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同相供电系统中负载突变时的电流检测方法

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摘 要:在同相供电系统中负载突变时,传统检测方法在检测基波有功电流及无功电流时存在一个时间缓冲,这影响电网侧基波有功电流及无功电流的检测效果,可能导致无法及时对负载侧的无功与谐波电流进行补偿。基于上述问题,提出一种 Scott 平衡变压器结合平衡变换装置的同相牵引供电系统工作模式。通过两相平衡变压器特有的供电方式分析两相电压与电流,采用两相电路瞬时无功功率理论对整个单相基波有功与无功电流信号进行功率检测。通过对整个单相电路的有功电流进行功率分解,得到在基波突变情况下的负序量,再结合基波稳定下的正序量,使其在负载突变时的动态检测性能明显提高。仿真与理论的综合分析验证了该方法的合理性。

关 键 词:基波有功电流;同相供电; Scott 平衡变压器;平衡变换装置

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Abstract: When it occurs load mutation in cophase power supply system, conventional detection method in detecting the fundamental active current and reactive current will exist a time buffer, which in turn directly affects the detection effect of fundamental active current and reactive current at power grid side. It may lead to not timely compensate the reactive and harmonic current in load side. Based on the above problems, this paper proposed a Scott balance transformer combined balance transform device of cophase traction power supply system mode. The two-phase voltage and current analysis Through the special power supply mode of the two-phase balance transformer. According to the instantaneous reactive power theory of two-phase circuit, the whole single-phase fundamental wave active and reactive current signals are detected. The active current in the whole single-phase circuit is decomposed. Thus, the amount of negative sequence can be obtained in the case of mutation, and then the positive sequence under the condition of fundamental wave stability is recombined with the negative sequence. Therefore, the dynamic performance gets greatly improved when it occurs load mutation. Simulation and theoretical comprehensive analysis verify the rationality of this method.

Key words: fundamental wave active current; cophase power supply; Scott balance transformer; balancing gear

目前,中国高速铁路普遍为单相工频交流牵引供电负荷系统,其电力机车是大功率的单相整流负荷,会对电网产生大量的负序、谐波等电能质量影响,同时其电分相问题也严重制约了铁路朝高速和强承载能力方向发展。

为了解决这些问题,相关学者提出了同相供电方式,对检测原理与控制方式提供了依据^[1-3]。文献[4-7]提出了基于瞬时无功功率检测理论的三相电路谐波电流与源电压矢量同步坐标变换的有源滤波器无功与谐波电流的检测方法,能够很好地跟踪补偿电流,该法只对三相电路的谐波电流进行检测,单相电路则并不适用;文献[8-9]提出了基于 Fryze 功率定义的延时,能同时检测谐波与无功电流,但不能单独检测,更不用说在负载突变情况下对电流会产生很大的不良影响;文献[10]提出了一种能将单相变换为三相的坐标变换电流检测方法,基于三相坐标系进行变换,但摆脱不了繁琐的矩阵运算,且缺乏对单相负载突变的考虑;文献[11]考虑了在同相电路中当负载由牵引变为制动时的电流检测研究,但也只是增加了特定的几次谐波稳定直流侧的电容;文献[12]提出了将单相变为两相系统,但只是从基波有功和无功来分析电流的检测方法,并没有考虑负载电流的突变情况;文献[13]提出了一种根据正交函数的特性,对畸变电流中的基波有功和无功电流分量分别进行差值分解,并且从电压畸变的角度扩展了这种范围,虽然简单易实现,但没有考虑在负载突变的情况下能够同步追踪其动态性能,稳定性得不到保证;文献[14]提出了基于 FBD 原理的牵引电网各项电流检测方法,该法不仅可以检测各种扰动电能质量的谐波参数,还可以直接实现基波正负序分量的提取,但是不能应用于单相,且没有考虑在负载突变的节点上对检测效果的影响。

为了更好地提高负载突变时电流检测的动态性能,该文结合两相系统并通过基波的正负序有功与无功分量来分析电流的动态变化情况,其中对负序分量的考虑尤为突出,检测的效果能快速地响应负载突变的变化,相比单一基波有功、无功的检测效果更好。

1 Scott 同相牵引供电系统

Scott 变压器牵引供电系统如图 1 所示,通过分

相牵引断路器隔离 2 个牵引变电所, T 为牵引网, R 为钢轨,中性线圈与地相连,这样就形成了一个单相电源 u_α 供电接触网,另一侧 u_β 对平衡装置进行补偿。

$$u_\alpha = u_\beta e^{j\frac{\pi}{2}} \quad (1)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{1}{k} \begin{bmatrix} 2 & -1 \\ \sqrt{3} & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

式中 i_a, i_b, i_c 为原边三相电流; i_α, i_β 为副边两相电流, $i_\alpha = I_\alpha e^{-j\varphi_\alpha}$, $i_\beta = I_\beta e^{-j(\varphi_\beta+90^\circ)}$, 其中, $\varphi_\alpha, \varphi_\beta$ 为两臂电流滞后各自电压的相角。

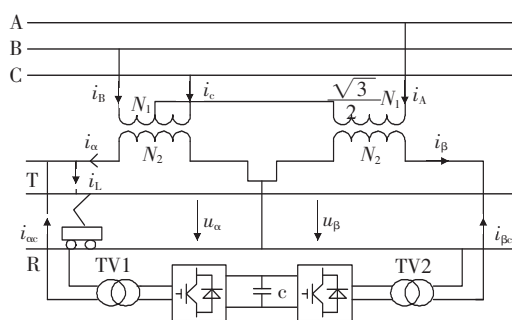


图 1 同相牵引供电系统结构

Figure 1 Cophase traction power supply system structure

2 传统基波有功与无功电流的检测

该文在分析负载电流的同时考虑了负载电压^[11-13],由于每个变压器副端的接触网与 α 相相连,故只需检测 α 侧负载电流中的基波有功电流^[14],假设:

$$u_\alpha = \sqrt{2}U \sin(\omega t + \theta) \quad (3)$$

其中, ω 恒为 50 Hz。

$$\begin{aligned} i_L &= \sqrt{2} I_{L1} \sin(\omega t + \varphi) + i_h = \sqrt{2} I_{L1} \cos(\theta - \varphi) \sin(\omega t + \theta) + \sqrt{2} I_{L1} \sin(\theta - \varphi) \cos(\omega t + \theta) \\ &+ i_h = \sqrt{2} I_{1p\alpha} \sin(\omega t + \theta) + \sqrt{2} I_{1q\alpha} \cos(\omega t + \theta) + i_h \end{aligned} \quad (4)$$

式中 i_L, I_{L1}, i_h 分别为负载电流、负载基波电流有效值、负载谐波电流; $I_{1p\alpha}, I_{1q\alpha}$ 分别为 α 侧负载基波有功、无功电流的有效值,其中, $I_{1p\alpha} = I_{L1} \cos(\theta -$

$\varphi)$, $I_{1qa} = I_{L1} \sin(\theta - \varphi)$ 。

通过锁相环(PLL)得到 u_a 对应的单位正、余弦函数 $\sin(\omega t + \theta)$ 、 $\cos(\omega t + \theta)$, 利用积分器与乘法器, 在式(4)两边同乘以 u_a 对应的单位正弦函数 $\sin(\omega t + \theta)$, 再乘以 $\sqrt{2}$ 后通过低通滤波器, 得到:

$$I_{1pa} =$$

$$I_{L1} \cos(\theta - \varphi) = I_{L1} \cos \theta \cos \varphi + \sin \theta \sin \varphi \quad (5)$$

将 I_{1pa} 乘以单位正弦函数 $\sin(\omega t + \theta)$, 得到 α 侧瞬时基波有功电流:

$$i_{1p} = I_{L1} \cos(\theta - \varphi) \sin(\omega t + \theta) \quad (6)$$

同理, 将式(4)两边同时乘以 u_a 对应的单位余弦函数 $\cos(\omega t + \theta)$, 再乘以 $\sqrt{2}$ 后通过低通滤波器, 然后乘以单位余弦函数 $\cos(\omega t + \theta)$, 得到 α 侧瞬时基波无功电流:

$$i_{1q} = I_{L1} \sin(\theta - \varphi) \cos(\omega t + \theta) \quad (7)$$

由相关文献可知, 当补偿装置使牵引变压器副端两侧输出有功功率为负载总的有功功率的一半时, 则负荷反馈到电网侧的将是一个对称的三相纯电阻负载, 电网侧将实现三相平衡, 牵引变压器副端两侧的理想输出电流^[15]为

$$i_a = \frac{1}{2} I_{1pm} \sin(\omega t + \varphi) \quad (8)$$

$$i_\beta = \frac{1}{2} I_{1pm} \cos(\omega t + \varphi) \quad (9)$$

综上所述, 传统基波有功、无功电流检测所对应的原理如图 2 所示。

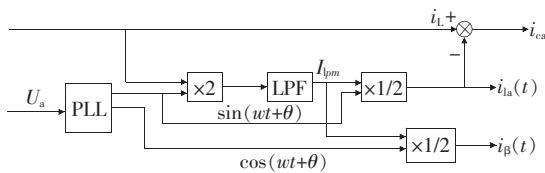


图 2 综合补偿电流实时检测电路

Figure 2 Real-time detecting circuit diagram of comprehensive compensation current

3 改进型单相电路基波无功与有功实时检测

三相瞬时功率^[14]是以计算三相电路的瞬时有功和无功功率为前提, 将三相电流与电压变换至 α - β 坐标系, 求出两相瞬时电压与电流, 利用瞬时有

功和无功功率通过低通滤波器得到直流分量, 然后进行矩阵变换得到三相侧的基波瞬时有功和无功电流, 分别称为 p - q 运算方式和 i_p - i_q 法。

由 Scott 平衡变压器副端两侧的电压相位刚好互差 90° ^[15]可知, 假设:

$$\begin{cases} u_a = \sqrt{2} U \cos \omega t \\ u_\beta = \sqrt{2} U \sin \omega t \end{cases} \quad (10)$$

$$i_a = \sqrt{2} \sum_{n=1}^{\infty} [I_{1n} \cos(n\omega t + \theta_{1n}) + I_{2n} \cos(n\omega t + \theta_{2n})] \quad (11)$$

$$i_\beta = \sqrt{2} \sum_{n=1}^{\infty} [I_{1n} \cos(n\omega t + \theta_{1n} - \frac{\pi}{2}) + I_{2n} \cos(n\omega t + \theta_{2n} + \frac{\pi}{2})] \quad (12)$$

式(10)~(12)中 u_a 、 u_β 分别为 α 、 β 侧的电源电压; i_a 、 i_β 分别为 α 、 β 侧的电流。

由式(10)可知, 副端两侧的电压相位相差 90° , 同相供电系统中只需检测 α 侧的基波有功和无功电流。将 i_a 再分解为基波正、负序有功和无功电流, 得到:

$$\begin{aligned} i_a &= i_{1a1p} + i_{1a2p} + \sqrt{2} \sum_{n=2}^{\infty} I_{an} \sin(n\omega t - \theta_n) = \\ &= i_{1a1q} + i_{1a2q} + i_{1a2p} + i_{1a1p} + \\ &= \sqrt{2} \sum_{n=2}^{\infty} I_{an} \sin(n\omega t - \theta_n) \end{aligned} \quad (13)$$

式中 i_{1a1p} 、 i_{1a2p} 分别为 α 侧基波正、负序有功电流; i_{1a1q} 、 i_{1a2q} 分别为 α 侧基波正、负序无功电流。

对两相系统来说, 其正、负序之间相位刚好相差 90° ^[14], 故将其 Scott 变压器副端两侧电压用相位延迟器滞后 90° , 得到 α 、 β 侧的无功电压:

$$u_a^* = \sqrt{2} U \sin \omega t \quad (14)$$

$$u_\beta^* = \sqrt{2} U \cos \omega t \quad (15)$$

单相正序电流的检测原理: α 侧对应的正序有功和无功功率分量为

$$\begin{aligned} G_{a1p} &= (u_a i_a + u_\beta i_\beta) = \\ &= 2U \sum_{n=1}^{\infty} I_{1n} \cos[(n-1)\omega t + \theta_{1n}] + \\ &= 2U \sum_{n=1}^{\infty} I_{2n} \cos[(n+1)\omega t + \theta_{2n}] \end{aligned} \quad (16)$$

$$\begin{aligned}
G_{a1q} &= u_{\alpha}^* i_{\alpha} + u_{\beta}^* i_{\beta} = \\
&-2U \sum_{n=1}^{\infty} I_{1n} \sin [(n-1)\omega t + \theta_{1n}] + \\
&2U \sum_{n=1}^{\infty} I_{2n} \sin [(n+1)\omega t + \theta_{2n}] \quad (17)
\end{aligned}$$

式(16)、(17)中包含了正序有功和无功功率的直流与交流分量。通过低通滤波器得到 α 侧基波正序有功和无功功率分量的直流分量表达式:

$$\bar{G}_{1a1p} = 2UI_{11} \cos \theta_{11} \quad (18)$$

$$\bar{G}_{1a1q} = -2UI_{11} \sin \theta_{11} \quad (19)$$

将式(18)、(19)两边同时乘以 α 侧电压 u_{α} 的幅值,得到表达式:

$$\frac{1}{\sqrt{u_{\alpha}^2 + u_{\beta}^2}} \bar{G}_{1a1p} = \frac{2}{\sqrt{u_{\alpha}^2 + u_{\beta}^2}} UI_{11} \cos \theta_{11} \quad (20)$$

$$\frac{1}{\sqrt{u_{\alpha}^2 + u_{\beta}^2}} \bar{G}_{1a1q} = \frac{-2}{\sqrt{u_{\alpha}^2 + u_{\beta}^2}} UI_{11} \sin \theta_{11} \quad (21)$$

将式(20)、(21)分别与单相锁相环得出的单位正、余弦信号 $\sin \omega t$ 、 $\cos \omega t$ 相乘,再乘以增益信号的 $\frac{\sqrt{2}}{2}$ 倍,得到单相瞬时基波正序有功和无功电流:

$$i_{1a1p} = \sqrt{2} I_{11} \cos \theta_{11} \cos \omega t \quad (22)$$

$$i_{1a1q} = -\sqrt{2} I_{11} \sin \theta_{11} \sin \omega t \quad (23)$$

根据正、负序的特性,可以反转 90° 方向,用求基波正序有功电流的方法求解基波负序有功和无功电流。以逆时针方向旋转 β 相参考电压 90° ,得到:

$$u_{\beta}^T = -\sqrt{2} U \sin \omega t = -u_{\beta} \quad (24)$$

$$u_{\beta}^{*T} = \sqrt{2} U \cos \omega t = -u_{\beta}^* \quad (25)$$

同样,用式(16)中求基波正序有功和无功功率分量的方法来求出 α 侧负序有功和无功功率分量:

$$\begin{aligned}
G_{a2p} &= u_{\alpha} i_{\alpha} - u_{\beta} i_{\beta} = \\
&2 \sum_{n=1}^{\infty} I_{1n} \cos [(n+1)\omega t + \theta_{1n}] + \\
&2 \sum_{n=1}^{\infty} I_{2n} \cos [(n-1)\omega t + \theta_{2n}] \quad (26) \\
G_{a2q} &= u_{\alpha}^* i_{\alpha} - u_{\beta}^* i_{\beta} = \\
&2 \sum_{n=1}^{\infty} I_{1n} \sin [(n+1)\omega t + \theta_{1n}] - \\
&2 \sum_{n=1}^{\infty} I_{2n} \sin [(n-1)\omega t + \theta_{2n}] \quad (27)
\end{aligned}$$

将式(26)、(27)所得 α 侧负序有功和无功功率分量

通过低通滤波器,得到 α 侧基波负序有功和无功功率中的直流分量表达式:

$$\bar{G}_{1a2p} = 2UI_{21} \cos \theta_{21} \quad (28)$$

$$\bar{G}_{1a2q} = -2UI_{21} \sin \theta_{21} \quad (29)$$

同理,将式(28)、(29)两边同时乘以 α 侧电压 u_{α} 的幅值,得到表达式:

$$\begin{aligned}
&\frac{1}{\sqrt{u_{\alpha}^2 + u_{\beta}^2}} \bar{G}_{1a2p} = \\
&\frac{1}{\sqrt{u_{\alpha}^2 + u_{\beta}^2}} 2UI_{21} \cos \theta_{21} = 2I_{21} \cos \theta_{21} \quad (30)
\end{aligned}$$

$$\frac{1}{\sqrt{u_{\alpha}^2 + u_{\beta}^2}} \bar{G}_{1a2q} = \frac{-1}{\sqrt{u_{\alpha}^2 + u_{\beta}^2}} 2UI_{21} \sin \theta_{21} \quad (31)$$

将式(30)、(31)分别与单相锁相环得出的单位正、余弦信号 $\sin \omega t$ 、 $\cos \omega t$ 相乘,再乘以增益信号的 $\sqrt{2}/2$ 倍,得到单相瞬时基波负序有功和无功电流:

$$i_{1a2p} = \sqrt{2} I_{21} \cos \theta_{21} \cos \omega t \quad (32)$$

$$i_{1a2q} = -\sqrt{2} I_{21} \sin \theta_{21} \sin \omega t \quad (33)$$

再通过相位对应的基波正序和负序电流求和,可以分别得到负荷电流基波对应的有功和无功电流:

$$\begin{aligned}
i_{1ap} &= i_{1a1p} + i_{1a2p} = \\
&\sqrt{2} I_{11} \cos \theta_{11} \cos \omega t + \sqrt{2} I_{21} \cos \theta_{21} \cos \omega t \quad (34)
\end{aligned}$$

$$\begin{aligned}
i_{1aq} &= i_{1a1q} + i_{1a2q} = \\
&\sqrt{2} I_{11} \sin \theta_{11} \sin \omega t + \sqrt{2} I_{21} \sin \theta_{21} \sin \omega t \quad (35)
\end{aligned}$$

将式(26)、(27)中 α 侧的负序有功和无功功率分量通过低通滤波为均值的滤波器,传统的低通滤波器受截止频率及阶数的影响使得动态效应速度慢,不适合用于负载变化的滤波,而均值滤波器有快速的响应速度,模块实现也简单。

通过将负载基波电流分解为正、负序有功和无功分量,分别得到单相负载基波有功和无功电流,进而得到单相负载电流中的基波、谐波电流:

$$i_{1a} = i_{1aq} + i_{1ap} \quad (36)$$

$$i_{1ha} = i_{\alpha} - i_{1a} \quad (37)$$

检测负载电流中基波有功和无功电流的方法原理如图3所示,其中, i_{Ls} 为负载谐波电流, i_{L1} 为负载侧基波电流。图3中的检测模型简单,模型运行不复杂,不需要矩阵运算,并且多了一个负序分量环节,使得检测在负载突变时能够更加的准确。同时,通过断路器能随意切换到需要的目标电流值,对其他分量的检测没有影响。

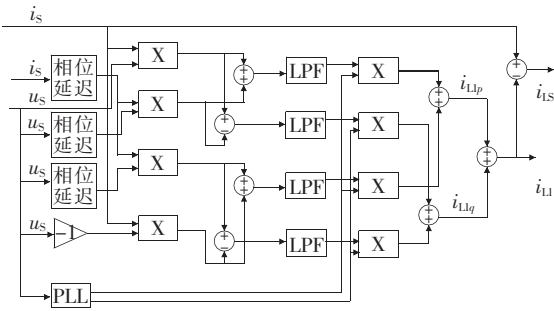


图 3 检测原理示意

Figure 3 Detecting principle diagram

4 系统仿真

针对供电模型(图 1),利用 Matlab/Simulink 仿真电路软件设计搭建仿真供电模型,设置电网侧的电压等级为 110 kV,牵引传动网侧电压为 27.5 kV,其中, L 为 1.5×10^{-3} H,电阻为 $1\ \Omega$,其电力机车上的负载电流变化设置在 $0\sim 0.05$ 、 $0.05\sim 0.3$ s 这 2 个阶段,负载侧的电流波形如图 4 所示,负荷电流在 0.05 s 时有明显的变化,且负荷电流中含有大量的谐波和无功电流分量。

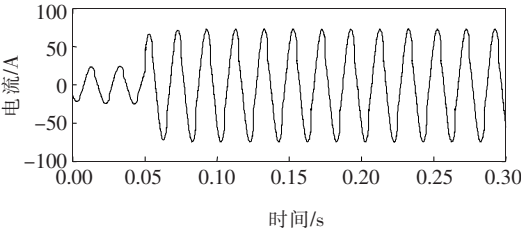


图 4 变压器负载侧电流波形

Figure 4 Current waveform at load side of transformer

检测到的基波正序有功电流如图 5 所示,基波负序无功电流如图 6 所示,可以看出,由于负载突变时负序电流也会立即发生变化,故将负载电流分解为正、负序有功与无功电流,算出负载电流中的负序有功与无功电流大小,可以实现在负载发生突变时也能检测负载基波有功与无功电流大小的目的。

改良方法与传统方法检测的基波有功电流的比较如图 7 所示,可以看出,改良方法在开始检测负载突变时的基波有功与无功电流能很快稳定下来,大大减少了传统方法跟踪负载突变时检测基波有功与无功电流的缓冲时间,在 0.05 s 负载突变时,改良方法检测到突变的基波有功与无功电流只需要四分

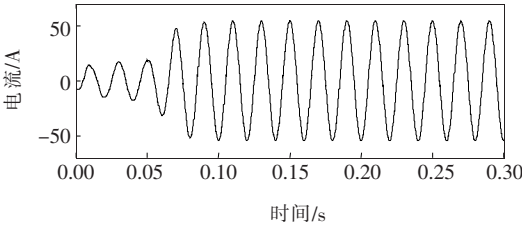


图 5 基波正序有功电流

Figure 5 Fundamental positive sequence active current

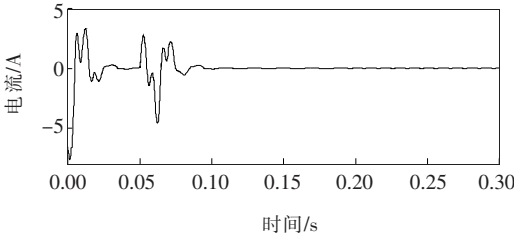


图 6 基波负序无功电流

Figure 6 Fundamental negative sequence reactive current

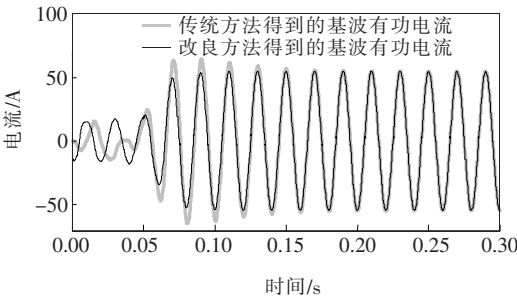


图 7 瞬时基波有功电流比较

Figure 7 Comparison of instantaneous fundamental active current

之一个周期的缓冲时间,而传统方法需要 3 个周期的缓冲时间才能跟踪到基波瞬时有功与无功电流,在负载不变时其负载电流中的基波负序有功分量为 0。在负载突变的情况下,上述方法检测的基波有功电流检测效果更好。

该次检测采样得到的基波正序、负序无功电流分别如图 8、9 所示,可以看出,在负载突变时,0、0.05 s 时会有一段明显的负序分量。检测到的瞬时基波无功电流比较如图 10 所示,可以看出,由传统方法检测得到的波形在检测初期和负载变化时会会有一个明显的缓冲时段,其瞬时基波无功电流在 0.05 s 的缓冲时刻内大约需要 3 个周波的缓冲时间才能稳定下来,而采用重新改良后的方法检测基波有功电流时,除了检测开始阶段与 0.05 s 时刻,变压器副端两侧负载突变会有四分之一的延时,其他

时间的电流都能很快地稳定下来,并实时跟踪突变的负序分量,大大提高了电流在负荷突变的动态性能。

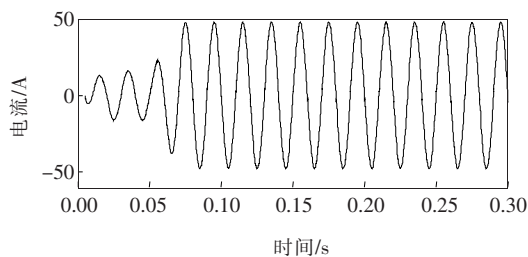


图 8 基波正序无功电流

Figure 8 Fundamental positive sequence reactive current

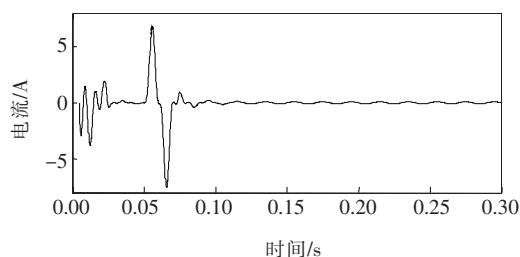


图 9 基波负序无功电流

Figure 9 Fundamental negative sequence reactive current

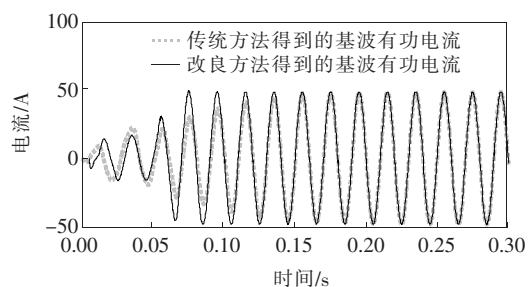


图 10 瞬时基波无功电流比较

Figure 10 Comparison of instantaneous fundamental reactive current

5 结语

该文提出的改良方法在单相负载突变的情况下能更好地检测出基波有功和无功电流,通过利用相位延迟器将 Scott 变压器副端两侧电压滞后 90° ,形成各自的无功电压,结合瞬时无功功率理论,在负载电流突变时,将基波有功和无功电流中的正、负序分量分解出来,得到负载突变时的负序有功和无功分量,其动态性能得到了很大的提高,减少了因突变引起的检测缓冲时间,为后续的平衡补偿装置提供了及时的补偿信息。

该法也可应用于铁路供电系统中的四相供电系统,省去延迟器构造另外两相无功电压的时间,不需检测负序有功和无功电流的四分之一延时,检测效果更好。

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