Fig. 6. Modulation index and triggering angle generation for shunt and series converter.

Table 1 Design parameters of UPFC model

Parameters	Values
Base Power	100 MVA
UPFC rating	33.33MVA
Line to line voltage	110kV
DC link capacitor voltage	33kV
Coupling transformer shunt inductance	0.15 p.u
Coupling transformer series inductance	0.0166 p.u
Sending end voltage	$1\angle 30^\circ(pu)$
Receiving end voltage	$1\angle 0^\circ(pu)$

7. Conclusion

Feedback linearization is a technique used in control systems to convert a nonlinear system into an equivalent linear system by manipulating state variables and selecting a suitable control input 'u'. This paper focus on the non linear modeling of UPFC and Feedback Linearization Control technique applied to linearize it. The stability of the linearized system is improved by using LQR control techniques. And also there is no pole zero cancellation in the system because of that state information is remains unaltered.FBLC can also control the converter operation with tracking of the references signals. So FBLC has two control loops, one is for linearizing states and another is for tracking the reference signals. The operating range of the system can be widened by using this control technique.

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