

# 一种 UPQC 直流侧电压控制器的设计方法研究

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**摘要:** 统一电能质量调节器 (UPQC) 的直流侧电容电压维持恒定与其和电源的有功功率平衡有关, 为获得直流电压闭环控制模型, 将直流电压表示成为电源有功电流的函数是必要的。提出了一种利用 UPQC 小信号模型推导出直流侧电压和电源电流的线性表达式的方法, 据此获得了直流侧电压控制的闭环模型。以此为基础, 探讨了直流侧电压控制器的设计方法。利用这种方法, 针对实际的控制策略, 计算出控制器的参数。仿真结果显示, 采用这种方法设计的直流侧电压控制系统具有较好的频率特性, 获得了较好的直流侧电压, 表明这种方法是有效的。

**关键词:** UPQC; 小信号模型; 线性模型; 控制器设计

## Design of voltage controller for UPQC on its DC side

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**Abstract:** For UPQC, maintaining its constant DC voltage is related to the active power balance between it and sources. So, to get a mathematical model of the closed loop controller of DC voltage, expressing it as a function of the active current of sources is critical. This paper proposes a method of designing the DC voltage controller by using the small signal model of UPQC, with which mathematical relationship between DC voltage and the active current of sources is deduced, based on which the mathematical model of closed loop of DC voltage is promoted. Parameters of the controller are calculated with it. The simulation results show that the DC control system has good frequency characteristic and DC side voltage, which verifies the effectivity.

This work is supported by National Natural Science Foundation of China(No.50807049).

**Key words:** UPQC; small signal model; linearized model; design of controller

中图分类号: TM76 文献标识码: A 文章编号: 1674-3415(2010)22-0190-06

## 0 引言

统一电能质量调节器 (UPQC) 的串并联补偿器可以看作是两个电压源逆变器, 直流侧电容电压可以看成电压源<sup>[1-3]</sup>。所以, 维持直流侧电压为恒定值对 UPQC 能正常运行, 完成其补偿功能具有重要的意义。图 1 所示为三相四线 UPQC 的原理图。直流侧电压维持恒定值与 UPQC 和电源的功率平衡有关, 即输入 UPQC 的有功功率和它消耗的有功功率相等<sup>[4-6]</sup>, 因此, 直流侧电压的控制涉及电源的有功电流。如果直流侧电压控制器的输入信号是直流电压的误差信号, 其输出信号应为电源有功电流, 这种情况下, 为获得直流电压闭环控制模型, 将直流电压表示成为电源电流的函数是必要的。本文提出了一种利用 UPQC 小信号模型推导出直流侧电压和

电源电流的线性表达式, 获得直流侧电压控制的闭环模型, 以此为基础, 探讨了直流侧电压控制器的设计方法, 利用这种方法, 计算出控制器的参数。仿真结果显示, 采用这种方法设计的直流侧电压控制系统具有较好的频率特性, 获得了较好的直流侧电压, 表明这种方法是有效的。

## 1 UPQC 在 d-q-0 坐标中的小信号模型

当系统工作在稳定条件下时, 系统中的任意电量  $x$  能表示成为稳态分量  $X$  和一个小波动量  $\tilde{x}$  的和, 即  $x = X + \tilde{x}$ 。不同电量的小波动量, 即小信号  $\tilde{x}$  之间的数学关系可认为是一种线性关系, 系统的小信号表达式可以认为是系统的线性模型<sup>[7-10]</sup>。因此, 如果我们获得直流侧电压和电源电流的小信号模型, 就可以按照常用的线性系统的设计方法来设计直流侧电压控制器。为了获得这一线性模型, 首先推导 UPQC 在 d-q-0 坐标中的小信号模型。

**基金项目:** 国家自然科学基金项目 (50807049); 中国地质大学优秀青年教师资助计划项目 (CUGQNL0842)

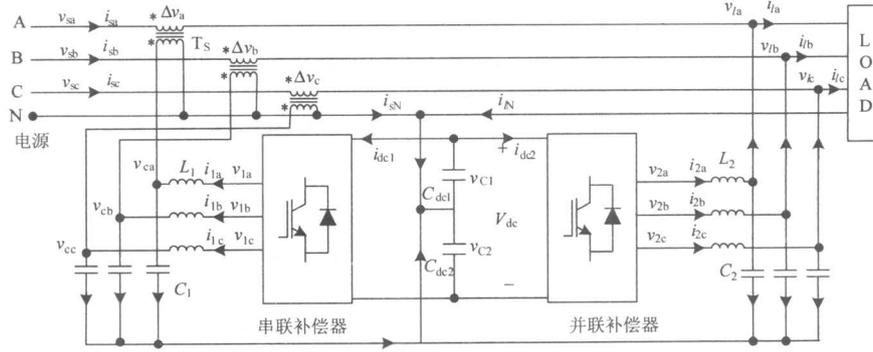


图 1 UPQC 的原理图

Fig.1 Circuit configuration of the proposed UPQC

当 UPQC 在稳定状态下运行时, 将串、并联侧三相电流和电压信号通过同步坐标变换到  $d$ - $q$ - $0$  坐标中, 对串联补偿器, 其稳态分量可表示为:

$$\begin{cases} (V_{sd} - V_{ld}) \cdot N = -L_1 \frac{dI_{ld}}{dt} + \omega L_1 I_{lq} + D_{ld} V_{dc} \\ (V_{sq} - V_{lq}) \cdot N = -L_1 \frac{dI_{lq}}{dt} - \omega L_1 I_{ld} + D_{lq} V_{dc} \\ (V_{s0} - V_{l0}) \cdot N = -L_1 \frac{dI_{l0}}{dt} + D_{l0} V_{dc} \end{cases} \quad (1)$$

$$\begin{cases} I_{ld} = C_1 \frac{d(V_{sd} - V_{ld}) \cdot N}{dt} - \omega C_1 (V_{sq} - V_{lq}) \cdot N + \frac{1}{N} I_{sd} \\ I_{lq} = C_1 \frac{d(V_{sq} - V_{lq}) \cdot N}{dt} + \omega C_1 (V_{sd} - V_{ld}) \cdot N + \frac{1}{N} I_{sq} \\ I_{l0} = C_1 \frac{d(V_{s0} - V_{l0}) \cdot N}{dt} + \frac{1}{N} I_{s0} \end{cases} \quad (2)$$

对并联补偿器, 其稳态分量可表示为:

$$\begin{cases} d_{2d} V_{dc} = L_2 \frac{dI_{2d}}{dt} - \omega L_2 I_{2q} + V_{ld} \\ d_{2q} V_{dc} = L_2 \frac{dI_{2q}}{dt} + \omega L_2 I_{2d} + V_{lq} \\ d_{20} V_{dc} = L_2 \frac{dI_{20}}{dt} + V_{l0} \end{cases} \quad (3)$$

$$\begin{cases} I_{2d} = C_2 \frac{dV_{ld}}{dt} - \omega C_2 V_{lq} + I_{ld} - I_{sd} \\ I_{2q} = C_2 \frac{dV_{lq}}{dt} + \omega C_2 V_{ld} + I_{lq} - I_{sq} \\ I_{20} = C_2 \frac{dV_{l0}}{dt} + I_{l0} - I_{s0} \end{cases} \quad (4)$$

对直流侧

$$\frac{V_{dc}}{R_{loss}} + C_{dc} \cdot \frac{dV_{dc}}{2dt} = -(D_{ld} I_{ld} + D_{lq} I_{lq} + D_{l0} I_{l0}) - (D_{2d} I_{2d} + D_{2q} I_{2q} + D_{20} I_{20}) \quad (5)$$

式中,  $R_{loss}$  表示 UPQC 的功率损耗对应的等效电阻。

对串联侧, 其电压和电流的表达式为:

$$\begin{cases} [(V_{sd} + \tilde{v}_{sd}) - (V_{ld} + \tilde{v}_{ld})] \cdot N = \\ -L_1 \frac{d(I_{ld} + \tilde{i}_{ld})}{dt} + \omega L_1 (I_{lq} + \tilde{i}_{lq}) + (D_{ld} + \tilde{d}_{ld})(V_{dc} + \tilde{v}_{dc}) \\ [(V_{sq} + \tilde{v}_{sq}) - (V_{lq} + \tilde{v}_{lq})] \cdot N = \\ -L_1 \frac{d(I_{lq} + \tilde{i}_{lq})}{dt} - \omega L_1 (I_{ld} + \tilde{i}_{ld}) + (D_{lq} + \tilde{d}_{lq})(V_{dc} + \tilde{v}_{dc}) \\ [(V_{s0} + \tilde{v}_{s0}) - (V_{l0} + \tilde{v}_{l0})] \cdot N = \\ -L_1 \frac{d(I_{l0} + \tilde{i}_{l0})}{dt} + (D_{l0} + \tilde{d}_{l0})(V_{dc} + \tilde{v}_{dc}) \end{cases} \quad (6)$$

$$\begin{cases} I_{ld} + \tilde{i}_{ld} = C_1 \frac{d[(V_{sd} + \tilde{v}_{sd}) - (V_{ld} + \tilde{v}_{ld})] \cdot N}{dt} - \\ \omega C_1 [(V_{sq} + \tilde{v}_{sq}) - (V_{lq} + \tilde{v}_{lq})] \cdot N + \frac{1}{N} (I_{sd} + \tilde{i}_{sd}) \\ I_{lq} + \tilde{i}_{lq} = C_1 \frac{d[(V_{sq} + \tilde{v}_{sq}) - (V_{lq} + \tilde{v}_{lq})] \cdot N}{dt} + \\ \omega C_1 [(V_{sd} + \tilde{v}_{sd}) - (V_{ld} + \tilde{v}_{ld})] \cdot N + \frac{1}{N} (I_{sq} + \tilde{i}_{sq}) \\ I_{l0} + \tilde{i}_{l0} = C_1 \frac{d[(V_{s0} + \tilde{v}_{s0}) - (V_{l0} + \tilde{v}_{l0})] \cdot N}{dt} + \\ \frac{1}{N} (I_{s0} + \tilde{i}_{s0}) \end{cases} \quad (7)$$

将式 (1)、(2) 分别代入式 (6) 及式 (7), 电压和电流的小信号 (即小波动量) 之间的数学关系可表示成式 (8) 及式 (9)。

$$\begin{cases} D_{ld} \tilde{v}_{dc} + \tilde{d}_{ld} V_{dc} = L_1 \frac{d\tilde{i}_{ld}}{dt} - \omega L_1 \tilde{i}_{lq} + (\tilde{v}_{sd} - \tilde{v}_{ld}) \cdot N \\ D_{lq} \tilde{v}_{dc} + \tilde{d}_{lq} V_{dc} = L_1 \frac{d\tilde{i}_{lq}}{dt} + \omega L_1 \tilde{i}_{ld} + (\tilde{v}_{sq} - \tilde{v}_{lq}) \cdot N \\ D_{l0} \tilde{v}_{dc} + \tilde{d}_{l0} V_{dc} = L_1 \frac{d\tilde{i}_{l0}}{dt} + (\tilde{v}_{s0} - \tilde{v}_{l0}) \cdot N \end{cases} \quad (8)$$

$$\begin{cases} \tilde{i}_{1d} = C_1 \frac{d(\tilde{v}_{sd} - \tilde{v}_{1d}) \cdot N}{dt} - \omega C_1 (\tilde{v}_{sq} - \tilde{v}_{1q}) \cdot N + \frac{1}{N} \tilde{i}_{sd} \\ \tilde{i}_{1q} = C_1 \frac{d(\tilde{v}_{sq} - \tilde{v}_{1q}) \cdot N}{dt} + \omega C_1 (\tilde{v}_{sd} - \tilde{v}_{1d}) \cdot N + \frac{1}{N} \tilde{i}_{sq} \\ \tilde{i}_{10} = C_1 \frac{d(\tilde{v}_{s0} - \tilde{v}_{10}) \cdot N}{dt} + \frac{1}{N} \tilde{i}_{s0} \end{cases} \quad (9)$$

并联侧的小信号关系如式 (10) 和式 (11) 所示。

$$\begin{cases} D_{2d} \tilde{v}_{dc} + \tilde{d}_{2d} V_{dc} = L_2 \frac{d\tilde{i}_{2d}}{dt} - \omega L_2 \tilde{i}_{2q} + \tilde{v}_{1d} \\ D_{2q} \tilde{v}_{dc} + \tilde{d}_{2q} V_{dc} = L_2 \frac{d\tilde{i}_{2q}}{dt} + \omega L_2 \tilde{i}_{2d} + \tilde{v}_{1q} \\ D_{20} \tilde{v}_{dc} + \tilde{d}_{20} V_{dc} = L_2 \frac{d\tilde{i}_{20}}{dt} + \tilde{v}_{10} \end{cases} \quad (10)$$

$$\begin{cases} \tilde{i}_{2d} = C_2 \frac{d\tilde{v}_{1d}}{dt} - \omega C_2 \tilde{v}_{1q} + \tilde{i}_{1d} - \tilde{i}_{sd} \\ \tilde{i}_{2q} = C_2 \frac{d\tilde{v}_{1q}}{dt} + \omega C_2 \tilde{v}_{1d} + \tilde{i}_{1q} - \tilde{i}_{sq} \\ \tilde{i}_{20} = C_2 \frac{d\tilde{v}_{10}}{dt} + \tilde{i}_{10} - \tilde{i}_{s0} \end{cases} \quad (11)$$

直流侧电压与电流的关系如式 (12) 所示：

$$\begin{aligned} \frac{V_{dc} + \tilde{v}_{dc}}{R_{loss}} + C_{dc} \cdot \frac{d(V_{dc} + \tilde{v}_{dc})}{2dt} = & -(D_{1d} + \tilde{d}_{1d})(I_{1d} + \tilde{i}_{1d}) - \\ & (D_{1q} + \tilde{d}_{1q})(I_{1q} + \tilde{i}_{1q}) - (D_{10} + \tilde{d}_{10})(I_{10} + \tilde{i}_{10}) - \\ & (D_{2d} + \tilde{d}_{2d})(I_{2d} + \tilde{i}_{2d}) - (D_{2q} + \tilde{d}_{2q})(I_{2q} + \tilde{i}_{2q}) - (D_{20} + \tilde{d}_{20})(I_{20} + \tilde{i}_{20}) \end{aligned} \quad (12)$$

将式 (5) 代入式 (12)，则直流侧电压与电流的小信号表达式如式 (13) 所示：

$$\begin{aligned} \frac{\tilde{v}_{dc}}{R_{loss}} + C_{dc} \cdot \frac{d\tilde{v}_{dc}}{2dt} = & -(D_{1d} \tilde{i}_{1d} + \tilde{d}_{1d} I_{1d} + D_{1q} \tilde{i}_{1q} + \tilde{d}_{1q} I_{1q} + D_{10} \tilde{i}_{10} + \\ & \tilde{d}_{10} I_{10} + D_{2d} \tilde{i}_{2d} + \tilde{d}_{2d} I_{2d} + D_{2q} \tilde{i}_{2q} + \tilde{d}_{2q} I_{2q} + D_{20} \tilde{i}_{20} + \tilde{d}_{20} I_{20}) \end{aligned} \quad (13)$$

利用式 (8)~(11) 和式 (13)，可以获得 UPQC 的小信号模型，如图 2 所示。

## 2 直流侧电压和电源有功电流的线性关系

从上面的分析可知，稳定状态下，直流侧电压和电源有功电流的线性关系可由它们的小信号分量  $\tilde{v}_{dc}$  和  $\tilde{i}_{sd}$  的数学关系描述。为获得这一线性模型，假设 UPQC 工作在其理想的工作状态，即电源电流和负载电压都是平衡的且不包含谐波，负载电流和

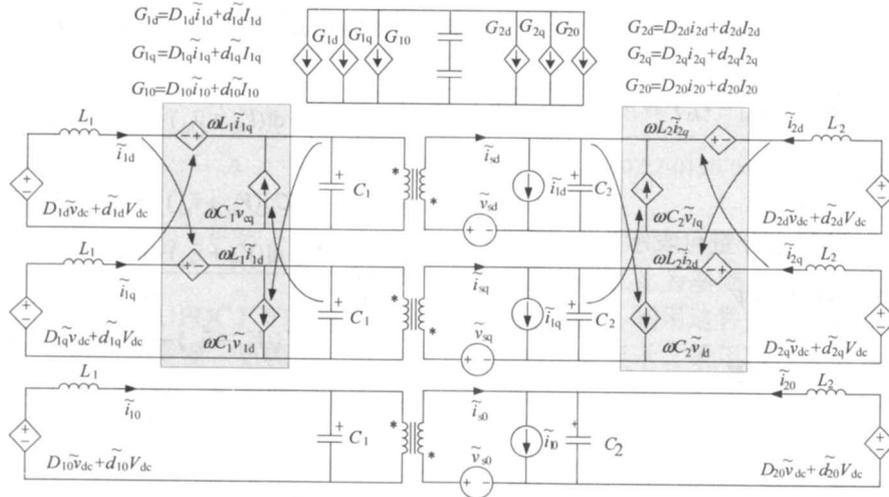


图 2 UPQC 在 d-q-0 坐标中的小信号模型

Fig.2 The small signal model of UPQC in d-q-0 coordinates

电源电压都运行在稳定状态，所以在下面的分析中，以下小信号设置为 0。

$$\begin{cases} \tilde{v}_{sd} = 0 & \tilde{v}_{sq} = 0 & \tilde{v}_{s0} = 0 \\ \tilde{v}_{1d} = 0 & \tilde{v}_{1q} = 0 & \tilde{v}_{10} = 0 \\ \tilde{i}_{sq} = 0 & \tilde{i}_{s0} = 0 \\ \tilde{i}_{1d} = 0 & \tilde{i}_{1q} = 0 & \tilde{i}_{10} = 0 \end{cases} \quad (14)$$

由于电源电流和负载电压都是平衡的且不包含

谐波，电源电流及负载电压在 d 轴上的分量为直流，在 q 轴及 0 轴上的分量为 0，这样，根据式 (1) 可得

$$\begin{cases} (V_{sd} - V_{1d}) \cdot N - \omega L_1 I_{1q} = D_{1d} V_{dc} \\ (V_{sq} - 0) \cdot N + \omega L_1 I_{1d} = D_{1q} V_{dc} \\ (V_{s0} - 0) \cdot N = D_{10} V_{dc} \end{cases} \quad (15)$$

同理，对并联补偿器，根据式 (3) 可得

$$\begin{cases} D_{2d}V_{dc} = -\omega L_2 I_{2q} + V_{ld} \\ D_{2q}V_{dc} = \omega L_2 I_{2d} \\ D_{20}V_{dc} = 0 \end{cases} \quad (16)$$

由式 (8) 和式 (14) 可得

$$\begin{cases} \tilde{d}_{1d} = -\frac{1}{V_{dc}} \left( \frac{L_1}{N} \frac{d\tilde{i}_{sd}}{dt} + D_{1d}\tilde{v}_{dc} \right) \\ \tilde{d}_{1q} = -\frac{1}{V_{dc}} \left( \omega L_1 \frac{\tilde{i}_{sd}}{N} + D_{1q}\tilde{v}_{dc} \right) \\ \tilde{d}_{10} = -\frac{1}{V_{dc}} D_{10}\tilde{v}_{dc} \end{cases} \quad (17)$$

由式 (10) 和式 (14) 可得

$$\begin{cases} \tilde{d}_{2d} = -\frac{1}{V_{dc}} \left( L_2 \frac{d\tilde{i}_{sd}}{dt} + D_{2d}\tilde{v}_{dc} \right) \\ \tilde{d}_{2q} = -\frac{1}{V_{dc}} \left( \omega L_2 \tilde{i}_{sd} + D_{2q}\tilde{v}_{dc} \right) \\ \tilde{d}_{20} = -\frac{1}{V_{dc}} D_{20}\tilde{v}_{dc} \end{cases} \quad (18)$$

将式 (17) 和式 (18) 代入式 (13), 可得

$$\begin{aligned} \frac{\tilde{v}_{dc}}{R_{loss}} + C_{dc} \cdot \frac{d\tilde{v}_{dc}}{2dt} = & -D_{1d} \frac{\tilde{i}_{sd}}{N} + \frac{1}{V_{dc}} \left( \frac{L_1}{N} \frac{d\tilde{i}_{sd}}{dt} + D_{1d}\tilde{v}_{dc} \right) I_{1d} + \\ & \frac{1}{V_{dc}} \left( \omega L_1 \frac{\tilde{i}_{sd}}{N} + D_{1q}\tilde{v}_{dc} \right) I_{1q} + \frac{1}{V_{dc}} D_{10}\tilde{v}_{dc} I_{10} + D_{2d}\tilde{i}_{sd} + \\ & \frac{1}{V_{dc}} \left( L_2 \frac{d\tilde{i}_{sd}}{dt} + D_{2d}\tilde{v}_{dc} \right) I_{2d} + \frac{1}{V_{dc}} \left( \omega L_2 \tilde{i}_{sd} + D_{2q}\tilde{v}_{dc} \right) I_{2q} + \\ & \frac{1}{V_{dc}} D_{20}\tilde{v}_{dc} I_{20} \end{aligned} \quad (19)$$

将式 (14) 式代入式 (19), 可得

$$\begin{aligned} \frac{\tilde{v}_{dc}}{R_{loss}} + C_{dc} \cdot \frac{d\tilde{v}_{dc}}{2dt} = & \left( -\frac{D_{1d}}{N} + \frac{\omega L_1 I_{1q}}{V_{dc} N} + D_{2d} + \frac{\omega L_2 I_{2q}}{V_{dc}} \right) \tilde{i}_{sd} + \\ & \left( \frac{L_1 I_{1d}}{V_{dc} N} + \frac{L_2 I_{2d}}{V_{dc}} \right) \frac{d\tilde{i}_{sd}}{dt} + \left( \frac{D_{1d} I_{1d}}{V_{dc}} + \frac{D_{1q} I_{1q}}{V_{dc}} + \right. \\ & \left. \frac{D_{10} I_{10}}{V_{dc}} + \frac{D_{2d} I_{2d}}{V_{dc}} + \frac{D_{2q} I_{2q}}{V_{dc}} + \frac{D_{20} I_{20}}{V_{dc}} \right) \tilde{v}_{dc} \end{aligned} \quad (20)$$

将式 (13) 拉氏变换, 利用式 (5)、(15)、(16) 可得到电源有功电流和直流侧电压的线性关系即其传递函数模型, 可以用其小信号比  $\tilde{v}_{dc}(s)/\tilde{i}_{sd}(s)$  表示, 如式 (14) 所示。它是直流侧电压控制器的基础。

$$G(s) = \frac{\tilde{v}_{dc}(s)}{\tilde{i}_{sd}(s)} = \frac{\frac{V_{sd}}{V_{dc}} + \left( \frac{L_1 I_{1d}}{V_{dc} N} + \frac{L_2 I_{2d}}{V_{dc}} \right) s}{\frac{C_{dc}}{2} s + \frac{2}{R_{loss}} + \frac{\sqrt{3}}{2} \cdot \frac{I_{10} + I_{20}}{V_{dc}}} \quad (21)$$

### 3 直流侧电压控制器的设计

直流侧电压控制的闭环框图如图 3 所示。这种控制策略中, 控制器被设计为 PI 调节器, 其比例系数  $k_{vdp}$  和微分系数  $k_{vdi}$  可以按下面的方法计算。电源有功电流  $i_{sd}(s)$  和直流侧电压  $v_{dc}(s)$  的传递函数可由式 (21) 得到

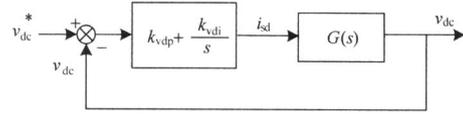


图 3 直流电压闭环控制框图

Fig.3 DC voltage closed-loop control diagram

$$G(s) = \frac{\tilde{v}_{dc}(s)}{\tilde{i}_{sd}(s)} = \frac{V_{sd}}{V_{dc}} \cdot \frac{2}{C_{dc}} \cdot \frac{1 + \left( \frac{L_1 I_{1d}}{V_{sd} N} + \frac{L_2 I_{2d}}{V_{sd}} \right) s}{s + \frac{4}{R_{loss} C_{dc}} + \sqrt{3} \cdot \frac{I_{10} + I_{20}}{V_{dc} C_{dc}}} = \frac{V_{sd}}{V_{dc}} \cdot \frac{2}{C_{dc}} \cdot \frac{1 + \frac{1}{z_d} s}{s + p_d} \quad (22)$$

$$\text{其中} \quad \frac{1}{z_d} = \frac{L_1 I_{1d}}{V_{sd} N} + \frac{L_2 I_{2d}}{V_{sd}} \quad (23)$$

$$p_d = \frac{4}{R_{loss} C_{dc}} + \sqrt{3} \cdot \frac{I_{10} + I_{20}}{V_{dc} C_{dc}} \quad (24)$$

从目前研究的 UPQC 的电路结构来看, 以低电压等级、功率为 kVA 级别的居多。以其为例, 电感 mH 级别, 直流侧电容范围为几千到几万  $\mu\text{F}$ , 直流电压为 1 000 V 以下<sup>[5-6,11]</sup>。基于以上所述的情况,  $z_d$  的数量级大约在  $10^3 \sim 10^4$ 。再看  $p_d$ ,  $R_{loss}$  的值在几十到几百欧之间, 考虑  $p_d$  的另一部分, 其值的数量级大约在  $10^1 \sim 10^2$  之间。如果是 MVA 容量级别的, 其电压等级更高<sup>[12]</sup>,  $z_d$  会更大, 这个意义上讲,  $z_d \gg p_d$  是成立的。另外, 直流电压闭环控制系统需要较低的带宽, 因此,  $z_d$  可以忽略, 这样, 系统的开环传递函数可以表示为:

$$G_{dco}(s) = G_{dpi} \cdot G(s) = \left( k_{vdp} + \frac{k_{vdi}}{s} \right) \cdot \frac{V_{sd}}{V_{dc}} \cdot \frac{2}{C_{dc}} \cdot \frac{1}{s + p_d} \quad (25)$$

$$\text{如果} \quad p_d = \frac{k_{vdi}}{k_{vdp}} \quad (26)$$

那么闭环传递函数可以表示为

$$G_{dcc}(s) = \frac{2k_{vdp} V_{sd}}{s V_{dc} C_{dc} + 2k_{vdp} V_{sd}} = \frac{(2k_{vdp} V_{sd}) / (V_{dc} C_{dc})}{s + (2k_{vdp} V_{sd}) / (V_{dc} C_{dc})} \quad (27)$$

考虑直流电压闭环控制低带宽的要求设置闭环传递函数的截止频率为  $2\pi$ , 则

$$\frac{2k_{vdp} V_{sd}}{V_{dc} C_{dc}} = 2\pi \quad (28)$$

这样比例系数  $k_{vdp}$  和积分系数  $k_{vdi}$  能够从式 (26) 和式 (28) 计算出来。

### 4 仿真结果分析

为了验证这种设计方法的正确性,进行了系统仿真。表 1 是 UPQC 的电路参数,假设其效率为 80%,  $I_{10}$  和  $I_{20}$  假设分别为  $I_{ld}$  和  $I_{ld}$  的 30%, 开环和闭环伯德图如图 4 和图 5 所示。可以看出,直流侧电压控制系统具有较好的稳定裕度和较好的闭环带宽,同时获得了较稳定的直流侧电压,具有较好的动态响应特性。图 6 示出将本文的方法用于参考文献[11]提出的控制策略的情况。这种控制策略将串联补偿器控制为电流源,直流电压与给定值的偏差经 PI 调节器后,其输出做为有功电流指令的一部分<sup>[11]</sup>,即通过控制串联侧的有功电流维持其直流侧电压恒定。其直流电压随着电源电压变化和负载电流变化时的仿真波形如图 6 所示。同时给出了补偿后的电源电流和负载电压的波形。从图中可以看出,在不同负载和电源电压的情况下,直流电压  $v_{dc}$  都能稳定在设定值附近,表明这种直流侧电压控制器的设计方法是有效的。

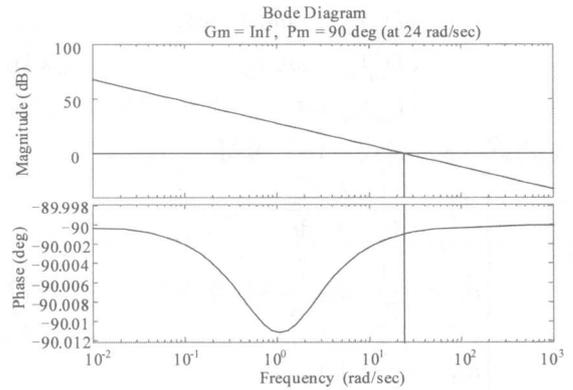


图 4 开环伯德图

Fig.4 Open-loop bode diagram

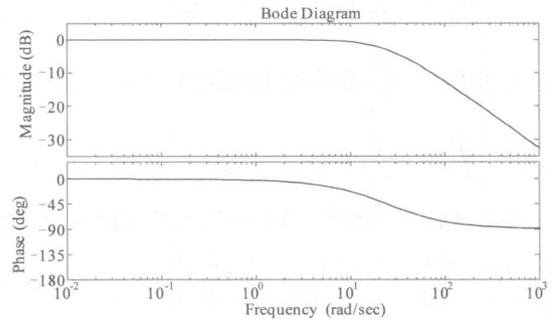


图 5 闭环伯德图

Fig.5 Close-loop bode diagram

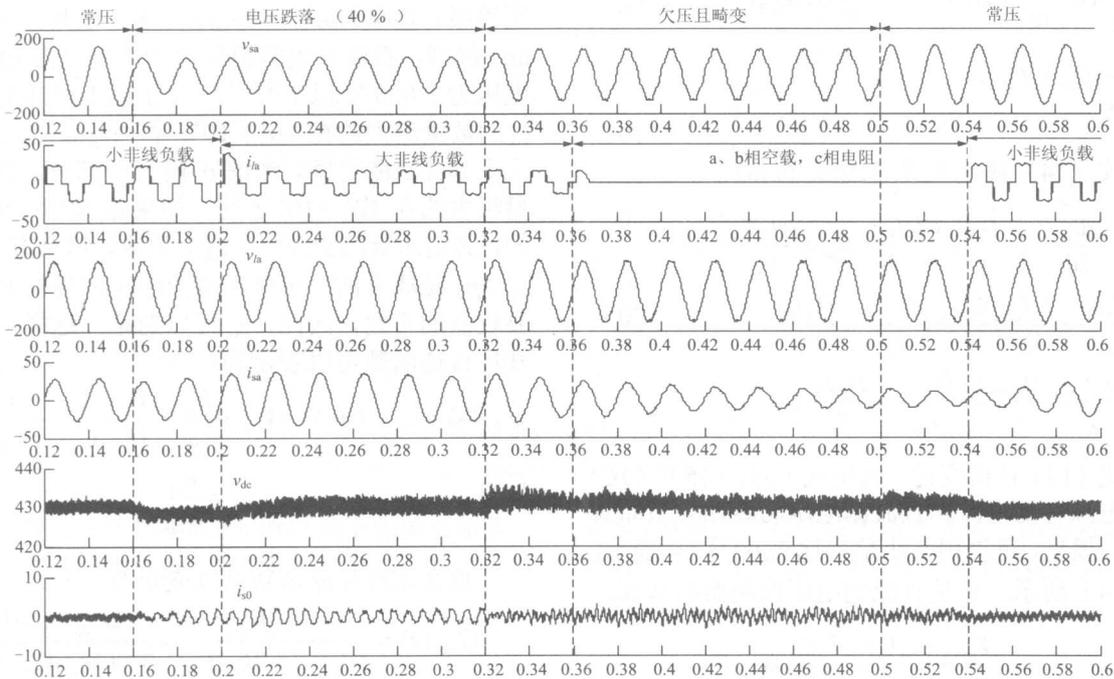


图 6 仿真实验波形

Fig.6 The DC voltage in an example used the proposed DC controller

表 1 仿真电路参数

Tab.1 Circuit parameter of the UPQC

电源电压	不平衡	有效值: 86 V, 92 V, 105 V, 50 Hz
直流侧	电容	$C = 6\ 600\ \mu\text{F}$
	参考电压	432 V
并联补偿器	$L, C$	$L_2 = 2\ \text{mH}, C_2 = 100\ \mu\text{F}$
	开关频率	9 kHz
串联补偿器	滤波电感、电容	$L_1 = 5.8\ \text{mH}, C_1 = 33\ \mu\text{F}$
	开关频率	9 kHz
	变压器变比	$n_2 : n_1 = 3.464, 7\text{kVA}$
负载	额定电压	110V
	不平衡及非线性负载	$P=4\ \text{kW}, Q=3\ \text{kvar}$

## 5 结论

本文以三相四线 UPQC 为研究对象,分析了维持其直流侧电压为恒定值对 UPQC 能正常运行,完成其补偿功能具有重要意义。为获得直流侧电压控制器的数学模型,首先得到 UPQC 小信号模型,然后推导出直流侧电压和电源电流的线性表达式,获得了直流电压闭环控制模型,以此为基础,获得了直流侧电压控制器的设计方法,利用这种方法,计算出控制器的参数。仿真结果显示,采用这种方法设计的直流侧电压控制系统具有较好的频率特性。将设计好的直流侧电压控制器用于三相四线 UPQC 的控制策略中,仿真结果显示,在电网电压和负载变化时,直流侧电压能维持稳定,UPQC 获得了较好的补偿效果,表明这种直流侧电压控制器的设计方法是有效的。

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收稿日期: 2009-11-25; 修回日期: 2010-01-12

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