# A Nonlinear Controller for Unified Power Flow Controller

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**Abstract**: A unified power flow controller (UPFC) can independently control real power and reactive power in power line, which makes it attractive in increasing the transmission capability of transmission line. This paper presents a nonlinear control law with better stability and dynamic performance in comparison with PI controller and classical decoupled strategy. The analysis is based on the rotating reference frame, and the nonlinear property of UPFC model is partly dealt through the exact linearization via feedback. The control law is tested with the EMTDC/PSCAD program system.

**Key words**: unified power flow controller (UPFC); exact linearization via feedback; nonlinear control law

**CLC number**: TM761

## 0 Introduction

A unified power flow controller (UPFC) can provide simultaneous, real-time control of all or any combination of the basic power system parameters (transmission voltage, line impedance and phase angle), which determine the transmittable power. Thus, the UPFC can fulfill all the functions of reactive shunt compensation, series compensation, and phase shifting, and thereby meet multiple power flow control objectives.

A UPFC consists of 2 voltage-sourced converters connected by a common dc link. The series converter provides the main function of UPFC by injecting an ac voltage with controllable magnitude and phase, therefore to control the transmission line's real/reactive power. The shunt converter supplies the real power demanded by the series converter and controls the bus voltage.

The UPFC control system is to enable the device to follow the changes in reference values of active and reactive power. In reference [1], PI regulators was used to control dc link voltage and bus voltage, which would cause excessive delay in balancing real power between series and shunt converter, and would lead to the collapse of dc link voltage under transient conditions. In references [2~4], decoupled control algorithm was proposed based on rotating reference frame theory to reduce the interactions between the active and reactive power control. As had been pointed out in reference [5] that one limit of this decoupling method was neglecting of coupling through the dc link voltage. Besides, more than 6 PI regulators were employed to control series and shunt converters connected through dc link, and they were very difficult to be tuned.

The active and reactive power flows in the series converter are determined by the magnitude and phase of the injected voltage, and can be set according to the references in an open loop mode. If dc link voltage is controlled to be constant during transitions, dynamics of power flow control will not be degraded. Under that condition, the shunt converter can be viewed as a typical static var compensator (STATCOM) that is easy to be controlled. In this paper, a nonlinear control law based on linearization via exact feedback theory is proposed to control the bus voltage and dc link voltage, while the series converter operates in an open loop mode. The control system is depicted and its performance is tested through simulation.

## 1 Control System for UPFC

The basic scheme of a UPFC is depicted in Fig. 1. The series converter and shunt converter are controlled according to different laws as follow.

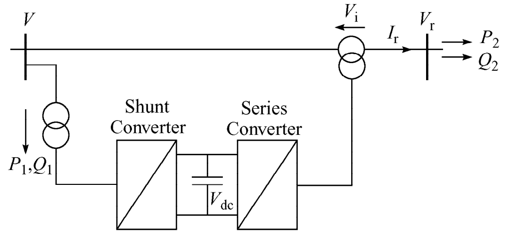


**Fig. 1 Basic scheme of a UPFC**

### 1.1 Control for Series Converter

Series converter injected a voltage with controllable magnitude and phase between sending end and receiving end of power line. The real and reactive power flow under control could be described as follows[6]:

$$\begin{cases} P_2 = \dfrac{VV_r}{X}\sin\delta + \dfrac{V_rV_i}{X}\sin(\delta+\rho) \\ Q_2 = \dfrac{VV_r}{X}(1-\cos\delta) + \dfrac{V_rV_i}{X}\cos(\delta+\rho) \end{cases} \tag{1}$$

where, $V$ is the bus voltage of sending end; $V_r$ is the bus voltage of receiving end; $X$ is transmission line reactance; $\delta$ is power angle; $V_i$ and $\rho$ are the magnitude and phase of injected voltage by series converter.

Under open loop control mode, $V_i$ and $\rho$ can be

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determined by solving equation (1) according to real and reactive power references, and to be used as control parameters of pulse width modulation (PWM) strategy of series converter. The control configuration for series converter is depicted in Fig. 2.

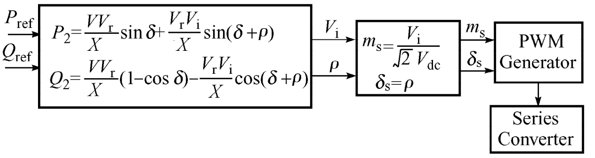


**Fig. 2 Open loop control law of series converter**

Considering the control structure of series converter, it is clear that real and reactive power flow under control can step from one reference to another, only if dc link voltage remains constant during the transition. This is a primary and critical task of the control law for shunt converter.

### 1.2 Control for Shunt Converter

The fundamental analysis method of STATCOM was established in references [7～10] based on rotating reference frame, which can be extended to the analysis of shunt branch of UPFC. The shunt branch of UPFC can be viewed as a voltage-sourced converter connected to power line. So the mathematical model of UPFC can be established based on simplified model of a converter connected to the system (shown in Fig. 3).

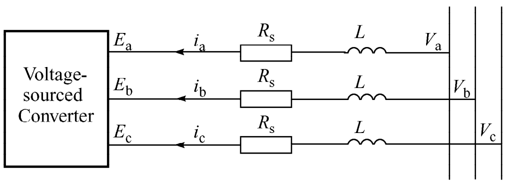


**Fig. 3 Simplified model of a converter connected to the system**

Using abc-$dq$ transformation, the full state equation of a converter connected to the system is described in the synchronously rotating reference frame as follows [7～10]:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix}=\begin{bmatrix} -\frac{R_s}{L} & \omega & \frac{-m\cos\delta_s}{L} \\ -\omega & -\frac{R_s}{L} & \frac{-m\sin\delta_s}{L} \\ \frac{m\cos\delta_s}{C} & \frac{m\sin\delta_s}{C} & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix}+\frac{1}{L}\begin{bmatrix} V_s \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

where, $i_d$, $i_q$ are the $d$ and $q$ axis currents respectively; $V_{dc}$ is the dc link voltage; $\omega$ is the synchronously rotating angle speed; $R_s$ and $L$ are the series resistance and inductance respectively; $C$ is the capacitance of dc link; $V_s$ is the $d$-axis component of power line voltage; $m$ is modulation ratio; $\delta_s$ is the phase angle between power line voltage and converter output voltage.

$m$ and $\delta_s$ are the control inputs of PWM strategy for converter. When selecting the state vector as:

$$\boldsymbol{X}=[x_1,x_2,x_3]^{\mathrm{T}}=[i_d,i_q,V_{dc}]^{\mathrm{T}}$$

and the new control vector as:

$$\boldsymbol{U}=\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}=\begin{bmatrix} m\cos\delta_s \\ m\sin\delta_s \end{bmatrix}$$

then, according to the theory of exact linearization via feedback [11～13], the equation (2) can be transformed as follows:

$$\begin{cases} \dot{\boldsymbol{X}}=\boldsymbol{f}(\boldsymbol{X})+\boldsymbol{g}_1(\boldsymbol{X})u_1+\boldsymbol{g}_2(\boldsymbol{X})u_2 \\ \boldsymbol{Y}=\begin{bmatrix} h_1(\boldsymbol{X}) \\ h_2(\boldsymbol{X}) \end{bmatrix} \end{cases} \tag{3}$$

where,

$$\boldsymbol{f}(\boldsymbol{X})=\begin{bmatrix} \frac{-R_s}{L}x_1+\omega x_2+\frac{V_s}{L} \\ -\omega x_1-\frac{R_s}{L}x_2 \\ 0 \end{bmatrix}$$

$\boldsymbol{g}_1(\boldsymbol{X})=\left[\frac{-x_3}{L},0,\frac{x_1}{C}\right]^{\mathrm{T}}$; $\boldsymbol{g}_2(\boldsymbol{X})=\left[0,\frac{-x_3}{L},\frac{x_2}{C}\right]^{\mathrm{T}}$; $h_1(\boldsymbol{X})=x_1$; $h_2(\boldsymbol{X})=x_2$.

It can be valid that the system described by equation (3) has a relative degree of $r=\{1,1\}$, which has a fairly standard form. In order to make the output $\boldsymbol{Y}$ asymptotically track a reference vector $\boldsymbol{Y}_{ref}$, derivates of $\boldsymbol{Y}$ is obtained.

$$\dot{\boldsymbol{Y}}=\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix}=\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix}=\begin{bmatrix} \frac{-R_s}{L}x_1+\omega x_2+\frac{V_s}{L}-\frac{x_3}{L}u_1 \\ -\omega x_1-\frac{R_s}{L}x_2-\frac{x_3}{L}u_2 \end{bmatrix}$$

Selecting the new state vector as:

$$\boldsymbol{Z}=[z_1\quad z_2]^{\mathrm{T}}=[y_1\quad y_2]^{\mathrm{T}}$$

and new control vector as:

$$\boldsymbol{V}_c=\begin{bmatrix} v_1 \\ v_2 \end{bmatrix}=\begin{bmatrix} \frac{-R_s}{L}x_1+\omega x_2+\frac{V_s}{L}-\frac{x_3}{L}u_1 \\ -\omega x_1-\frac{R_s}{L}x_2-\frac{x_3}{L}u_2 \end{bmatrix} \tag{4}$$

the system can be rewritten as follows:

$$\begin{cases} \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix}=\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \\ \boldsymbol{Y}=\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \end{cases} \tag{5}$$

According to the above equation (5) and stability control theory, the P controller is obtained.

$$\begin{cases} v_1=\lambda_1(z_{1ref}-z_1)=\lambda_1(i_d^*-i_d) \\ v_2=\lambda_2(z_{2ref}-z_2)=\lambda_2(i_q^*-i_q) \end{cases} \tag{6}$$

where, $\lambda_1$, $\lambda_2$ are the proportional factors, which determine the response speed of active and reactive current.

By transforming the equation (4) and equation (6), the control law is then obtained.

$$\boldsymbol{U}=\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}=\begin{bmatrix} \frac{L}{x_3}\left(\frac{-R_s}{L}x_1+\omega x_2+\frac{V_s}{L}-v_1\right) \\ \frac{L}{x_3}\left(-\omega x_1-\frac{R_s}{L}x_2-v_2\right) \end{bmatrix}=$$

$$\begin{bmatrix} \frac{L}{x_3}\left[\frac{-R_s}{L}x_1+\omega x_2+\frac{V_s}{L}-\lambda_1(i_d^*-i_d)\right] \\ \frac{L}{x_3}\left[-\omega x_1-\frac{R_s}{L}x_2-\lambda_2(i_q^*-i_q)\right] \end{bmatrix} \tag{7}$$

Since, a primary and critical task of the control law for shunt converter is to control dc link voltage to remain constant. So $i_d^*$ is varied in response to the error of the dc link voltage via a proportional plus integral compensation. Similarly, $i_q^*$ varies in response to the error of bus voltage so as to control the bus voltage at a constant level. The system with nonlinear control law and 4 controllers is described in Fig. 4.

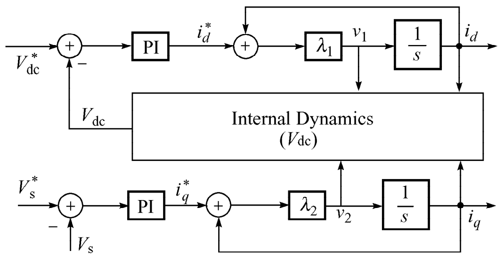


**Fig. 4 Structure of the nonlinear controller**

## 2 Simulation Results

A 100 Mvar UPFC connected to a simple power system is simulated using EMTDC/PSCAD program system. Both inverters of the UPFC are three phase full bridge PWM converters. The coupling transformer at shunt side is a 230 kV/20 kV Y, d configured transformer with leak reactance equal to 0.1 p.u. The coupling transformer at series side are three single phase 20 kV/132 kV transformer with leak reactance equal to 0.1 p.u. DC-link capacitor is 2 000 μF. Responses to real/reactive power reference steps and single phase to ground fault are studied. Two cases are considered:

Case 1: The UPFC is controlled by PI controllers only, as presented in reference [1].

Case 2: The series converter operates in open loop mode (Fig. 2) while the shunt converter is controlled according to nonlinear control law (Fig. 4). The parameters of controller are: $\lambda_1=\lambda_2=1\ 000$; DC-link voltage regulator: $K_{P1}=2$, $K_{I1}=10$; bus voltage regulator: $K_{P2}=3.5$, $K_{I2}=10$.

Both cases are operated as follows: at 3 s, real power reference steps rise from 0 to 100 MW, and then to −100 MW at 4 s. A single phase to ground fault happens at 5 s and is cleared at 5.05 s. Fig. 5 and Fig. 6 show the simulation results of case 1 and case 2 accordingly. It appears that during transitions of reference steps, real power injected to dc link capacitor swings at case 1, causing dc link voltage increases or decreases consequently, which degrades dynamic performance of power flow transition and profile of bus voltage. When nonlinear control law is applied to shunt converter, the dc link voltage remains almost constant during transitions. Consequently, the dynamic performances of power flow and bus voltage appear to be "stiffer". When single phase to ground fault happens at 5 s, bus voltage decreases at both cases. After the fault is cleared at 5.05 s, bus voltage restores in different mode: an overshoot appears at case 1 while no overshoot appears at case 2, which proves the superiority of controlling dc link voltage at a constant level.

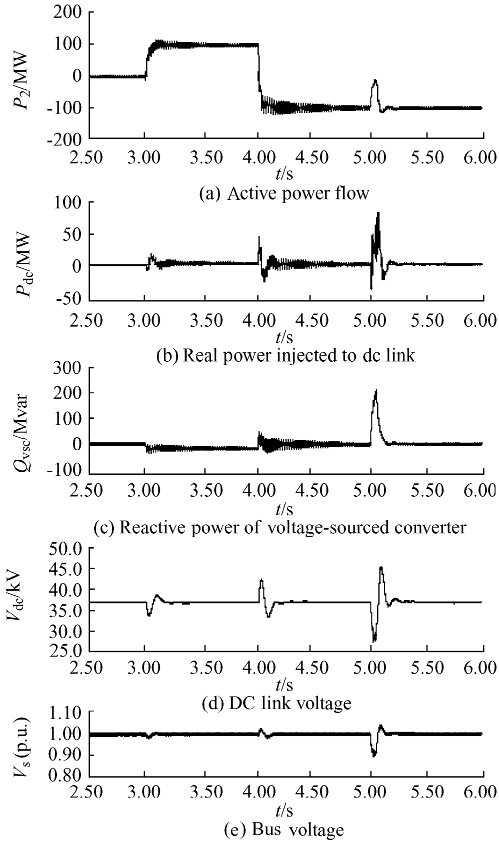


**Fig. 5 Simulation results of case 1 (PI controller)**

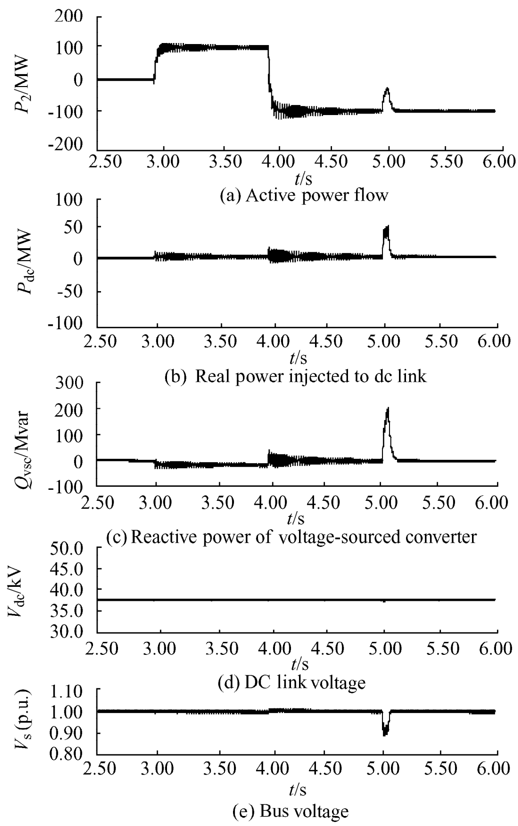


**Fig. 6 Simulation results of case 2 (nonlinear controller)**

## 3 Conclusions

In this paper a nonlinear control system for the UPFC is proposed, its salient features are:

1) Nonlinear properties of voltage-sourced converter connected to power system are thoroughly considered. Based on the theory of linearization via feedback, a nonlinear control law is applied to the shunt branch of UPFC.

2) The series converter of UPFC is controlled in an open loop mode, which reduces the complexity of control system and makes it easier to tune the parameters of regulators.

3) During the transitions of reference steps or system faults, dc link voltage of UPFC remains almost constant, which consequently enables the good dynamic performance of power flow and bus voltage.

Besides, the whole process of controller design can be easily generalized to other power electronics converters.

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# 统一潮流控制器的非线性控制

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**摘要：**通过独立控制线路的有功和无功功率，统一潮流控制器(UPFC)能够大大提高线路的传输能力。为实现这一目标，装置需要尽可能快的动态响应速度和稳定性。文中提出一种适用于UPFC装置的非线性控制策略，该控制器的理论分析基于同步旋转坐标系，充分考虑了UPFC模型的非线性特点，采用反馈精确线性化的方法进行分析。在此基础上设计得到的控制器较之传统的PI控制和解耦控制策略具有更好的稳定性和更快的动态响应。在EMTDC/PSCAD平台下的仿真结果验证了这种控制策略的优越性能。

**关键词：**统一潮流控制器(UPFC)；反馈精确线性化；非线性控制规律