A single-phase twin-buck inverter

by Hanny Tumbelaka

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Felix Pasila
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Contents

Introduction

This book includes the original, peer-reviewed research papers from the 2nd International Conference on Electrical Systems, Technology and Information (ICESTI 2015), held during 9–12 September 2015, at Patra Jasa Resort & Villas Bali, Indonesia.

The primary objective of this book is to provide references for dissemination and discussion of the topics that have been presented in the conference. This volume is unique in that it includes work related to Electrical Engineering, Technology and Information towards their sustainable development. Engineers, researchers as well as lecturers from universities and professionals in industry and government will gain valuable insights into interdisciplinary solutions in the field of Electrical Systems, Technology and Information, and its applications.

The topics of ICESTI 2015 provide a forum for accessing the most up-to-date and authoritative knowledge and the best practices in the field of Electrical Engineering, Technology and Information towards their sustainable development. The editors selected high quality papers from the conference that passed through a minimum of three reviewers, with an acceptance rate of 50.6 %.

In the conference there were three invited papers from keynote speakers, whose papers are also included in this book, entitled: "Computational Intelligence based Regulation of the DC bus in the On-Grid Photovoltaic System", "Virtual Prototyping of a Compliant Spindle for Robotic Deburring" and "A Concept of Multi Rough Sets Defined on Multi-Contextual Information Systems".

The conference also classified the technology innovation topics into five parts: "Technology Innovation in Robotics, Image Recognition and Computational Intelligence Applications", "Technology Innovation in Electrical Engineering, Electric Vehicle and Energy Management", "Technology Innovation in Electronic, Manufacturing, Instrumentation and Material Engineering", "Technology Innovation in Internet of Things and Its Applications" and "Technology Innovation in Information, Modeling and Mobile Applications".

In addition, we are really thankful for the contributions and for the valuable time spent in the review process by our Advisory Boards, Committee Members and Reviewers. Also, we appreciate our collaboration partners (Petra Christian

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On behalf of the editors Felix Pasila

Chapter 21
A Single-Phase Twin-Buck Inverter

Hanny H. Tumbelaka

Abstract This paper proposes a simple single-phase twin-buck inverter to interface a DC source such as a renewable energy source to AC loads. It consisted of two identical buck converters with a sinusoidal duty ratio. The first converter produced a positive half cycle of a 50 Hz sinusoidal output voltage, and the second converter produced the negative one. Then, both of them are integrated using transistors Q3 and Q4. By shifting the phase angle of signals for triggering transistor Q3 and Q4 from a sinusoidal reference signal, the distortion around zero crossing was reduced. The computer simulation results show that the output voltage and current were sinusoidal with harmonic distortion of 1.12 and 0.49 % respectively.

Keywords Buck converter · Single-phase inverter

21.1 Introduction

An inverter converts a DC voltage source or a DC current source to an AC voltage/current. It takes power from a DC source and sends the power to AC loads using power electronic devices. An inverter can be used to interface a renewable energy source such as PV panels to AC loads or a grid [1, 2]. A solar home system is one of the single-phase inverter application. Lamps and home appliances are connected to PV panels as well as to batteries through a single-phase inverter.

There are many types of a single-phase inverter. The most common inverter, especially a voltage source inverter (VSI) is a single-stage bridge pulse-width-modulation (PWM) inverter [2–4]. It generally consists of four switches configured as a bridge with a filter. PWM signals trigger the switches to generate a sinusoidal AC waveform. Recently, a dual-buck full-bridge inverter [5, 6] as well as a two identical boost or buck-boost inverter [1] has been proposed. The main idea in

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developing this inverter was to mitigate a shoot-through problem in a bridge voltage source inverter, which was usually overcome by a dead time to block the upper and lower transistors of each leg.

A different configuration for a single-phase stand-alone inverter comprising of two identical but independent step-down DC-DC converters is presented in this paper to generate a sinusoidal voltage. Basically, a step-down (buck) DC-DC converter changes a high DC value from a DC source to a low DC value needed by a DC load. Therefore, this proposed inverter is very simple and easy to implement. The controller is uncomplicated as well. By varying the duty ratio, it is possible to create a sinusoidal inverter.

21.2 Circuit Configuration

21.2.1 A Basic Step-Down DC-DC Converter

A Single-phase Twin-Buck inverter basically consists of two step-down DC-DC converters. A schematic diagram of a single step-down (buck) DC-DC converter is shown in Fig. 21.1. The working principle of a buck converter has been elaborated in [3, 4]. The transistor is switched ON (during t_{ON}) and OFF (during t_{OFF}). $t_{ON} + t_{OFF} = T_S = 1/f_S$, f_S is a fixed switching frequency. When the transistor is on (mode 1), the inductor current (i_L) builds up. Energy is transferred to the capacitor and the load from the DC voltage source (V_S). The inductor current for mode 1 ($0 \leq t \leq t_{ON}$) is:

$$V_S = V_O + L\frac{di_L}{dt} \tag{21.1}$$

$$i_L(t) = \frac{V_S - V_O}{L}t + I_{L1(0)} \tag{21.2}$$

where $I_{L1(0)}$ = initial value of i_L for mode 1, and V_O = output voltage

When the transistor is switched off (mode 2), the energy stored in the inductor (L) is released to the capacitor and the load through the free-wheeling diode (D_F). The inductor current decreases. The inductor current for mode 2 ($t_{ON} \leq t \leq T_S$) is:

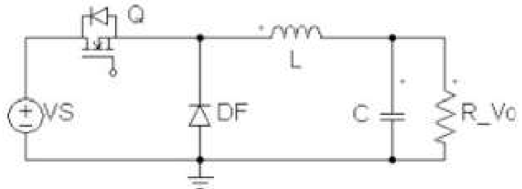

Fig. 21.1 A Step-down (buck) DC-DC converter

$$0 = V_O + L\frac{di_L}{dt} \tag{21.3}$$

$$i_L(t) = \frac{-V_O}{L}t + I_{L2(0)} \tag{21.4}$$

where $I_{L2(0)}$ = initial condition of i_L for mode 2.

In a stable operating cycle, the average inductor voltage is zero, then

$$(V_S - V_O)t_{ON} - V_O t_{OFF} = 0 \tag{21.5}$$

where $t_{ON} = KT_S$ and $t_{OFF} = (1\text{-}K)\,T_S$. K = duty ratio, constant value in a range 0–1.

Solving the Eq. (21.5), the relationship of the input-output voltage of the step-down converter is

$$\frac{\boldsymbol{V_O}}{\boldsymbol{V_S}} = \frac{\boldsymbol{t_{ON}}}{\boldsymbol{t_{ON}} + \boldsymbol{t_{OFF}}} = \boldsymbol{K} \tag{21.6}$$

The Eq. (21.6) is valid when the inductor current stays in a continues conduction mode (CCM), which is i_L (t) > 0. $I_{L1(0)}$ and $I_{L2(0)}$ never go to zero.

21.2.2 A Single-Phase Twin-Buck Inverter

In order to generate a sinusoidal output voltage using a buck converter, t_{ON} and t_{OFF} can be varied in proportion to the amplitude of a sine wave. In this case, the duty ratio K is not a constant but has to be controlled according to a sinusoidal pulse-width-modulation (SPWM) rule [3]. The duty ratio becomes k (t) = m_a sin t, where $0 \le m_a \le 100$ %. Then, from Eq. (21.6), the output voltage becomes

$$V_O = V_S m_a \sin t \tag{21.7}$$

However, the converter only produces a positive voltage. Therefore, to generate a complete 50 Hz sinusoidal output voltage, two identical step-down (buck) DC-DC converters are needed. The first converter produces a positive half cycle of a sine wave, while the second converter produces a negative half cycle of a sine wave by inverting the output voltage. Both of them are independent. Hence, each converter only operates in a half period (10 ms).

Figure 21.2 shows the two identical (twin) step-down (buck) DC-DC converter working as an inverter.

From Fig. 21.2, both the upper and the lower buck converter generate a positive half cycle of a 50 Hz sine wave. To produce a sinusoidal output voltage, transistors Q3 and Q4 are used to connect both converters to the load. When Q3 is switched on (Q4 is switched off), the load receives the voltage from the upper converter.

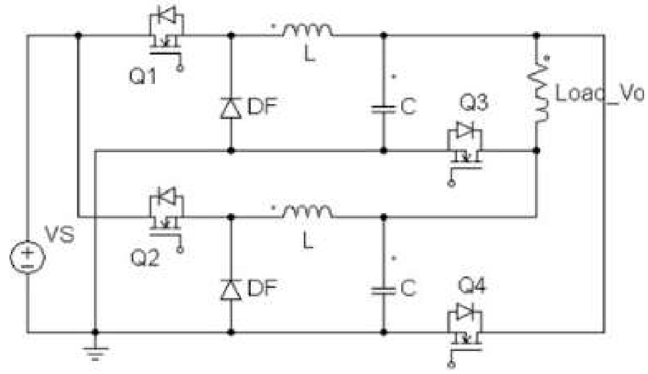

Fig. 21.2 A twin-buck inverter circuit

When Q4 is switched on (Q3 is switched off), the load receives the voltage (inverting) from the lower converter. The transition happens in zero crossing of a sine wave. Hence, for a full period (20 ms for 50 Hz), the load receives an AC sinusoidal voltage.

21.3 Inverter Controller

In order to generate a sinusoidal duty ratio (k(t)), a SPWM controller is used. The circuit diagram of the controller is shown in Fig. 21.3.

V_{REF} is a sinusoidal reference signal with frequency of 50 Hz and the amplitude of m_a. As carrier signals with a constant high switching frequency, V_{TRI} (1) is a triangular wave above the t axis, and V_{TRI} (2) is a triangular wave below the t axis. As a result, during a positive half cycle, the controller produces SPWM signals to trigger transistors Q1, while signals for Q2 are low. The controller also generates a 50 Hz signal for transistor Q3, which is high. During a negative half cycle, the controller produce SPWM signals to trigger Q2, while signals for Q1 are low. The controller also generates a 50 Hz signal for transistor Q4, which is high.

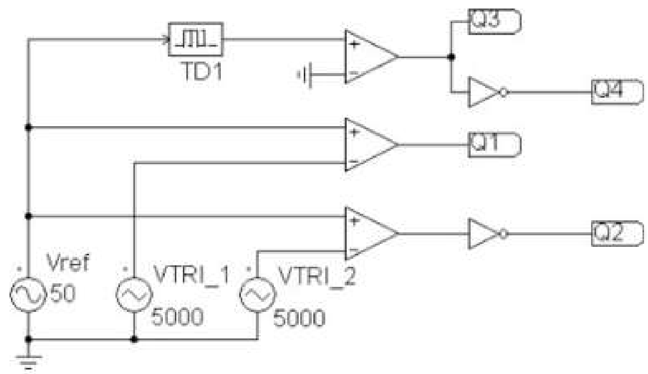

Fig. 21.3 Control circuit diagram

Figures 21.4 and 21.5 demonstrate the sinusoidal reference signal V_{REF} and the carrier signals V_{TRI} (1) and V_{TRI} (2). In this case, the V_{TRI} amplitude = 1 and the frequency is 5 kHz. The amplitude of V_{REF} (m_a) = 0.95 and the frequency is 50 Hz. By using comparators, the controller generates SPWM signals for triggering transistor Q1 and Q2 as shown in Fig. 21.6.

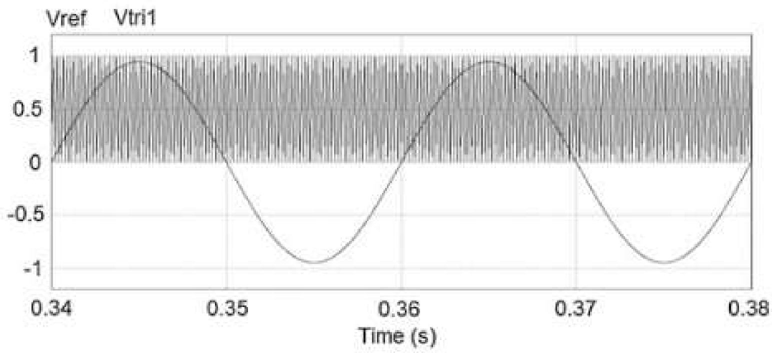

Fig. 21.4 V_{REF} and V_{TRI} (1)

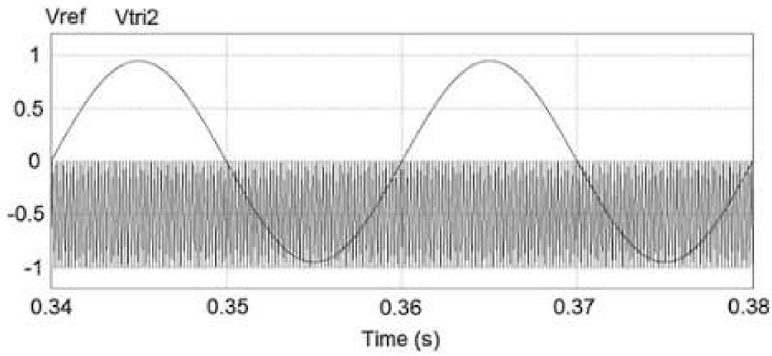

Fig. 21.5 V_{REF} and V_{TRI} (2)

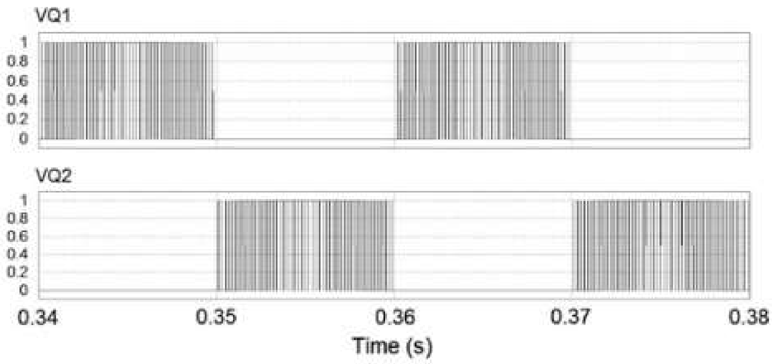

Fig. 21.6 SPWM signals for triggering transistors Q1 and Q2

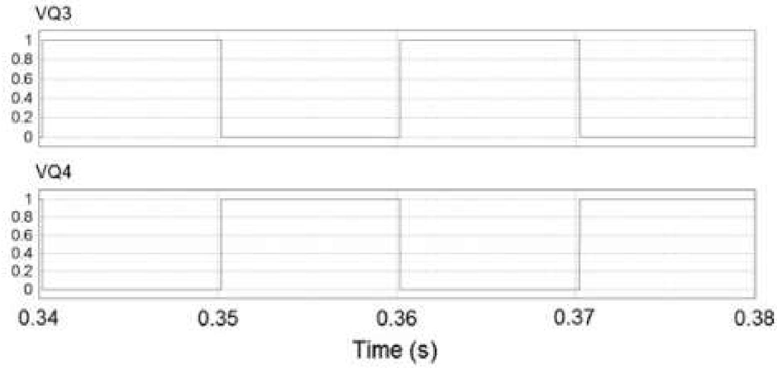

Fig. 21.7 Square signals for triggering transistors Q3 and Q4

Figure 21.7 shows signals for triggering transistors Q3 and Q4. V_{REF} is compared to a zero voltage. During a positive half cycle, the comparator output voltage (Q3) becomes high, and Q4 becomes low. During a negative half cycle, the comparator output voltage (Q3) becomes low, and Q4 becomes high. TD1 is used to shift V_{REF} for several degrees. As a result, the phase of the comparator output voltage Q3 and Q4 will also be shifted compared to the phase of V_{REF}.

21.4 Simulation Results

The circuits in Figs. 21.2 and 21.3 are tested using PSIM simulator to verify the concepts described in previous sections. Circuit parameter values for simulation: source voltage V_S = 24 V, L = 1.2 mH, C = 47 μF, Rload = 6 Ω and Lload = 1.4 mH.

Figure 21.8 demonstrates that the output voltage of the twin-buck inverter is sinusoidal similar to the sinusoidal reference signal V_{REF}. The amplitude equals to a

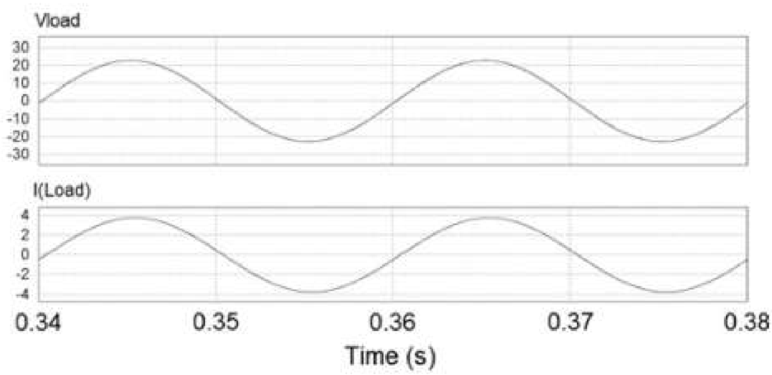

Fig. 21.8 Output voltage and current

DC input voltage (V_S) multiplied by m_a. It is proven that the twin-buck inverter is able to generate an AC sinusoidal voltage. The transition between a positive half cycle and a negative half cycle is smooth. The total harmonic distortion (THD) of this output voltage is 1.12 %. Figure 21.8 also shows the load current, which is an AC sinusoidal current. There is a small phase difference between the output voltage and current due to an inductive component of the load. The total harmonic distortion (THD) of this output current is 0.49 %.

The process to create an AC sinusoidal voltage can be seen from inductor currents i_L (Fig. 21.9) and capacitor voltages V_C (Fig. 21.10). The inductor currents is going up and down in high frequency when the transistor is switched on and off. Because t_{ON} and t_{OFF} are varied according to a sinusoidal duty ratio, then the inductor currents look like a sinusoidal waveform with ripples according to Eqs. (21.2) and (21.4). Figure 21.9b shows the inductor current in detail. The inductor currents are in continuous conduction. Figure 21.10 shows the capacitor voltages. The value of a capacitor determines the ripple of the output voltage. It can be seen that each step-down DC-DC converter operates in a half period and generates a positive half cycle of a sinusoidal waveform.

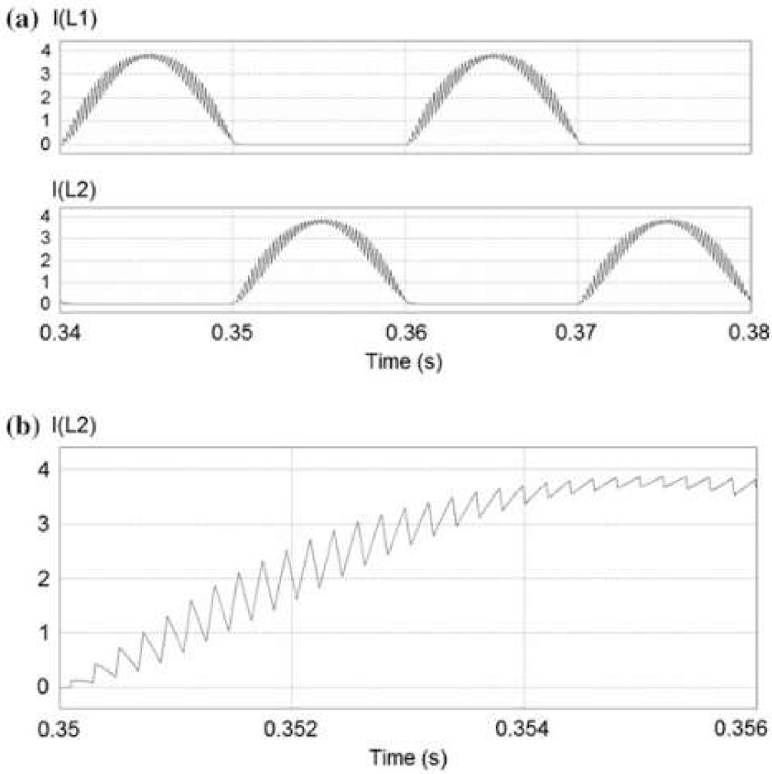

Fig. 21.9 **a** inductor current **b** inductor current in details for time period 0.35 s–0.356 s

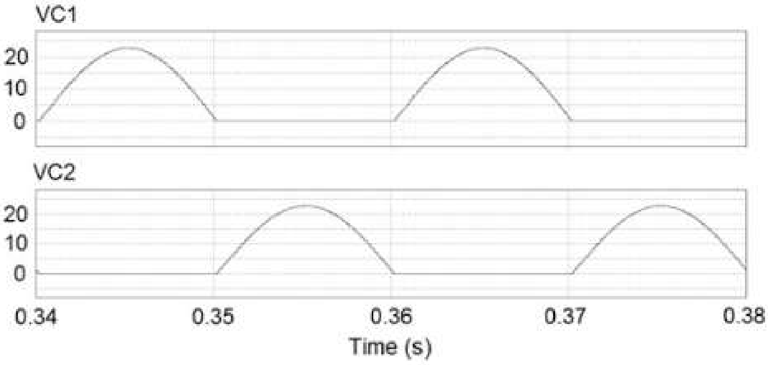

Fig. 21.10 Capacitor (output) voltages

21.4.1 V_{REF} Phase Delay

As mention before in Fig. 21.3, there is a function block TD1 that shifts V_{REF} for several degree. As a result, there is a phase difference between V_{REF} and square signals to trigger transistors Q3 and Q4. The phase shift is needed to overcome the problem of zero-crossing distortion [6]. In the simulation results above, the phase delay is selected to be 3.5^{o}.

Figure 21.11 shows the output voltage and current without phase shift. It can be seen that there is a distortion around zero crossing of the sinusoidal waveform. The total harmonic distortion (THD) of the output voltage and current are 2.42 % and 1.43 % respectively. Compare to inductor current in Fig. 21.9b, the inductor current without phase shift (Fig. 21.12) goes to discontinuous conduction around zero crossing. Consequently, the capacitor voltage is distorted (Fig. 21.13).

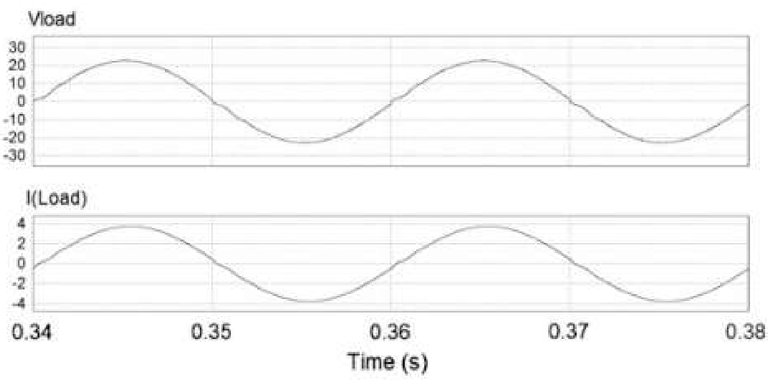

Fig. 21.11 Output voltage and current without phase shift

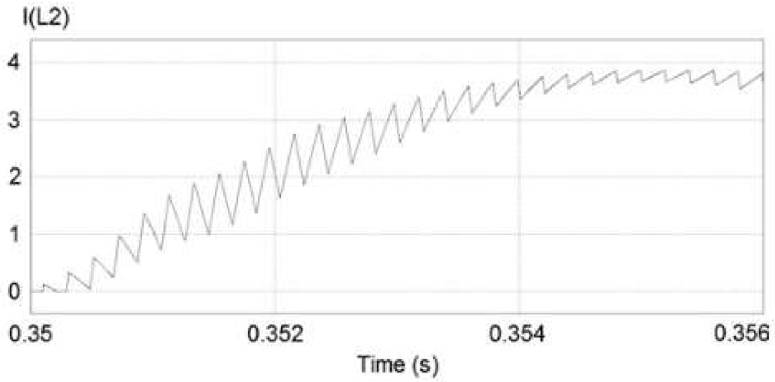

Fig. 21.12 Inductor current without phase shift

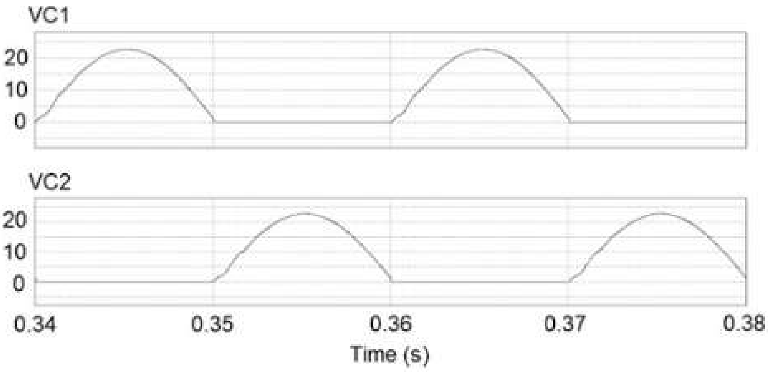

Fig. 21.13 Capacitor voltages without phase shift

21.5 Conclusion

This paper proposes a single-phase twin-buck inverter. The inverter interfaces a DC source to AC loads. It consists of two identical step-down (buck) DC-DC converters with a sinusoidal duty ratio. The first converter produces a positive half cycle of a 50 Hz sinusoidal output voltage, and the second converter produces the negative one. Each converter operates in a half period and generates a positive half cycle of a sinusoidal waveform. Then, both of them are integrated using 2 transistor that operate alternately every 10 ms. By shifting the phase angle of signals (3.5^{o}) for triggering transistor Q3 and Q4 from V_{REF}, the distortion around zero crossing is reduced. Simulation using PSIM shows that the inverter generates a 50 Hz sine wave. The output voltage THD becomes 1.12 %.

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