Analysis and design of reduced order linear quadratic regulator control for three phase power factor correction using Cuk rectifiers

M.G. Umamaheswarī, G. Uma

A D I T I O N A L A N D E N C O R R E C T I O N

In this paper, the analysis and design of reduced order linear quadratic regulator (ROLQR) control for power factor correction (PFC) in a three phase system is presented. The front end is a three phase diode rectifier followed by DC–DC Cuk converter modules with the common DC output. Instantaneous symmetrical component theory is used for the generation of reference current. The control strategy uses three inner ROLQR current controllers for source current shaping and an outer voltage loop using PI controller for load voltage regulation. It uses a single stage converter for both PFC and voltage regulation. The proposed method offers simple control strategy, fast transient response and power factor close to unity. This type of three-phase three switch PFC converter features a simple and robust configuration compared to conventional six switch topology. To validate the proposed method, a prototype controlled by dSPACE 1104 signal processor is set up. Simulation and experimental results indicate that the proposed system offers regulated output voltage for wide load variations and power factor close to unity. © 2012 Elsevier B.V. All rights reserved.

1. Introduction

Recently, there is growing awareness about line pollution and deteriorating power factor due to the usage of pervading inductive and non-linear loads. Although many solutions were offered for single phase power factor correction (PFC), three phase active PFC was seldom considered. As all high power equipment derive electrical power from three phase mains, incorporating an active three phase PFC front end can contribute significantly in improving the overall power factor and reducing line pollution. Many literature have been proposed for PFC. A three-phase single switch PFC topology has the merits of simple control and few components [1–5]. This type of converter suffers due to Discontinuous Conduction Mode (DCM) operation, causing high current stresses on the power devices. A three phase six switch Pulse Width Modulation (PWM) boost rectifier is widely used for high–power applications. Advantages of this type of rectifier are high efficiency and good current quality. But the PWM rectifier needs a complex control structure and the efficiency is lower than the diode rectifier due to additional switching losses [6–13]. A three-phase three-switch topology composed of three single-phase single-switch modules was proposed for PFC in [14,15]. Even though the above method offers simple control implementation, it fails to operate in case of one or two module failures. A derived version of buck boost rectifier is a Cuk rectifier that inverts the voltage polarity and can also simultaneously increase or decrease the voltage magnitude. It has excellent features such as capacitive energy transfer, magnetic components integrability, full transformer utilization and good steady-state performance. It also provides smooth input and output currents due to the presence of inductors in the input and output side [16].

Many methods for generating the reference template were proposed. In [17–19] the instantaneous reactive power theory was proposed (i.e. p–q theory) for calculating the reference currents. The general equation for deriving the reference current which relates the new concept of instantaneous active and reactive theory was reported in [20], but no detailed information was given for DC bus voltage compensation. In [21], the extended p–q theory was proposed to derive a more general vector equation for calculating the reference currents. This method does not operate satisfactorily for module loss. In [22], only the final formulation of the extracted reference current was reported. In [23] and [24], PFC using Cuk rectifier modules was proposed and reference current was generated using power balance control technique. The extraction of reference current based on instantaneous symmetrical component theory involves simple computations based on the instantaneous
source voltages and currents and it does not require any three phase
to two phase conversions.

The classic Linear Quadratic Regulator (LQR) approach deals
with the optimization of a cost function or performance index. Thus,
the designer can weigh which states are more important in the con-
trol action to seek for appropriate performance. This feature of LQR
control has initiated several researchers to successfully apply this
technique in the field of power electronics. In [25] and [26], the
performance indices are selected using pole placement technique.
This method depends on the exact placement of closed loop poles.
In [27], the cost function is derived from an initial controller by
frequency domain method which is a time consuming procedure.
Optimal control provides a systematic way of designing a LQR con-
troller and problem of where to place the closed loop poles does
not arise and is robust to parameter and load variations.

Hence, it is proposed to develop a single stage three phase
AC–DC converter using Cuk rectifier modules based on ROLQR con-
trol for achieving voltage regulation and PFC. The instantaneous
symmetrical component theory is used for calculating the refer-
ence currents. To reduce the complexity in analysis, a reduced order
model of Cuk converter is obtained from the higher order state
space model [28,29] by Padé’s approximation technique. The outer
voltage loop compensator is designed using Ziegler Nichol’s tuning
procedure.

2. Modeling of DC–DC Cuk converter

Fig. 1(a) represents the circuit diagram of the Cuk converter. It
consists of two inductors \( L_i \), \( L_o \) and two capacitors \( C_t \), \( C_o \), \( V_s \) and
\( V_o \) represent supply and output voltage, respectively, \( S \) is an active
switch, \( D \) is a freewheeling diode and \( R_o \) is the load resistance. \( S \)
operates at a switching frequency \( f_s \) with duty ratio \( d \).

To obtain the mathematical model of the controller, the state
model of Cuk converter is derived by considering \( S = 1 \) during the
MOSFET switch conduction subinterval and \( S = 0 \) during the diode
conduction subinterval. The converter dynamics is described by
state–space averaging method and by using the same method, the
state equations during switch-on and switch-off conditions are
combined as follows:

\[
\begin{align*}
\frac{d x_1}{dt} & = \frac{(1-d)}{L_i} x_3 + \frac{V_s}{L_i} \\
\frac{d x_2}{dt} & = \frac{d}{L_o} x_3 - \frac{1}{L_o} x_4 \\
\frac{d x_3}{dt} & = \frac{(1-d)}{C_t} x_1 - \frac{d}{C_t} x_2 \\
\frac{d x_4}{dt} & = \frac{1}{C_o} x_2 - \frac{1}{R_i C_o} x_4
\end{align*}
\]

(1)

where \( x_1, x_2, x_3, x_4 \) are the current through the inductor \( (i_i) \), cur-
rent through the inductor \( (i_o) \), voltage across the transfer capacitor
\( (v_t) \), voltage across the output capacitor \( (v_o) \), respectively, and \( d \)
represents the duty cycle. From Eqs. (1)–(4), the averaged system
matrices are derived as given below:

\[
A = \begin{bmatrix}
0 & 0 & (1-d) & 0 \\
0 & 0 & d & -1 \\
(1-d) & -d & 0 & 0 \\
0 & 1 & 0 & -1/R_o C_o
\end{bmatrix}, \quad B = \begin{bmatrix}
1 \\
0 \\
0 \\
0 \end{bmatrix}
\]

(5)

2.1. Design of DC–DC Cuk converter components

A Cuk PFC was designed [23] with the following specifications:
rectified input voltage \( V_s = 24 \text{ V} \), line frequency 50 Hz, power fac-
tor \( > 0.99 \), maximum output power \( P_o = 56 \text{ W} \), \( R_i = 10 \text{ } \Omega \), output DC
voltage \( V_o = -24 \text{ V} \), efficiency \( \eta > 85\% \). DC voltage conversion
ratio \( M \) is given by

\[
M = \frac{V_o}{V_s} = 0.704
\]

(6)

Conduction parameter of the Cuk PFC circuit

\[
K_a > \frac{1}{(2(M + |\sin(\theta)|)^2)} > 0.1752
\]

(7)

An equivalent inductance is given by

\[
L_{eq} = \frac{R_i T_o K_a}{2} = 0.667 \text{ mH}
\]

(8)

By choosing the input inductor current with 6.75% current ripple,
\( \Delta i_l = 0.169 \text{ A} \). The design of \( L_i \) and \( L_o \) is made using the desired
ripple value of the input current. For the duty ratio \( d = 0.5 \), switching
frequency \( = 50 \text{ kHz} \), switching period \( T_o = 0.25 \mu \text{s} \), the input in-
ductor value is found to be

\[
L_i = \frac{V_s d T_o}{\Delta i_l} = 2 \text{ mH}
\]

(9)

The output inductor value is found to be

\[
L_o = \frac{L_i L_{eq}}{L_i - L_{eq}} = 1 \text{ mH}
\]

(10)

Transfer capacitor value is calculated by considering a resonant
frequency of 1 kHz and is given by

\[
C_t = \frac{1}{\omega_o^2 (L_i - L_o)} = 25.35 \text{ } \mu \text{F}
\]

(11)

To select the output capacitance value in this circuit, the main
factor is the output ripple voltage which is caused by the second
harmonic. The equation to define the output capacitance value can
be expressed as

\[
C_o = \frac{P_m}{2 \pi f_r V_o \Delta V_o} = 2211 \text{ } \mu \text{F}
\]

(12)

where \( \Delta V_o \) is the peak value of the output ripple voltage \( = 0.6 \text{ V} \)
(2.5% of the output voltage) and \( f_r \) is the second harmonic frequency.
The design values are substituted in (5) and after applying phase
variable transformation, A and B matrices become,

\[
A = \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
-6.3 \times 10^{-12} & -1.87 \times 10^5 & -3.8 \times 10^7 & -50 \\
0 & 0 & 0 & 1
\end{bmatrix}, \quad B = \begin{bmatrix}
0 \\
0 \\
0 \\
1
\end{bmatrix}
\]

(13)

The main objective is to shape the input source current and to regu-
late the output voltage of the DC–DC Cuk converter. The converter
requires sensing of four state variables, which is not acceptable
from practical point of view. In order to reduce the complexity in
controller design, the fourth order model of a Cuk converter is
reduced to a second order model. The model reduction technique
used is Padé’s approximation, wherein the two dominant poles of
the system i.e. the input inductor current, \( i_l \) and the output capaci-
tor voltage, \( v_o \), are retained and the effects of the transfer capacitor
\( C_t \), and the output inductor \( L_o \) are neglected. Hence it becomes suf-
cient to regulate these two variables \( i_l, v_o \) using the ROLQR control
strategy. The reduced order matrix for the above system is given as

\[
A = \begin{bmatrix}
0 & 1 \\
-1.64 \times 10^4 & -49.34
\end{bmatrix}, \quad B = \begin{bmatrix}
0 \\
1
\end{bmatrix}
\]

(14)
دریافت فوری
متن کامل مقاله

امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات