Delay Dependent H_∞ Based Robust Control Strategy for Unified Power Quality Conditioner in a Microgrid

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Abstract

This paper proposes a novel robust control scheme based on delay-dependent *H*∞ for unified power quality conditioner (UPQC) in a microgrid under the influence of the delay and parameter uncertainties. A new UPQC model considering the effects of the delay and parameter uncertainties is established. Then, the *H*∞ controller is designed based on the cone complementarity linearization (CCL) algorithm. Finally, the effectiveness of the proposed control method is demonstrated by numerical simulations.

Keywords—UPQC; Delay; Parameter uncertainties; H∞ controller; Microgrid

1. Introduction

Recently, the microgrids have been investigated widely by many researchers. Among these studies, the research on the power quality problems of a microgrid is a promising scientific direction. The power quality problems in a microgrid are mainly from the following three aspects: 1) Power electronic switches and inverters are widely used in a microgrid. The use of power electronic devices will inevitably bring a lot of harmonics to a microgrid [1]. 2) Due to the impact of natural conditions, photovoltaic cells, wind turbines and other distributed generations have intermittence and volatility. These characteristics are easy to cause voltage fluctuation and flicker of a microgrid [2]. 3) The asymmetry of nonlinear loads will cause the generation of the negative-sequence currents in a microgrid [3].

Currently, the main control method to solve the power quality problems in a microgrid is to install various compensating devices such as static var compensators [4], dynamic voltage restorers [5], active power filters (APFs) [6] and so on. These compensating devices have been widely used in practice. But each of them can only compensate for one or two particular power quality problems [7]. Previous literatures [8,9] have suggested that the unified power quality conditioner (UPQC) can be used to compensate a lot of power quality problems in a microgrid. The UPQC is formed by series active power filter (APF) and shunt APF connected back to back with a common energy storage element. It can compensate for voltage flicker/imbalance, reactive power, negative-sequence current, harmonics and other power quality problems simultaneously [10,11]. Considering the complexity and diversity of power quality problems in a microgrid, using the UPQC to solve its power quality problems is very effective.

Currently, the detection methods of the UPQC are classified as frequency domain methods and time domain methods. Frequency domain methods are mainly based on improved fast Fourier transform methods. Because of the large delays in the calculation, the real-time performance of these methods is poor. Time domain methods are based on instantaneous derivation of compensating commands in the form of either voltage or current signals [13]. Instantaneous active and reactive power theory based $\alpha\beta$ transformation method [10] and synchronous rotating coordinate transformation method [11,12] are the two commonly used time domain methods for the UPQC. Both methods also have the delay problems due to complicated coordinate transformation.

The delays probably have a bad effect on the stability of the UPQC. If the delays are large, they may lead to the instability of the entire system. Moreover, under the influence of the delay, the control performance of the controller in the power system will be deteriorated. The delay and parameter uncertainties in the UPQC are the two factors which can seriously deteriorate the stability and control performance of the system. However, there are almost no literature considering both the stability problems and control performance problems of the UPQC under the influence of the delay and parameter uncertainties so far.

In this paper, a new control design for the UPQC in a microgrid is proposed. Both the delay and parameter uncertainties are taken into account in the modeling and stability analysis of the UPQC. Numerical simulations of the UPQC in a microgrid are conducted to confirm the validity of the proposed control design.

2. Modeling of the UPQC

The microgrid is an integration of distributed generations, loads, energy storage batteries and other devices. Fig. 1 shows a single-phase microgrid with the UPQC [8]. The UPQC in it is made up of series and shunt APFs with a common DC link capacitor. Through a coupling transformer, the series APF is connected in series between the distributed generations and the loads. It can compensate for voltage harmonics and voltage fluctuation caused by distributed generations [14]. The shunt APF is connected in parallel to the side near the loads through an output inductor. It can compensate for current harmonics and negative-sequence currents caused by nonlinear loads. The single-phase equivalent circuit of the UPQC is shown in Fig. 2. The V_s

represents the supply voltage. Due to the intermittence and volatility of the distributed generations in the microgrid, V_s will be distorted. The distorted V_s is composed of the fundamental component V_f and harmonic component V_h. The load current is denoted by i_L. For the use of the nonlinear loads in the microgrid, i_L will also be distorted. The distorted i_L consists of fundamental component if and harmonic component i_h. i_s represents the supply current and V_L denotes the load voltage. A task of the UPQC is to compensate for i_s and V_L under the influence of the distorted i_L and V_s , so that i_s and V_L can remain standard sine waves without any harmonics. R_l and L_l compose the line impedance.

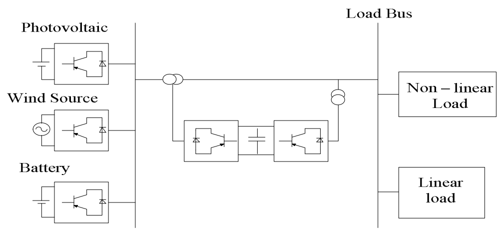

Fig.1 Single-phase microgrid with UPQC

In Fig. 2, the output voltages of the voltage source inverters (VSIs) in the series and shunt APFs of the UPQC are represented by $\frac{V_{dc}}{2}u_1$ and $\frac{V_{dc}}{2}u_2$, respectively. $\frac{V_{dc}}{2}$ denote the reference voltage of the DC link capacitor in the UPQC. The internal resistances of the series and shunt VSIs are modeled by Rse and R_{sh}, respectively. L_{se}, C_{se} and L_{sh}, C_{sh} compose two low-pass filters which can be used to eliminate the higher harmonics in the output voltage of the VSIs. The injected voltage of the series APF and the injected current of the shunt APF are represented by V_{inj} and I_{inj}, respectively.

Applying the Kirchhoff's voltage and current laws to the three current loops in Fig. 2, the state-space equations of the UPQC can be obtained as [15]:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + B_W w(t) \\ Z(t) = Cx(t) + Du(t) \end{cases} \tag{1}$$

where

$$A = \begin{bmatrix} -\frac{R_l}{L_l} & -\frac{1}{L_l} & 0 & 0 & -\frac{1}{L_l} \\ \frac{1}{C_{sh}} & 0 & 0 & \frac{1}{C_{sh}} & 0 \\ 0 & 0 & -\frac{R_{se}}{L_{se}} & 0 & -\frac{1}{L_{se}} \\ 0 & -\frac{1}{L_{sh}} & 0 & -\frac{R_{sh}}{L_{sh}} & 0 \\ \frac{1}{C_{se}} & 0 & \frac{1}{C_{se}} & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{V_{dc}}{2L_{se}} & 0 \\ 0 & \frac{V_{dc}}{2L_{sh}} \\ 0 & 0 \end{bmatrix},$$

$$B_W = \begin{bmatrix} \frac{1}{L_l} & 0 \\ 0 & -\frac{1}{C_{sh}} \\ 0 & 0 \\ 0 & 0 \\ 0 & \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \quad D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$x(t) = [i_S(t) \quad v_L(t) \quad i_{se}(t) \quad i_{inj}(t) \quad v_{inj}(t)]^T$ is the state vector, $u(t) = [u_1(t) \quad u_2(t)]^T$ and $w(t) = [v_S(t) \quad i_L(t)]^T$ are the control input vector and disturbance input vector, respectively. $z(t) = [i_S(t) \quad v_L(t)]^T$ is the output vector.

On the basis of the above state-space model, a new UPQC model considering the influence of the delay and parameter uncertainties is built as follows:

$$\begin{cases} \dot{x}(t) = (A + \Delta A)x(t) + (B + \Delta B)u(t - d(t)) + (B_W + \Delta B_W)w(t) \\ z(t) = Cx(t) + Du(t) \\ x(t) = 0, \quad t \in [-h_2, 0] \end{cases} \tag{2}$$

where x(t), w(t), z(t), A, B, B_w and C have been defined in (1). ΔA, ΔB and ΔB_w are uncertain matrices. that satisfy the following conditions:

$$[\Delta A \quad \Delta B \quad \Delta B_W] = HF[E_1 \quad E_2 \quad E_3] \tag{3}$$

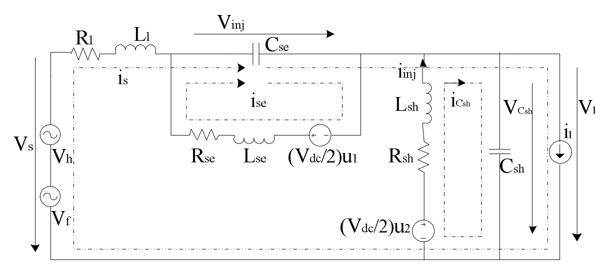

Fig.2 Single-phase equivalent circuit of the UPQC

where

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}, \quad E_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 \\ 0 & -1 & 0 & 0 & 0 \end{bmatrix},$$

$$E_2 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{V_{dc}}{2} & 0 \\ 0 & \frac{V_{dc}}{2} \end{bmatrix}, \quad E_3 = \begin{bmatrix} 0 & 0 \\ 0 & -1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$F=\begin{bmatrix}0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & \frac{-\Delta C_{sh}}{C_{sh}(C_{sh}+\Delta C_{sh})} & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & \frac{R_{se}\Delta L_{se}}{L_{se}(L_{se}+\Delta L_{se})} & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{R_{sh}\Delta L_{sh}}{L_{sh}(L_{sh}+\Delta L_{sh})} & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{-\Delta C_{se}}{C_{se}(C_{se}+\Delta C_{se})} & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{-\Delta L_{se}}{L_{se}(L_{se}+\Delta L_{se})} & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{-\Delta L_{sh}}{L_{sh}(L_{sh}+\Delta L_{sh})}\end{bmatrix}$$

H, E_1, E_2 and E_3 are known constant matrices which reflect the structural information of uncertain parameters. F is an uncertain parameter matrix which satisfies

$$F^T F \le I \tag{4}$$

d(t) represents the total delay of the UPQC, which includes the delays caused by detection methods, hardware circuits as well as software programs. Because these delays are mainly from the detection process, d(t) is placed in the control input term. In addition, due to the signal detection in the UPQC is a dynamic process, we assume that d(t) is a time-varying delay and satisfies the following conditions:

$$0 \le h_1 \le d(t) \le h_2,\ \dot{d}(t) \le \mu \tag{5}$$

where h_1, h_2 and μ are constants. x(t) = 0, t □ [−h_2, 0] denotes the zero initial conditions.

3. . Control design

A memory-less state feedback control law for the UPQC is designed as

$$u(t) = Kx(t) \tag{6}$$

x(t) is defined in (1) and K is a constant gain matrix which need to be determined later.

Under (6), the closed-loop system of (2) can be obtained as

$$\begin{cases}\dot{x}(t) = (A + HFE_1)x(t) + (BK + HFE_2K)x(t-d(t)) \\ \qquad + (B_W + HFE_3)w(t) \\ z(t) = Cx(t) + Du(t) \\ x(t) = 0, \quad t \in [-h_2, 0]\end{cases} \tag{7}$$

The Lyapunov-Krasovskii functional approach and H∞ control theory will be applied to derive a delay-dependent stability criterion.

Given scalars $\gamma > 0$, $h_2 > h_1 > 0$ and μ, if there exist appropriately dimensional matrices $\bar{P} > 0$, $\bar{Q}_i > 0$, i = 1, 2, 3, $\bar{R}_j > 0$, $j = 1, 2$, V and a scalar $\xi > 0$ such that the following matrix inequality holds:

$$\Theta=\begin{bmatrix}\Theta_{11} & BV & 0 & \bar{R}_1 & B_w & h_2\bar{P}A^T & h_{12}\bar{P}A^T & \xi H & \bar{P}E_1^T & \bar{P}C^T\\ * & \Theta_{22} & \bar{R}_2 & \bar{R}_2 & 0 & h_2V^TB^T & h_{12}V^TB^T & 0 & V^TE_2^T & 0\\ * & * & \Theta_{33} & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ * & * & * & \Theta_{44} & 0 & 0 & 0 & 0 & 0 & 0\\ * & * & * & * & -\gamma^2 I & h_2B_W^T & h_{12}B_W^T & 0 & E_3^T & 0\\ * & * & * & * & * & -PR_1^{-1}P & 0 & h_2\xi H & 0 & 0\\ * & * & * & * & * & * & -\bar{P}\bar{R}_2^{-1}\bar{P} & h_{12}\xi H & 0 & 0\\ * & * & * & * & * & * & * & -\xi I & 0 & 0\\ * & * & * & * & * & * & * & * & -\xi I & 0\\ * & * & * & * & * & * & * & * & * & -I\end{bmatrix}<0 \tag{8}$$

where

$$\begin{cases}\Theta_{11} = A\bar{P} + \bar{P}A^T + \bar{Q}_1 + \bar{Q}_2 + \bar{Q}_3 - \bar{R}_1\\ \Theta_{22} = -(1-\mu)\bar{Q}_1 - 2\bar{R}_2\\ \Theta_{33} = -\bar{Q}_2 - \bar{R}_2\\ \Theta_{44} = -\bar{Q}_3 - \bar{R}_1 - \bar{R}_2\end{cases}$$

then the closed-loop system (7) is asymptotically stable for any parameter uncertainties satisfying (4) and any delay satisfying (5). Besides, the system (7) has a given H∞ performance under zero initial conditions. Moreover, the H∞ controller gain matrix $K = V\bar{P}^{-1}$.

Defining $\bar{P} = P^{-1}$, $\bar{Q}_i = P^{-1}Q_iP^{-1}$, i = 1, 2, 3, $\bar{R}_j = P^{-1}R_jP^{-1}$, j = 1, 2, $K = V\bar{P}^{-1}$, $\xi = \varepsilon^{-1}$, formula (8) will be obtained.

Owing to the term $\bar{P}\bar{R}_1^{-1}\bar{P}$ and $\bar{P}\bar{R}_2^{-1}\bar{P}$ in (8), the condition in Theorem is not a linear matrix inequality (LMI) condition. So it couldn't solve the controller gain matrix by directly using a convex optimization algorithm. However, following the idea proposed in [16], By use the cone complementarity linearization (CCL) algorithm which is an iterative algorithm based on LMI to solve this problem. We define two new matrix variables S_1 and S_2 such that $\bar{P}\bar{R}_1^{-1}\bar{P} \ge S_1$ and $\bar{P}\bar{R}_2^{-1}\bar{P} \ge S_2$. Thus, the condition (8) can be replaced by the following inequalities:

$$\begin{bmatrix} \Theta_{11} & BV & 0 & R_1 & B_w & h_2PA^T & h_{12}PA^T & \xi H & PE_1^T & PC^T \\ * & \Theta_{22} & R_2 & R_2 & 0 & h_2V^TB^T & h_{12}V^TB^T & 0 & V^TE_2^T & 0 \\ * & * & \Theta_{33} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & \Theta_{44} & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & -\gamma^2 I & h_2B_W^T & h_{12}B_W^T & 0 & E_3^T & 0 \\ * & * & * & * & * & -S_1 & 0 & h_2\xi H & 0 & 0 \\ * & * & * & * & * & * & -S_2 & h_{12}\xi H & 0 & 0 \\ * & * & * & * & * & * & * & -\xi I & 0 & 0 \\ * & * & * & * & * & * & * & * & -\xi I & 0 \\ * & * & * & * & * & * & * & * & * & -I \end{bmatrix} < 0 \quad (9)$$

$$\overline{P}\overline{R}_1^{-1}\overline{P} \geq S_1 \quad (10)$$

$$\overline{P}\overline{R}_2^{-1}\overline{P} \geq S_2 \quad (11)$$

By defining new matrix variables $J = \overline{P}^{-1}$, $L_j = S_j^{-1}, G_j = \overline{R}_j^{-1}, j = 1,2$, (10) and (11) can be respectively expressed as

$$\begin{bmatrix} L_1 & J \\ * & G_1 \end{bmatrix} \geq 0 \text{ and } \begin{bmatrix} L_2 & J \\ * & G_2 \end{bmatrix} \geq 0$$

Based on the above analysis, following the idea proposed in [16], This non-convex problem will be transform into the following nonlinear minimization problem involved with LMI conditions:

Minimize $tr(S_1L_1 + S_2L_2 + \overline{P}J + \overline{R}_1G_1 + \overline{R}_2G_2)$

Subject to (9) and

$$\begin{cases} \begin{bmatrix} L_j & J \\ * & G_j \end{bmatrix} \geq 0, \overline{P} > 0, , \overline{Q}_i > 0, \overline{R}_j > 0, \quad (i = 1,2,3, j = 1,2) \\ \begin{bmatrix} S_j & I \\ * & L_j \end{bmatrix} \geq 0, \begin{bmatrix} \overline{P} & I \\ * & J \end{bmatrix} \geq 0, \begin{bmatrix} \overline{R}_j & I \\ * & G_j \end{bmatrix} \geq 0, \quad (j = 1,2) \end{cases} \quad (12)$$

Considering the time variation of d(t) in an actual UPQC system, it is difficult to find a definite lower bound of d(t).

Therefore, we assume h1 = 0 for convenience. Using the algorithm proposed in [16], a suboptimal maximum of h_2 can be obtained for given and μ. The specific iterative algorithm is as follows:

3.1. Proposed Algorithm

Step 1: Choose a sufficiently small initial h > 0 such that there exists a feasible solution to (9) and (12).

Set h_2=h.

Step 2: Find a feasible set $(\overline{P}^0, J^0, V^0, \overline{Q}_i^0, S_j^0, L_j^0, \overline{R}_j^0, G_j^0, i = 1,2,3, j = 1,2)$ satisfying (9) and (12). Set k=0.

Table.1 Parameters of UPQC

Component	L_1	R_1	R_{se}	R_{sh}	L_{se}	C_{se}	L_{sh}	C_{sh}
Value	3mH	0.5Ω	0.5Ω	0.5Ω	5mH	50μf	2mH	50μf

Step 3: Solve the following LMI problem for the $(\overline{P}, J, V, \overline{Q}_i, S_j, L, \overline{R}_j, G_j, i = 1,2,3, j = 1,2)$

$$\text{Minimize tr}\left(\sum_{j=1}^{2} \left(S_j^k L_j + L_j^k S_j + \overline{R}_j^k G_j + G_j^k \overline{R}_j \right) + \overline{P}^k J + J^k \overline{P} \right)$$

Subject to (9) and (12)

Set

$\overline{P}^{k+1} = \overline{P}, J^{k+1} = J, S_j^{k+1} = S_j, L_j^{k+1} = L_j, \overline{R}_j^{k+1} = \overline{R}_j, G_j^{k+1} = G_j, j = 1,2.$

Step 4: If the condition (8) is satisfied, then set h2 = h and return to Step 2 after increasing h to some extent.

If the condition (8) is not satisfied within a specified number of iterations, then exit. Otherwise, set k = k + 1 and go to Step 3.

4. Simulations

The control performance of the proposed controller will be verified by using MATLAB to conduct some numerical simulations of the UPQC in a single-phase microgrid rated at 220V/50Hz. Values of the circuit parameters of the system are shown in Table 1. By observing the simulation results, it can be verified whether the outputs of the UPQC are stabilized by using the proposed controller.

If γ= 2.5 and μ = 0.5, the maximum of h_2 is 50ms and the corresponding H_∞ controller gain matrix is as follows:

$$K = \begin{bmatrix} -.3297 & -0.1941 & -1.6323 & 0.0908 & -0.4018 \\ -0.4043 & 0.1492 & -0.1142 & -0.6827 & -0.3546 \end{bmatrix}$$

Then, by set of the total delay of the UPQC as 50ms and choose suitable parameter perturbations as well as disturbances to plot the output curves of the UPQC without the proposed controller, which are shown in Fig. 3 that shows the output curves of the UPQC have obvious oscillations. Especially, divergent oscillations occur in the supply current curve. Thus, the system is unstable under the influence of the delay and parameter uncertainties. Under the same conditions, the output curves of the UPQC with the corresponding H∞ controller are plotted in Fig. 4. It can be seen that the outputs of the UPQC are stabilized before 1.8s by using the proposed controller. When γ is chosen as 1.5, the maximums of h_2 is 37ms that is seen in Fig. 5. From the aforementioned simulation examples, we know that the proposed H_∞ controller is effective in stabilizing the UPQC system. Moreover, we can also see the maximum of h_2 reduces as decreases. It means that when the anti-interference capability of the UPQC system enhances, the upper bound of the delay for ensuring the stabilize ability of the system accordingly diminishes

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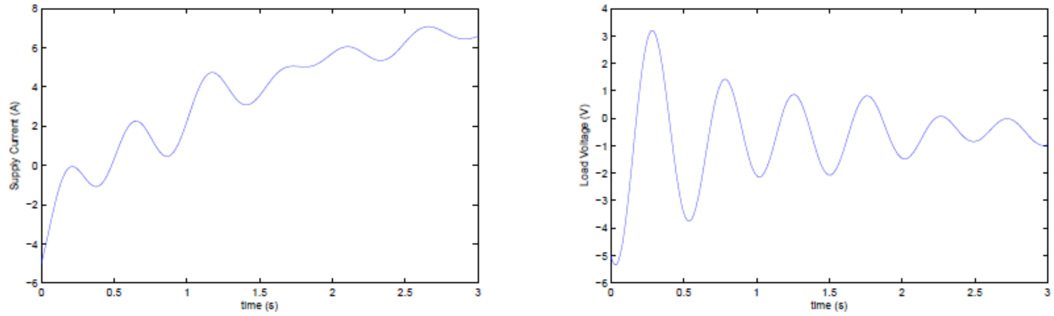

Fig.3 Output curves of the UPQC without the proposed controller (γ = 2.5)

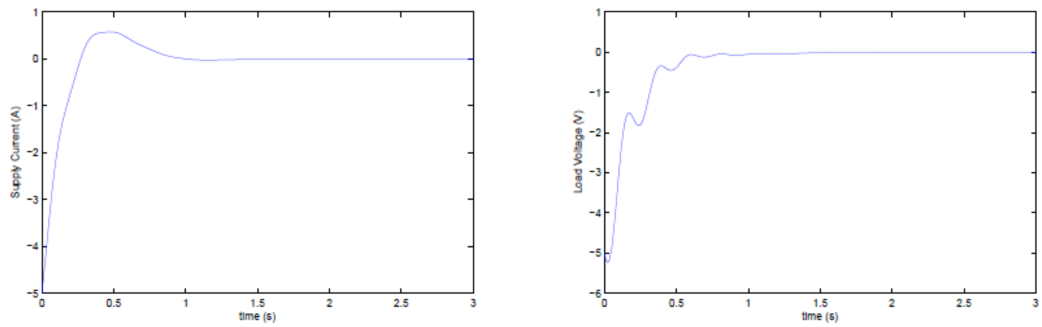

Fig.4 Output curves of the UPQC with the proposed controller (γ = 2.5)

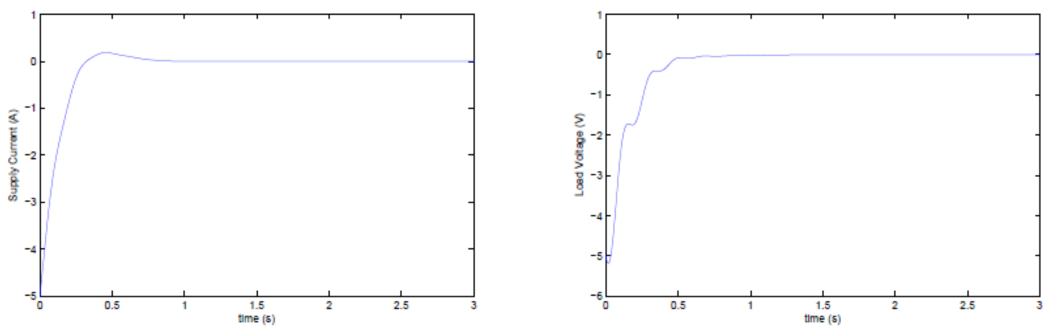

Fig.5 Output curves of the UPQC with the proposed controller (γ = 1.5)

5. . Conclusions

This paper presents a delay-dependent H∞ control method for the UPQC in a microgrid which considers the negative effects of the delay and parameter uncertainties. On the basis of the classical UPQC model, a new UPQC model with delay and parameter uncertainties is built. Then a delay-dependent stability criterion is established for the system by using the Lyapunov-Krasovskii functional approach and H_∞ control theory. The CCL iterative algorithm is used to solve the proposed H_∞ controller and the upper bound of the delay. Simulation results have shown that the proposed control method is an effective means to stabilize the UPQC system with the delay and parameter uncertainties.

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